The Radiological Accident in Yanango

The cover picture shows the hydroelectric plant at Yanango.

THE RADIOLOGICAL ACCIDENT IN YANANGO

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FOREWORD

The use of radioactive materials offers a wide range of benefits throughout the world in medicine, research and industry. Precautions are, however, necessary in order to limit the exposure of persons to the radiation that is emitted. Where the amount of radioactive material is substantial, such as with sources used in radiotherapy or industrial radiography, extreme care is necessary to prevent accidents that may result in severe consequences for the affected individuals. Nevertheless, in spite of the precautions taken, accidents with radiation sources continue to occur, albeit infrequently. As part of its activities dealing with the safety of radiation sources, the IAEA follows up severe accidents with a view to providing an account of their circumstances and the medical aspects from which those organizations with responsibilities for radiation protection and the safety of sources may learn.

A serious radiological accident occurred in Peru in February 1999 when a welder picked up an ^{192}Ir industrial radiography source and put it in his pocket for several hours. This resulted in his receiving a high radiation dose that necessitated the amputation of one leg. His wife and children were also exposed, but to a much lesser extent.

The Peruvian authorities requested assistance from the IAEA in obtaining advice on medical treatment. They also agreed to assist the IAEA with the subsequent review of the circumstances surrounding the accident.

The IAEA is grateful to the Instituto Peruano de Energía Nuclear for its willingness to assist in the preparation of this report and, thereby, share its experience with other Member States. The IAEA is also grateful for the assistance of staff and experts from the: University of New Mexico, Albuquerque, USA; the Radiation Emergency Assistance Center/Training Site (REACS/TS), US Department of Energy, USA; the Instituto de Enfermedades Neoplásicas, Peru; the Institut de protection et de sûreté nucléaire, France; and the Percy Hospital, Paris.

The IAEA technical officers responsible for preparation of this report were J. Wheatley and I. Turai of the Division of Radiation and Waste Safety.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Industrial radiography is used throughout the world to examine the structural integrity of materials in a non-destructive manner. In Peru there are 15 licensed users of industrial radiography sources. On 20 February 1999, a serious radiological accident occurred at the Yanango hydroelectric power plant in Peru when a worker (a welder) picked up an ^{192}Ir industrial radiography source and put it in his pocket, where it remained for several hours. This resulted in him receiving a high radiation dose that necessitated the amputation of one leg. His wife and children were also exposed, but fortunately to a much lesser extent. The accident is described in detail in Section 3.

The IAEA is authorized to establish standards for radiation protection and the safety of sources of radiation, and to assist in their application. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [1] establish the requirements for protection and safety. It is presumed in the BSS that States have an adequate legal and regulatory infrastructure within which the requirements can effectively be applied. Requirements and guidance relating to the establishment of an appropriate infrastructure and occupational radiation protection have been issued [2, 3].

1.2. OBJECTIVE

For a number of years, the IAEA has provided support and assistance, and conducted follow-up investigations upon request, in the event of serious accidents involving radiation sources. Reports have been published on these investigations of radiological accidents, for example, in San Salvador, El Salvador [4], Soreq, Israel [5], Hanoi, Viet Nam [6], Tammiku, Estonia [7] and Goiânia, Brazil [8, 9]. The findings and conclusions of these reports have provided a basis for lessons to be learned on safety improvements [10–12].

The objective of this report is to compile information about the causes of the accident, the subsequent emergency response and the medical aspects of the exposures. The information is intended for the use of 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. The report concludes with findings, conclusions and lessons to be applied in order to help avoid such accidents in the future and to minimize the consequences of any such accidents that do occur.

1.3. SCOPE

This report describes the circumstances and events relating to the accident. A number of uncertainties remain relating to the detail of those events. Also, there will be further health effects in the future for the exposed person. However, sufficient information is available at this stage for a report to be written giving some substantive conclusions and advice. The report also presents information and conclusions relevant to licensees, operating organizations, radiation protection staff and the medical community.

1.4. STRUCTURE

Background information about the radiation protection infrastructure in Peru, a description of the management of the company involved in the accident and details of the source are provided in Section 2. An account of the circumstances and events of the accident are given in Section 3. The emergency response to the accident, which included the recovery of the source, and the responses from the Peruvian authorities and from the IAEA are discussed in Section 4. Section 5 summarizes the health consequences and medical treatment of the patient, and Section 6 summarizes the dosimetric analysis. The account of the circumstances of the accident in Sections 2–6 is based on information made available to the IAEA by or through the authorities of Peru and France. The overall conclusions and lessons learned are presented in Section 7.

2. BACKGROUND INFORMATION ON THE CIRCUMSTANCES OF THE ACCIDENT

2.1. RADIATION PROTECTION INFRASTRUCTURE IN PERU

The national authority responsible for regulating radiation safety in Peru is the Instituto Peruano de Energía Nuclear (IPEN). There are almost 1200 authorized users of radiation sources in the country, 70% of which use medical diagnostic X ray equipment.

The regulatory functions of IPEN include inspection, enforcement and issuing of licences and regulations. These tasks are performed through the Technical Office for the National Authority, which reports directly to the President of IPEN. This Office consists of the Department of Installations Control and Safeguards, and the Department of Regulations and Authorization.

The regulatory activities in the Technical Office are performed by four staff members who are qualified in radiation and nuclear safety matters. Additionally, there are four contract staff members who are available to carry out inspections of medical X ray installations.

In addition to its regulatory functions, IPEN has other functions related to the development, research and promotion of nuclear energy (Fig. 1).

The first national regulation on radiation protection was issued in 1980 and was prepared by a joint technical committee of IPEN and the Health Ministry. The current 'Regulation for Radiological Safety' was approved by supreme decree in 1997 and is the main regulation in Peru. It includes recommendations from ICRP Publication 60 [13] and the BSS [1] and also those derived from national experience. All other rules are based on this main regulation.

The main regulation establishes the technical and administrative requirements to be accomplished by all persons performing activities involving radiation sources.

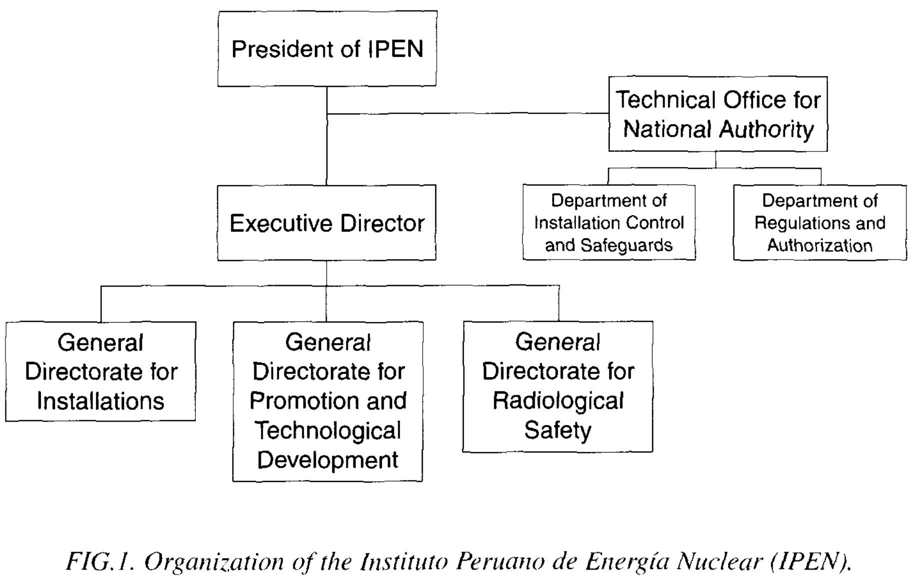

FIG.1. Organization of the Instituto Peruano de Energía Nuclear (IPEN).

The regulation also requires that users must (a) notify IPEN of all activities involving radiation sources and (b) request an authorization. Authorization is needed both for installations and for individuals who operate or handle radiation sources. There is no specific rule for industrial radiography and evaluation of the practice is based on the main regulation and other recommendations and criteria.

Legal actions can be undertaken by national authorities under the rule on the 'Regime of Sanctions against Violations of Radiation Safety Regulations'.

Authorizations from IPEN may be in the form of a registration or licence, depending on the type of installation. The categorization of installations is established in the rule on 'Control of Radiation' according to the potential radiation risk, type of authorization and frequency of inspection. Those installations that entail low radiation risk need only a registration, whereas high risk installations require a licence. Industrial radiography is categorized as a high risk practice and requires a licence. Currently, there are 15 radiography companies operating in Peru.

The licensing procedure begins when the user sends an application with attached technical information to IPEN. The technical information has to include a description of the installation and radiation sources, radiation safety measures, organizational procedures and emergency plans. The information is evaluated by staff of the Technical Office, who perform an inspection to verify that the information provided by the applicant is correct. If the results of the evaluation and the inspection satisfy the criteria on radiological safety, a licence is granted; otherwise the user is required to correct the identified deficiencies in a given time. The licence is issued with specific conditions and limitations that cover the authorized location, the authorized camera (manufacturer, model and serial number), the authorized source (radionuclide, maximum activity), operational requirements, emergency requirements, transport and source disposal. The licence must also request a specific authorization to import any replacement sources.

Since 1992, radiography companies are required to renew their licences annually. The renewal application is submitted to IPEN with an annual report stating how the licensee has adhered to the conditions and limitations of the licence, reporting any abnormal events, and providing copies of dosimetry records and a list of licensed workers. The renewal application is evaluated in conjunction with the conclusions from routine inspections by IPEN.

The inspection of industrial radiography installations is performed by the permanent staff of the Technical Office. The inspections are carried out annually unless more frequent ones are considered necessary. Initial inspections of a company generally consider occupational exposure levels, monitoring programme, storage safety, transport safety, equipment and radioactive source safety, operational procedures and emergency instructions. The findings of the inspection are conveyed to the users, who are required to correct any identified deficiencies in a given time. IPEN has the legal power to apply sanctions if necessary (fine, licence cancellation or closure of the installation). The sanction is applied following a legal and technical report issued by the Technical Office and the Legal Advisor's Office.

The radiography company involved in this reported accident was inspected at regular intervals over a 17 year period. Except for an enquiry about a source that was stolen in 1982, the findings of inspections were not considered to be critical to safety and any problems were appropriately solved by the company as described below.

During the planning of a regular inspection by the Technical Office in June 1998, it was discovered that the radiography company had moved to a new address without notifying IPEN. During the inspection performed at the new location, several deficiencies were noted regarding storage of the camera, procedures, dosimetry and personnel licences. The company was required to correct the deficiencies, which they did by July 1998 and its licence was granted for a further year by IPEN.

2.2. THE RADIOGRAPHY COMPANY

The radiography company had been in operation since 1980 but applied for its first licence in 1982. Licences were granted both for the installation and for operating personnel. In 1982, the company notified IPEN that a radiography camera housing a source had been stolen from an oilfield where its staff was working. IPEN was requested help to search for the camera and source, which were finally found hidden inside a large pipe. Fortunately, the camera had not been operated or dismantled so no significant doses had been received. In this case, IPEN was not able to apply any administrative sanctions because legal rules were lacking at the time, but a strong recommendation was made to the company to improve the physical security of its radiography equipment and radioactive sources.

When a new owner took over the company in 1990, a new licence was applied for and IPEN was supplied with new technical documentation (organizational structure, description of procedures and details of emergency plans). Since 1990, the company has renewed its licence at regular intervals as required by the regulatory authority.

The company was small, as are most radiography companies in Peru, and its organization was quite simple. At the top of the company was the general manager who was responsible for all legal, administrative and technical aspects and for providing all safety equipment. The general manager delegated to the radiation protection officer (RPO) all the duties related to radiation protection and for ensuring compliance with licensing conditions. The RPO's duties included:

— Keeping all licences and authorizations updated;
— Ensuring compliance with all national rules for industrial radiography;

— Ensuring that all radioactive sources had calibration and inspection certificates;
— Training personnel in radiation protection and emergency instructions, including practical exercises;
— Supervising all activities where radioactive sources were involved (storage, use, transportation);
— Keeping all records as required by IPEN;
— Ensuring the maintenance of all radiography equipment and radiation monitors;
— Training auxiliary personnel.

The management clearly stated in its documentation that the operators (radiographers) were responsible for all the tasks involving radioactive sources. The duties of the radiographers included:

— Keeping doses as low as reasonably achievable,
— Using suitable radiation monitors,
— Using protective equipment and devices,
— Performing only the tasks authorized in their personnel licence,
— Giving priority to radiation protection.

Auxiliary personnel received training in radiation protection, but were only permitted to perform tasks that were not directly related to radiation exposure.

It was established that in emergencies the radiographers and any other personnel would be under the supervision of the RPO. At the time of accident, however, the duties of the RPO were being undertaken by the company's radiographer (who was not qualified). In addition, the organization did not have a specific quality assurance programme relating to radiation safety and no qualified experts were appointed.

2.3. THE SOURCE, ITS CONTAINER AND ANCILLARY SAFETY EQUIPMENT

The radioactive source involved in the accident was ^{192}Ir, Model G-1, manufactured by the Source Production and Equipment Co., Inc. (SPEC) and etched with the serial number EK0504 (photo 1). The source had a 'Safe-T-Key' type connector (photo 2). This source was classified as 77C43515 by ANSI N542 and its initial activity was 3.7 TBq on 5 November 1998. On 21 February 1999, the day of the accident, the activity of the source was 1.37 TBq. Importation of the source had been authorized by IPEN in November 1998.

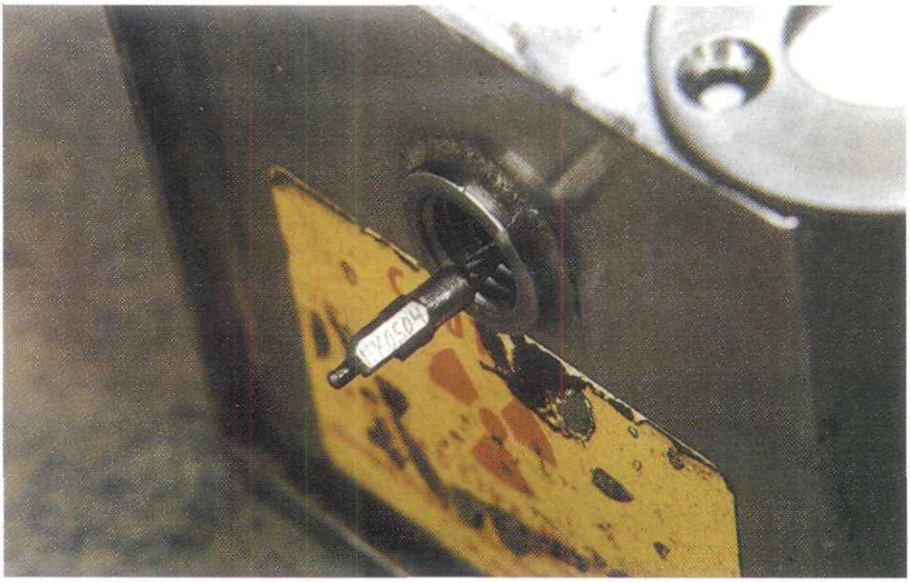

Photo 1. Source pigtail ready for connecting to drive cable.

Photo 2. Source pigtail connected to drive cable.

The source container ('camera') involved in the accident was not specified on the company's licence and had, thus, not been authorized by IPEN. This camera was manufactured by SPEC, Model T-2, serial number 1049, and reportedly came into Peru from Ecuador on 15 January 1999 without notification to IPEN. The container incorporated 35 kg of depleted uranium shielding and was designed to house an ^{192}Ir source up to a maximum of 7.4 TBq. The camera was a projection type that utilized a cable to drive the source in and out along a guide tube. A plug was located at each end of the camera and a key was needed to remove one of the plugs. The camera was fitted with both container and source labels (photo 3).

The safety systems used by the company included ropes and warning notices to prevent access to the controlled area during operations. Shielded collimators were also available for limiting the radiation field. Radiation monitoring devices included Geiger–Müller survey meters, pen dosimeters and film dosimeters. Even though this safety equipment was available, it was reportedly not used on a regular basis.

On 22 January 1999, the equipment was transported according to specific procedures, using a lockable cylindrical container that was labelled with warning notices.

The emergency kit included a radiation detector, handling tongs, additional shielding, warning signs and ropes.

3. THE ACCIDENT

3.1. INITIATING EVENTS

The accident happened on 20 February 1999 at the Yanango hydroelectric power plant, which is located in jungle in the San Ramon District of Junin Department, approximately 300 km east of Lima. On the morning of Saturday 20 February 1999, a welder and his assistant started to repair a weld of a 2 m diameter pipe.

At approximately 11:30, the radiographer and his assistant arrived and positioned the camera (with drive cable attached) close to the section of pipe being repaired. The objective was to make a radiograph of this section as soon as possible because the main contractor had requested urgent hydrostatic testing of the pipe. The plan was to carry out the radiography at midday when the other workers were out of the area at lunch but, since the repair was not finished, the radiography was not performed. The camera was left unsupervised, locked and with the drive cable connected, although the guide tube was not connected.

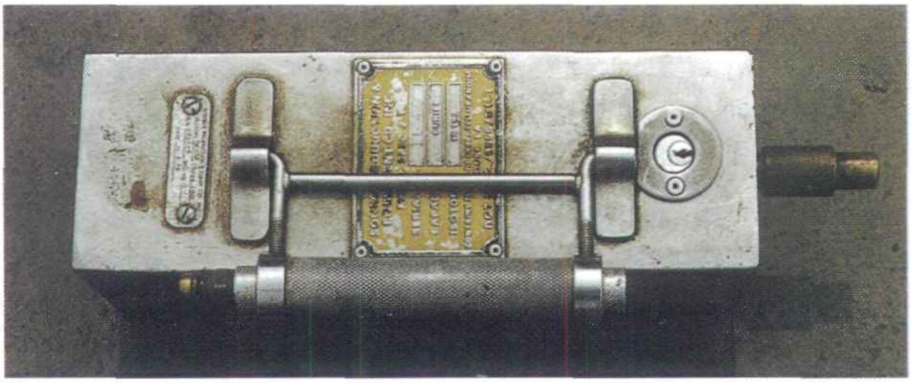

Photo 3. Radiography camera showing labels and lock.

Photo 4. Source pigtail.

The welder and his assistant came back from lunch at 14:00 and continued with the repairs to the pipe. One hour later, the radiographer started to use ultrasonic test equipment to examine the pipe, but the equipment failed and it could not be repaired.

At some time during the day the source became detached from the camera. At approximately 16:00, the welder picked up the unshielded ^{192}Ir source (photo 4) with his right hand and placed it in the back right pocket of his trousers (at the time of writing this report, investigations have not established how the source came to be outside the camera). At approximately 17:00, the radiographer spoke briefly to the welder who was inside the pipe, but the welder made no mention of picking up the source. At 18:00 the radiographer went to San Ramón to telephone for replacement ultrasound equipment from Lima. The radiography camera was left unsupervised during this time.

3.2. INITIAL EXPOSURE OF THE WELDER

After the welder had picked up the radioactive source he continued to work, spending much of the time in the pipe. He claims that he was sitting there for at least three of the next six hours. He was wearing loose fitting denim jeans and at around 21:00 he felt a pain in the back of his right thigh. He left work at approximately 22:00 and took a minibus home. The ride lasted about 30 minutes and there were 15 other people in the minibus.

3.3. EXPOSURE OF THE WELDER AND HIS FAMILY AT HOME

When the welder arrived home at approximately 22:30, he reportedly complained to his wife about the pain and she looked at his posterior right thigh and noted a red area of skin. He took off his jeans and, with the source still in the pocket, placed them on the floor. He visited a local doctor who told him he had an "insect bite" and that he should put a hot compress on the area. The welder's wife meanwhile spent about five to ten minutes squatting/sitting on his jeans while she breastfed their 18 month old child. Two other children who were at home, a girl of ten and a boy of seven, were about two to three metres from the source for approximately two hours. After discussing his pain with his wife, the welder remembered the source in his jeans pocket, took it out with his right hand and carried it to the bathroom which was about four metres away outside the house (at approximately 23:00).

At 01:00 on 21 February, the operator of the company arrived at the welder's home and asked whether he had seen the source. The welder went to the bathroom and carried the source in his hands to the door. The radiographer told him to throw the source onto the street, after which recovery actions were initiated.

4. THE EMERGENCY RESPONSE

4.1. DISCOVERY THAT A SOURCE WAS MISSING

On 20 February 1999, the radiographer came back from San Ramón at 20:00. At that time he was informed by his assistant that repairs were finished and that radiography could be started at 22:00.

At 22:00, the radiographer connected the guide tube to the camera and performed an exposure for five minutes. During this exposure, his assistant reported that the survey meter was not operating, i.e. it did not read any radiation. The radiographer went to develop the exposed films of the repaired section. This took longer than usual because apparently the film was mixed with other non-exposed films. None of the developed films showed any signs of having been exposed to radiation. Even so, at 22:30 the radiographer went to San Ramón to eat.

The operator reportedly came back to the site at approximately 00:00 and was concerned by the fact that the films had not been exposed. He took a lamp, went inside the pipe and started to check the camera, whereupon he discovered that the screws of the lock were apparently loose. He disassembled the drive cable and noticed that the source pigtail was not there.

4.2. SEARCH FOR THE SOURCE

Immediately after discovering that the source was missing, the operator reportedly started to search around the camera, but unsuccessfully. At 00:30, he went back to San Ramón to notify the company in Lima about the missing source and he asked for more survey meters and personnel.

At this time, the operator also notified the resident engineer of the contractor. They began to visit all of the personnel that had been working on the site that day. At 01:00 they arrived at the welder's house. The survey meter they were using indicated high radiation levels as the welder approached the door with the source in his hands. The welder was told to throw the source into the street and then the radiographer put a stone over the source and restricted access to the area. The resident engineer remained in the area to supervise the source while the radiographer went to fetch equipment for recovering the source.

4.3. RECOVERY OF THE SOURCE

To recover the source, the radiographer used a piece of iron 25.4 mm thick and the radiography camera. He put the shielding over the source, connected the source pigtail to the drive cable and retracted it inside the camera. The total time for connecting the source was about two minutes. It is, however, noted that the emergency kit was reportedly not used during the recovery of the source. The camera and source were safely stored at 02:00 on 21 February 1999. The welder and his family were taken to Lima for medical attention.

4.4. RESPONSE BY THE PERUVIAN AUTHORITIES

The event was notified to a staff member of the Technical Office of IPEN at 10:20 on Sunday, 21 February. He contacted the radiation physicist of IPEN and the head of the Radiotherapy Department of the Instituto de Enfermedades Neoplásicas (INEN) in accordance with an agreement to assist radiation injured patients. At 13:30 the welder was admitted to hospital.

The INEN initiated a medical examination of the welder and other potetially exposed persons. Clinical analyses were performed (blood counts of all persons). The first conclusion was that only the welder had been severely exposed.

According to previously defined procedures, the Technical Office carried out the following measures:

— Assessed doses to persons involved in the accident,
— Recorded statements from all people involved in the accident,
— Stopped operations of the radiography company,
— Requested a report from the radiography company,
— Requested the radiographic camera for investigation,
— Issued an official statement to the media.

The preliminary dose estimates provided to IPEN on 22 February showed high localized doses to the welder and low doses to his family and other persons. These estimates were made according to the information collected from the initial statements of personnel involved in the accident. There were, however, uncertainties about the magnitude of the high doses so other calculations were made by physicists from INEN. The resulting values were almost identical with the initial estimates and confirmed the seriousness of the accident. At that stage the authorities decided to ask the IAEA for assistance.

On 4 March 1999, the authorities sent an e-mail message to an IAEA staff member with notification of the accident (see Section 4.5). On 17 March 1999, the formal assistance of the IAEA was requested under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency.

The Technical Office of IPEN investigated the cause of the accident over a period of several months. It seemed clear that the root cause of the accident was inadequate control of the source by the company. There were, however, other contributory factors and it is not clear how the source came to be out of the camera. It could have been deliberately removed even though the container was reportedly locked. When this hypothesis was tested, it was discovered that:

— It was possible to use an ordinary screwdriver to loosen the screws holding the lock in place;
— When the screws were taken out, it was possible to withdraw the lock from the camera without using the key;
— This operation took only five to ten minutes;
— It was then possible to push the source out of the camera with a wire.

Alternatively, the source could have accidentally fallen out of the camera, although the radiographer reported that he had connected the pigtail to the cable drive at 11:30 on the day of the accident. The results of the investigation proved to be inconclusive so it was not possible to determine exactly how the ^{192}Ir source came to be out of the camera. At the time of issue of this report, legal and administrative actions were continuing.

4.5. RESPONSE FROM THE IAEA

As mentioned earlier, the IAEA received an e-mail message on 4 March 1999 from the Peruvian Regulatory Authority informing it that a radiological accident had occurred in Peru. However, this message was sent not to the IAEA's official emergency communication channel (the Emergency Response Centre (ERC)) but to a staff member who was then away on duty travel. This delayed the response because it was only after the staff member returned to work (one week later) that the message was read and passed on to the IAEA's ERC. After receiving the message, the ERC communicated through the official contact point in Peru to authenticate and verify the information received and to offer IAEA assistance.

On 17 March 1999, the ERC received a fax transmission from the official contact point giving further details about the accident, including a medical diagnosis of the exposed person, and informing the IAEA that a request for specialized medical assistance would be made through the Peruvian Permanent Mission in Vienna. This official request was received from the Mission at 17:00 UTC. It invoked the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the 'Assistance Convention').

Under the terms of the Assistance Convention, the ERC arranged for a team of three medical/dosimetric experts to fly from the USA to Lima immediately. The objectives of the mission were to:

— Examine and evaluate the patient's condition;
— Review the methodology of the dosimetry and the calculations;
— Determine whether the results of the patient's examination and the findings correlated with the estimated doses;
— Discuss whether surgery was indicated and, if so, what type;
— Review the expected course of the patient and issues related to future care;
— Review the possible causes of the accident;
— Make recommendations.

The team arrived in Lima on 18–19 March 1999.

The mission was concluded on 21 March 1999; on 22 March the team sent its report to the ERC. Since then, communication links between the ERC and the contact point in Peru have been periodically maintained to update information.

As the patient's health continued to deteriorate, the medical experts considered transferring him to a specialized medical centre abroad. The ERC therefore undertook initial contacts with the Peruvian and French authorities in order to transfer the patient to France for further treatment.

On 1 June 1999, Percy Hospital in Paris informed the ERC that the patient had arrived in Paris and was undergoing treatment. The treatment of the patient is discussed in Section 5.

On 14 October 1999, the French physicians treating the patient informed the ERC that his condition was critical. They also had consultations with their Peruvian counterparts and an agreement was reached to fly the patient back to Peru on Sunday, 17 October.

On 18 October 1999, the ERC was informed that the patient had arrived safely in Lima.

5. MEDICAL TREATMENT OF THE PATIENT

5.1. TREATMENT OF THE PATIENT'S PRIMARY LESIONS IN PERU

21 February 1999. The patient was admitted to the National Cancer Hospital (Instituto Nacional de Enfermedades Neoplasicas, 'INEN') in Lima approximately 20 hours after exposure to the radioactive source. The hospital physicians noted, during the physical examination, an area of erythema on the patient's right upper posterior thigh. He was immediately given hydration (glucose intravenously, 2 L in the first

24 hours and then 1 L per day for 20 days) and a course of Ciprofloxazin (500 mg orally every 12 hours) and Dexamethasone (8 mg intravenously every 8 hours). He also received a Naprosyn-like compound for pain relief.

22 February 1999. Blistering lesion surrounded with large inflammatory halo on the mid-upper line of the rear surface of the right thigh, on day 2 after irradiation (photo 5).

23 February 1999. The blister became larger (4 cm × 1 cm to 5 cm × 1 cm) at the junction of the thigh and the buttock. The profile of the blister is shown in photo 6. The first bone marrow aspiration from iliac crest proved changes compatible with reactive type granulocytic hyperplasia with severe deviation to the right.

Dosimetry was performed by the Peruvian physicists on the third day of the patient's admission using the Prowess 3000 treatment planning computer system (Table I).

TABLE I. DISTRIBUTION OF DOSES BY DEPTH AS CALCULATED BY INEN

OrganDistance	Dose	
	(cm)	(Gy)
Skin	1	9966
Soft tissue	2	2508
Soft tissue	3	1110
Soft tissue	4	617
Soft tissue	5	388
Soft tissue	6	265
Soft tissue	7	191
Femur	8	143
Femoral artery	8	143
Soft tissue	9	111
Soft tissue	10	88
Gonads	18	23
Bladder	20	18
Rectum	20	18
Thyroid	90	—

Photo 5. Blistering lesion surrounded with large inflammatory halo on the mid-upper line of the rear surface of the right thigh (22 February 1999).

Photo 6. Profile of the blister (4 cm × 1.5 cm × 1 cm) at the junction of the thigh and the buttock (23 February 1999).

24 February 1999. Drastic reduction in lymphocyte count were observed (Table II).

25 February 1999. Erythema of the posterior right thigh and a blistering lesion 4 cm x 4 cm was noted. The patient was switched to Clindamycin (300 mg/8 h) and Ciprofloxazin (dosage increased to 750 mg/12 h).

TABLE II. HAEMATOLOGICAL EVOLUTION

		Haematology			
		Leucocytes	Lymphocytes	Neutrophils	Platelets
	Normal range	4000–11000	1500–4000	2500–7000	100 000–400 000
1	Day 1 (20 Feb. 99)	7 600	1 500	6 000	250 000
2	Day 2 (21 Feb. 99)	7 100	1 064	5 822	248 000
3	Day 5 (24 Feb. 99)	6 000	120	5 880	252 000
4	Day 8 (27 Feb. 99)	4 200	42	4 074	294 000
5	Day 10 (01 Mar. 99)	3 800	304	3 420	280 000
6	Day 11 (02 Mar. 99)	3 700	111	3 515	
7	Day 13 (04 Mar. 99)	5 000	200	4 650	239 450
8	Day 15 (06 Mar. 99)	5 200	312	4 784	240 000
9	Day 17 (08 Mar. 99)	6 000	300	5 580	232 000
10	Day 20 (11 Mar. 99)	5 200	52	5 096	
11	Day 22 (13 Mar. 99)	5 800	290	5 220	
12	Day 26 (17 Mar. 99)	4 100	205	3 854	147 000
13	Day 31 (22 Mar. 99)	3 100	310	2 759	
14	Day 34 (25 Mar. 99)	1 500	30	1 440	99 900
15	Day 35 (26 Mar. 99)	2 500	175	2 275	152 000
16	Day 36 (27 Mar. 99)	2 000	340	1 580	157 500
17	Day 37 (28 Mar. 99)	4 000	160	3 720	109 000
18	Day 38 (29 Mar. 99)	4 200	420	3 696	210 000
19	Day 39 (30 Mar. 99)	3 600	540	2 988	156 000
20	Day 40 (31 Mar. 99)	7 900	474	7 347	
21	Day 41 (01 Apr. 99)	8 200	410	7 708	112 000
22	Day 42 (02 Apr. 99)	6 100	854	5 002	164 000
23	Day 43 (03 Apr. 99)	8 500	425	7 990	187 300
24	Day 44 (04 Apr. 99)	13 200	792	11 748	326 400
25	Day 45 (05 Apr. 99)	18 100	1 810	15 385	238 500
26	Day 46 (06 Apr. 99)	11 400	1 368	9 234	360 000
27	Day 47 (07 Apr. 99)	7 300	1 460	5 256	272 000
28	Day 49 (09 Apr. 99)	8 800	1 584	6 512	343 000

TABLE II. (cont.)

		Haematology			
	Normal range	Leucocytes 4000–11000	Lymphocytes 1500–4000	Neutrophils 2500–7000	Platelets 100 000–400 000
29	Day 50 (10 Apr. 99)	25 700	771	24 158	377 000
30	Day 51 (11 Apr. 99)	20 000	2 000	17 400	469 000
31	Day 52 (12 Apr. 99)	12 100	1 210	9 922	562 000
32	Day 56 (16 Apr. 99)	8 000	1 840	5 840	685 000
33	Day 59 (19 Apr. 99)	13 400	1 340	11 524	666 000
34	Day 61 (21 Apr. 99)	15 900	1431	12 879	698 000
35	Day 62 (22 Apr. 99)	11 800	118	11 682	582 000
36	Day 66 (26 Apr. 99)	13 400	670	11 524	520 000
37	Day 70 (30 Apr. 99)	13 900	556	12 232	
38	Day 72 (02 May 99)	13 500	540	12 555	696 000
39	Day 75 (05 May 99)	11 200	1 120	9 856	759 000
40	Day 82 (12 May 99)	7 100	1 278	5 467	629 000
41	Day 87 (17 May 99)	8 300	581	7 470	
42	Day 91 (21 May 99)	8 700	348	8 178	468 000
43	Transfer to France (28 May)				

26 February 1999. A computed tomography (CT) scan was performed and revealed a markedly swollen right thigh (photos 7 and 8) with extensive subcutaneous oedema, loss of the posterior fascial margins and swelling of almost all muscle groups of the thigh, centred between 10 and 20 cm below the hip. X ray of pelvis and bones revealed no bone or joint lesions.

28 February 1999. Oedema of the thigh was almost resolved. Progressive denudation and necrosis of the lesion started to become evident.

1 March 1999. Extended superficial erosion surrounded by a large dusky (hyperpigmented) inflammatory area in the rear surface of the right thigh on day 9 (photo 9).

6 March 1999. Physical examination revealed a superficial ulcerated lesion 8 × 8 cm, surrounded by a dark halo of 12 × 12 cm with the subcutaneous tissue being indurated, and the presence of genital herpes lesions.

9 March 1999. Administration of Ciprofloxazin was suspended. Zinnat 500 mg orally three times a day and Acyclovir (Zovirax), one tablet every 8 hours, was started.

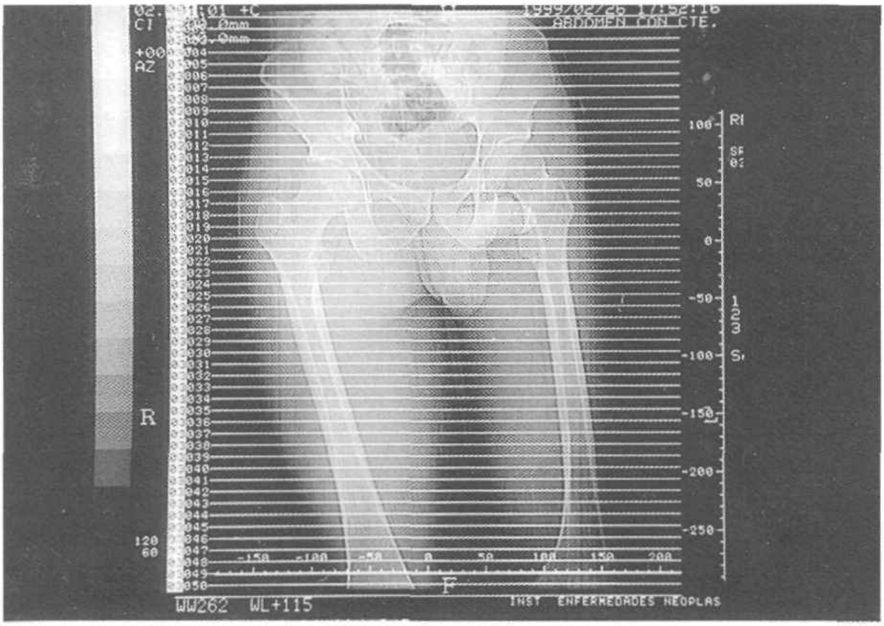

Photo 7. CT scan showing a significant increase of the volume of the right thigh (26 February 1999).

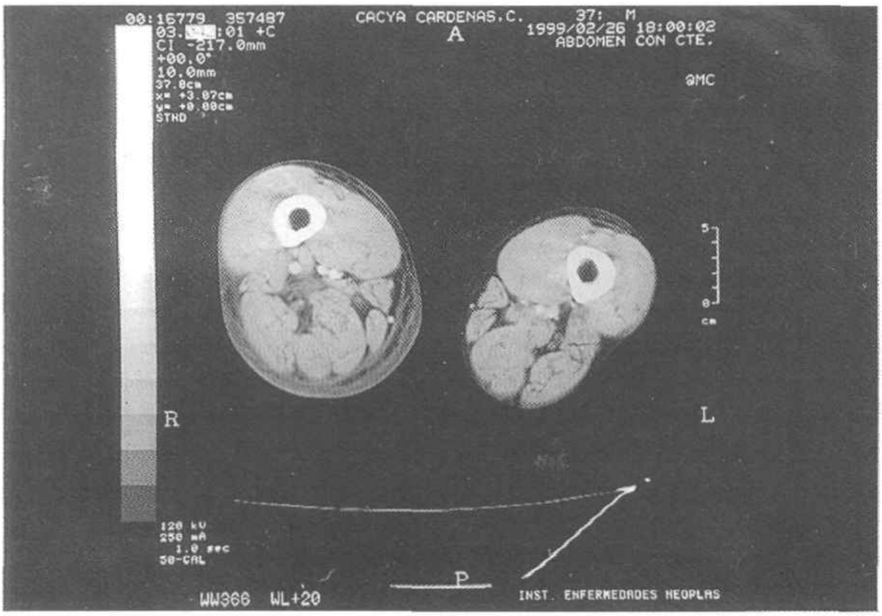

Photo 8. Horizontal section of both thighs by MRI demonstrating the magnitude of the oedema of the right thigh (26 February 1999).

Photo 9. Extended superficial erosion surrounded by a large dusky inflammatory area in the rear surface of the right thigh (1 March 1999).

Photo 10. Hyperpigmented reaction of the lesion. The lesion edges are well defined, and the skin is peeling off in some areas surrounding the central lesion (15 March 1999).

12 March 1999. The patient was experiencing intensive pain that made it difficult for him to move his right leg.

15 March 1999. Hyperpigmented reaction of the lesion on day 23. The lesion edges were well defined and the skin was peeling off in some areas surrounding the central lesion (photo 10).

16 March 1999. The patient had began to complain of numbness in the outer right thigh and hypersensitivity in the inner part. The herpetic lesions disappeared, so administration of Zinnat and Zovirax was suspended.

19 March 1999. The patient had lost approximately 7 kg in weight in a month. He lay on his left side almost all the time. On his right thigh there was a 10 × 10 cm lesion that was 2 cm deep. The subcutaneous fat was undergoing necrosis and the underlying muscle was faintly visible. The edge of the lesion was dark and firm. The lesion appeared to be a superinfected ulcer covered by a fibrin crust (photo 11).

An IAEA team of experts arrived from the USA and examined the patient jointly with the Peruvian doctors. One opinion was that a hemipelvectomy should be considered in view of the evolution of the patient's status combined with the results of a dosimetry study that had already been made by Peruvian experts. However, the IAEA medical team advised to defer this decision as they observed that the hair was firm at 14 cm and further from the lesion on the right thigh. This data was taken as a basis for dosimetric evaluation by the IAEA team.

Photo 11. Superinfected ulcer on the right thigh. The bottom of the lesion is covered by a fibrin crust (19 March 1999).

23 March 1999. Uretrocystoscopy showed normal mucosa in the bladder. Radiation neuropathy of the sciatic nerve on the right side was diagnosed. For this reason continuous infusion of morphine to the patient was performed.

24 March 1999. A necrotic ulcerated region of 20 × 15 cm was not infected and not bleeding as evaluated by the plastic and reconstructive surgeons. Vesicles and blisters in the proximal third and medium part of the second and third fingers of the right hand were found.

25 March 1999. Electromyography was done, which showed denervative signs of the sciatic right nerve of the subacute type, incipiently affecting the peroneal and tibial branches. The nadir of all peripheral haematological parameters was observed.

26 March 1999. Second bone marrow aspiration from iliac crest: Bone marrow with severe hypoplasia corresponding to significant exposure to radiation of this area of the body. It was necessary to fix an epidural catheter because of severe pain. Administration of haematopoietic granulocyte colony stimulating factor (G-CSF, Leucomax, 300 μg per day) was started.

30 March 1999. The patient had fever (39°C) for the first time. The necrotic ulcer appeared to be infected with pus. The culture of pus was positive for *Klebsiella* and *Streptococcus aureus*. The patient received Clindamycin (600 mg intravenously every 8 h) and Cefoterazone Sulbactan 7.5 g intravenously every 12 h.

31 March 1999. Physical examination revealed ulcerated lesions with clarification on both gluteal regions and scrotum. On the right hand there were erythema of the hypotenar and vesicles on the palm.

2 April 1999. Leucomax was stopped owing to an observed significant rise in white blood cell counts.

5 April 1999. The patient presented melena. A gastroscopy was done and erosion and haemorrhage were detected in the prepyloric area. Citomegalovirus in glandular cells of the stomach was found. A stress gastric ulcer was diagnosed. The patient was put on inhibitors (150 mg tablets of Ulceran were given orally every 8 h). The level of testosterone was significantly reduced to 29 ng/dL (normal values are 300–1000 ng/dL in adult men).

7 April 1999. Haemoglobin decreased to 7.9 g/L (the normal value is 15–17 g/L at the high altitude of the patient's residence) and whole blood transfusion (two units) was performed. Infection of the liquor with *Streptococcus epidermidis* was detected and the patient was given Vancomycin (1 g intravenously every 12 h).

10 April 1999. The second whole blood transfusion (two units) was performed.

13 April 1999. Blistering of the right hand palmar surface of the 2nd, 3rd, 4th and 5th fingers on day 52 (photo 12).

16 April 1999. Magnetic resonance imaging (MRI) of the pelvis and thighs was carried out: Diffused oedema was found to be most expressed in the superior limit of the psoas muscle, the iliac, and the muscles of the right paravertebral area. There was

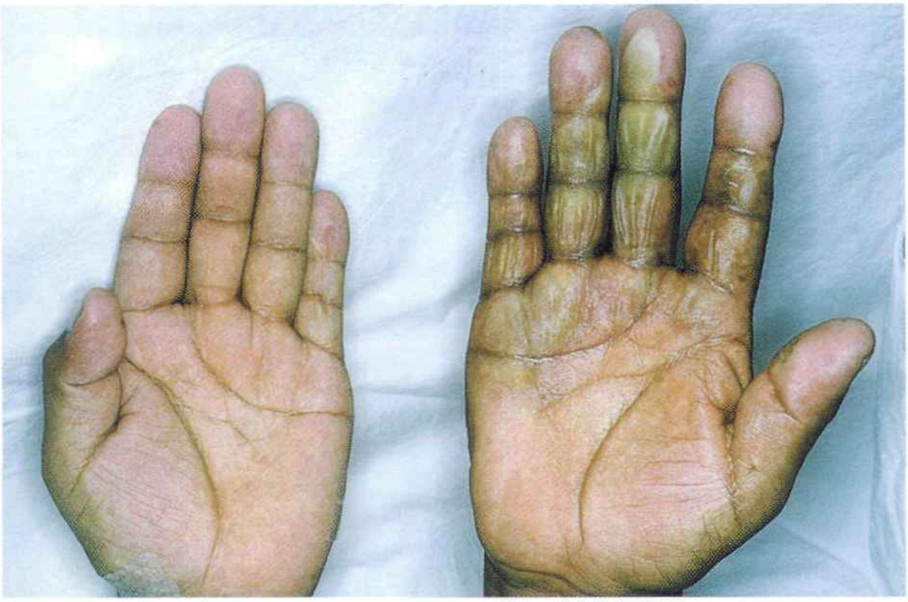

Photo 12. Blistering of the right hand palmar surface of the 2nd, 3rd, 4th and 5th fingers (13 April 1999).

a major swelling of the gluteus muscles and the medial and posterior compartments of the thigh. At this level an ulcerated lesion was observed. The oedema went down to the soft tissues of the knee joint. At the level of the bone marrow there was discrete oedema of the right iliac bone. No significant changes of the femur bone marrow were found by MRI.

19 April 1999. Culture of secretion of the necrotic ulcer contained *Enterobacter* and *Staphylococcus aureus*. Amikacyne was started (1 g intravenously every 24 h).

20 April 1999. Local radiation injury (erythema and dry desquamation) in the inferior external part of the right leg (photo 13).

23 April 1999. The third bone marrow aspiration from the sternum showed hyperplasia as a compensatory reaction of non-irradiated bone marrow.

27 April 1999. The patient was taken into the operating theatre for the first surgical debridement of the necrotic lesion in the posterior part of the right thigh. Ulcerated lesion 30 × 20 cm that went deep into the muscular layers, a small abscess in the muscle and sciatic nerve with signs of severe damage and fibrosis were observed. *Escherichia coli* was grown in the culture from the abscess. The

Photo 13. Local radiation injury (erythema and dry desquamation) in the inferior external part of the right leg (20 April 1999).

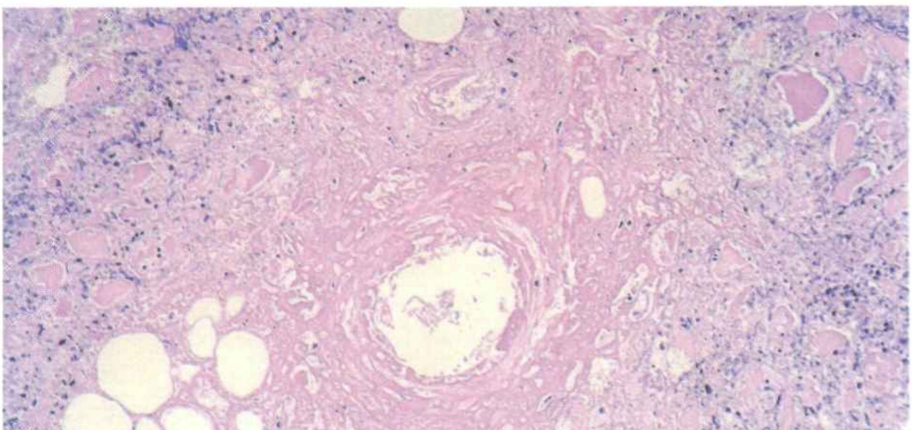

Photo 14. Post-radiation necrotizing vasculitis — the wall of the artery and the adjacent tissues are completely necrotized (27 April1999).

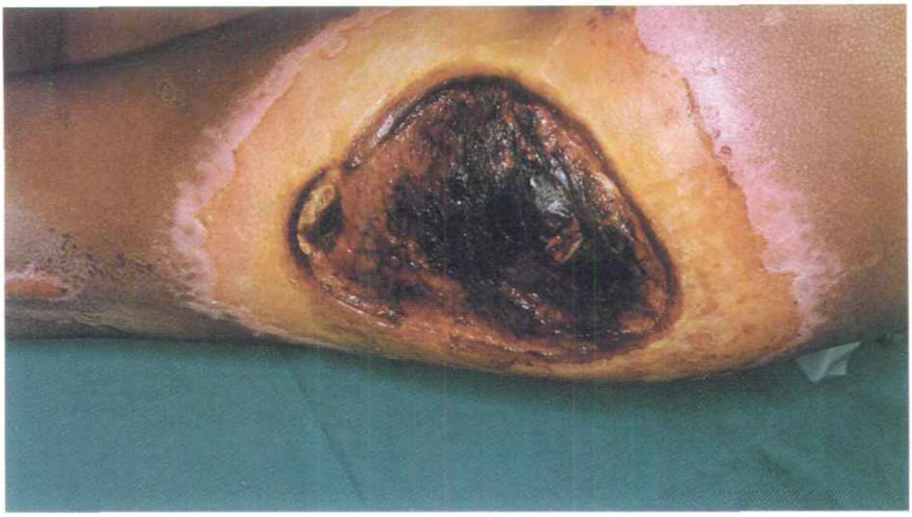

Photo 15. Very large necrotic lesion extended in the upper third of the right thigh. The depth of the defect is significant. The bottom is covered by a crust and is superinfected. The lesion edges are well defined, blistered and are above the surface of the surrounding tissue. They are surrounded by a depigmented halo (3 May 1999).

microscopic (histological) study of the necrotic lesions revealed extended haemorrhages, extensive areas of necrosis, oedema, and severe inflammation and destruction of vascular structures (photo 14).

3 May 1999 1999. Very large necrotic lesion extended in the upper third of the right thigh. The depth of the lesion was significant and most of it was covered by a crust and superinfected. The edges of the necrotic lesion were well defined and were surrounded by a wide depigmented halo (photo 15). In the culture of exudate from the operation wound, *Klepsiella* and *Streptococcus* were detected.

11 May 1999. *Macroscopic report of the pathology laboratory.* Lozenge (rhombi) of skin and subcutaneous tissue of size 15.5 cm × 12 cm × 2.5 cm, including a deep ulcer of 13.5 cm × 10 cm with irregular borders deep in which fibrin and necrotic tissue were seen. The deep ulcer involved the thigh muscles.

Microscopic report. Besides ulcers with extensive post-radiation necrosis of the skin, subcutaneous fat and striated muscular tissues, there was also vasculitis, fibrosis and degeneration of the superficial nervous branches on the surface and surgical borders.

13 May 1999. At the recommendation of the surgeons, treatment sessions in a chamber of hyperbaric oxygen were started. The patient went to the hyperbaric oxygen chamber for one hour daily for the next 20 days.

19 May 1999. As the haemoglobin was still low (12.6 g/L), two units of whole blood were transfused.

21 May 1999. *Electromyography:* Worsening of the lesion of the sciatic nerve was found which caused chronic and progressive suffering. There was no functional inervation of the muscles dependent on the peroneal nerve and posterior tibial nerve. The patient was put on Tegretol 200 mg three times per day to relieve pain.

The pathology report and slides were sent to medical consultants in the USA. After assessing the progression of the septic complications and its possible fatal consequence within a short time, the IAEA medical team (who examined the patient in March) advised a modified hemipelvectomy. To combat the life threatening condition, triple antibiotic therapy was recommended. Surgical intervention was, however, postponed because of the risk of sepsis.

25 May 1999. The report of the cytogenetic study of bone marrow showed normal chromosomes (46 *x, y*); however, the cell count in the sample was very poor.

28 May 1999. The patient was taken to France for treatment at the Percy Hospital in Paris.

5.2. TREATMENT IN FRANCE

The treatment strategy suggested for the patient by the French medical team was to apply the latest artificial skin graft techniques used with success in some very severe radiolesions observed in the victims of the accident in Lilo, Georgia [14]. After discussion with the Peruvian physicians, the principle of this strategy was accepted and the patient was admitted to the Burn Treatment Centre at the Percy Military Hospital on 29 May.

29 May 1999. *Initial medical check-up:* The patient weighed 56 kg, compared with his usual weight of over 60 kg. He was tired, apyretic and severely algesic. The lesion of the right thigh presented a dramatic aspect in the form of an extensive loss of tissue; it was atonic and superinfected, with necrotic tissue on the surface and in a fibrous muscle deep down. The size was 40 × 30 cm. There was intensive serous/pus leakage. The edges of the lesion were swollen and well defined, forming an inflammation barrier. The lesion was extremely painful. The lower right limb was in a distorted position with flexion of the thigh and the knee. This flexion was irreducible, even under general anaesthetic. There was already advanced fibrosis of the muscles of the rear face of the right thigh. The MRI confirmed massive radionecrosis of the rear face of the right thigh in the surrounding muscle and bone. The initial treatment consisted of major analgesics and the application of an occlusive dressing based on Tulle Gras and Bétadine ointment.

1 June 1999. Surgical exploration of the lesion on day 101 revealed the denudation, 10 cm long, of the sciatic nerve in the centre of the wound and the exposure of the femur for the whole length of the necrosis, up to the greater trochanter. The devitalized tissue was removed with excision of the lateralis vastus and the femoral biceps muscles. The lesion was covered with a porcine xenograft (EZ-DERM). Efforts to stimulate wound granulation by draining exudate by local depression was initiated. Dressings were applied under general anaesthetic drugs.

The bacteriological investigations revealed several germs multiresistant to the antibiotics *Staphylococcus aureus* resistant to methicillin, *Escherichi coli* secreting *beta-Lactamase* with a broad spectrum, *Enterobacter* and *Pseudomonas aeruginosa*. All these bacteria were sensitive to only one antibiotic (Imipenem) except for the *Staphylococcus*.

The algic situation was controlled with administration of alphamimetics (clonidine) combined with ketamine and continuous morphine administration (5 mg/h). Gabapentine was not completely effective.

13 June 1999. The patient's temperature peaked at 39°C with leucocytosis (15.9×10^9 per L) without sign of systemic bacterial dissemination. At the local level, stimulation of the granulation of the wound by the depression seemed to achieve a local reaction.

21 June 1999. The granulation process stopped and the wound again revealed a very infected and atonic local aspect. The presence of *Candida albicans* was noted in the bacteriological examinations. Several dressings were applied with sulphonamide (Mafenide) to try to control the local infection and the wound was surgically cleaned several times, refreshed with curette.

8 July 1999. Facing the total lack of wound granulation, further surgery was performed with extended debridement of the lesion and sacrifice of the sciatic nerve. The excision was wide, into the apparently healthy tissues. The necrotic sciatic nerve was sectioned and the proximal and the distal ends were buried in the muscles. The lesion was covered with a porcine xenograft (EZ-DERM).

Following the first post-surgical dressing, the xenograft was partially replaced. The persistence of the pain seemed better controlled after surgery but, one week after, no local improvement was observed and the wound aspect was again atonic and super infected, despite antibiotherapy (Imipenem and Amiklin) and local treatment by balneotherapy in a diluted solution of sodium hypochlorite.

16 August 1999. Radical surgery was planned and the exploration of the lesion showed that tracks of purulent necrosis were spreading towards the hip which prevented all preservative surgery of the hip. A wide exeresis of the whole internal rectus and the major and minor gluteus was followed by a disarticulation of the hip; the very large loss of substance was filled up by a large cutaneomuscular flap of the anterior face of the thigh vascularized by the superficial femoral vessels. This disarticulation of the hip was followed by a left iliac colostomy as a precaution, due to the proximity of the rear suture to the anal margin (4 cm).

The surgery proceeded without complications and the patient left the Burn Treatment Centre for transfer to the Functional Re-education Centre on 19 September 1999 (day 205). Unfortunately, the amputated tissue was discarded and was, therefore, unavailable for study.

23 September 1999. A sudden aggravation of the local status was observed with a dislocation of the stump which was again hyperalgic. A surgical exploration exhibited a dramatic extension of the radionecrosis to the perineum. The anal sphincter and the basal part of the scrotum were resected .

Facing this new dramatic extension of the radionecrosis at the level of the perineum, which could augur future extensions into the abdomen organs, the French and the Peruvian medical teams decided that the return of the patient to Peru was justified. For this patient, the endeavours to perform artificial skin graft techniques as used following the accident in Lilo, Georgia, were unsuccessful because of the lack of control of local infection and the major vascularitis phenomena. Taking into account the gravity of the medical and psychological condition of the patient, the absence of his family and his isolation, his transfer to Peru was planned.

5.3. TREATMENT OF DELAYED EFFECTS AND COMPLICATIONS ON RETURN TO PERU

17 October 1999. The patient came back from France very depressed and in intense pain. Because of the pain, a phenol application was provided with good palliative results. Because of the development of the necrosis in this case, a dosimetry simulation was done in a Perspex phantom, taking the original CT scans into consideration.

18 October 1999. The upper rear part of the left thigh was swollen with foci of dry desquamation, the ulcerated perineum was superinfected; there was ulceration at the medial edge of the surgical treatment (sutura area) above the right pelvis (photo 16).

14 December 1999. Severely superinfected large ulceronecrotic lesions spreading to the whole perineum (photo 17). Infected ulceronecrotic lesions in the external surface of the lower third of the left leg and at the external ankle on the same day (photo 18).

January–May 2000. Progression of severely superinfected large ulceronecrotic lesions spreading to the whole perineum with exposure of the ischial bone. The patient was treated in the intensive care unit in hospital in his home town.

Photo 16. The upper rear part of the left thigh is swollen with foci of dry desquamation, the ulcerated perineum is superinfected; ulceration at the medial edge of the surgical treatment above the right pelvis (18 October 1999).

The close contact with his family proved to be a tremendous psychological factor in his survival.

28 April 2000. Reopening of the ulceronecrotic lesions in the external surface of the lower third of the left leg (photo 19).

March 1999–April 2000. The patient's wife showed moist desquamation, ulcerative and fibrotic lesions in the lower back after her brief exposure to the source while sitting on her husband's jeans (photos 20–22). No haematological changes were observed in her or her children.

June 2000. Plastic reconstructive and urological surgery for the patient was considered.

Photo 17. Severely superinfected large ulceronecrotic lesions spreading to the whole perineum (14 December 1999).

Photo 18. Infected ulceronecrotic lesions in the external surface of the lower third of the left leg and at the external ankle (14 December 1999).

Photo 19. Reopening of the ulceronecrotic lesions in the external surface of the lower third of the left leg (28 April 2000).

Photo 20. Small infected circular lesion following moist desquamation surrounded by a colourless halo with punctual haemorrhages on the lower back of the patient's wife (18 March 1999).

Photo 21. Ulcerative lesion on the lower back of the patient's wife (April 1999).

Photo 22. Ulcerative lesion on the lower back of the patient's wife (18 October 1999).

6. DOSIMETRIC ANALYSIS

6.1. DOSE ESTIMATES OBTAINED BY PHYSICAL DOSIMETRY

A physical dosimetric reconstruction of the irradiation process at the level of the rear surface of the right thigh of the patient was carried out and it was assumed in this dose assessment that there was a single thigh–source geometry. This radiological accident is characterized by a major uncertainty about the exposure duration. Therefore, the numerical reconstruction was not based on the estimated exposure duration, but on clinical data (size of the necrosis). Consequently, the dose reconstruction was very dependent on the size of the lesion and the patient's clinical evolution.

The physical dosimetry assessment performed in France was based on Monte Carlo techniques and utilized computer programs to simulate the patient and the source. The way in which radiation was emitted from the source was calculated by a three dimensional transport code known as MORSE (Multigroup Oak Ridge Stochastic Experiment). A software package known as MDGE (Multidevice Graphics Editor) was used to model the complex shapes. The model was capable of taking into account the various organs and tissues, as well as the skeleton of the irradiated patient. This enabled the absorbed dose to be calculated at various points in areas of interest.

Various assumptions were made concerning the source geometry, the source–skin distance, the geometry of the phantom and the value of the threshold dose of the radionecrosis. It was assumed that the source was a cylinder, 4 mm in diameter and 8 mm long, enclosed in a steel capsule, 1 mm thick and 1.2 cm long. Two source–skin distances were considered: 3 mm corresponding to the man sitting, and 7 mm (due to the loose fitting jeans) when the man was standing. The source was considered to be static for each simulation. The numerical phantom used in the simulation comprised the right leg with the bones and the pelvic region. Its dimension fitted the true morphology taking into account anatomical data from radiography of the femur and CT scan of the legs. Normalization of the results was performed on the dose value at the rim of the lesion, which was estimated to be around 25 Gy with an uncertainty of about 30%. On the basis of these assumptions and calculations, taking a lesion 10 cm in diameter, the 100 Gy isodose at the surface of the skin would be located between 2 and 3 cm from the centre of the lesion. The skin dose at 14 cm from the centre of the lesion, where the hair was still firm, was estimated to be around 2 Gy. The estimated dose to the femur varied from 15 Gy at the entrance to 5 Gy at the exit. The dose to the femoral artery was estimated to range from 10 to 15 Gy, while the dose to the sciatic nerve, which was much closer to the source, was estimated to range between 25 and 30 Gy. These estimated doses were significantly different from those estimated in Peru (Section 5.1). This highlights the fact that dose estimation by physical dosimetry is extremely difficult when the exposure parameters are not accurately known. Furthermore, difficulties in estimating doses are compounded when the source is not static: every movement of the source will result in a varying dose being delivered to different regions of the body.

6.2. DOSE ESTIMATES OBTAINED BY BIOLOGICAL DOSIMETRY

Biological assessment of the dose was performed by scoring unstable chromosomal aberrations (dicentrics and centric rings) and stable aberrations (translocations) in peripheral blood lymphocytes. The assessment of the unstable and stable chromosomale aberrations was performed on day 106.

6.2.1. Dicentric and centric scoring

The techniques that were used are described in IAEA Technical Reports Series No. 260 [15] on biological dosimetry by cytogenetics. A total of 516 complete metaphases were examined but the results did not show signs of non-uniform exposure. This inability to detect the heterogeneity of the exposure can be explained by the long delay of the sampling after the irradiation (day 106) and the use of several blood transfusions during the treatment of the patient.

6.2.2. Translocation scoring

The translocations were scored following application of the fluorescence in situ hybridization (FISH) technique [16]. Translocations were scored in 1852 metaphases. Sixty-three cells exhibited chromosomal aberrations detected by FISH painting. The genomic translocation frequency for the complete reciprocal translocation was 46.7×10^{-3} T_{Rc}/cell. The genomic translocation for the total translocation frequency (T_{tot}) was 77.3×10^{-3} T_{tot}/cell.

The background population of the total translocation frequency (T_{tot}) varied from 2.4 to 14×10^{-3} per cell. The translocation frequency observed in the patient was much higher than the background level. To estimate the dose a laboratory dose effect relationship was established by irradiating lymphocytes in vitro [17].

The patient's dose, assuming whole body homogenous irradiation, was therefore estimated to be 1.2 Gy (dose range 1.2–1.5 Gy), based on the total translocation frequency (T_{tot}) and 1.3 Gy (dose range 1.15–1.35 Gy), based on the complete reciprocal translocation (T_{Rc}).

7. FINDINGS, CONCLUSIONS AND LESSONS TO BE LEARNED

The primary objectives of the follow-up investigation of the accident in Peru were to investigate the causes of the accident in order to draw conclusions based on the findings and to derive the lessons to be learned. The specific findings and conclusions drawn from the accident follow, together with general lessons to be learned (in italics).

7.1. OPERATING ORGANIZATIONS

Although the radiography company had procedures in place and had identified responsibilities of individuals, these were not effectively implemented by management.

The prime responsibility for radiation safety lies with the employer. Simply having policies and procedures in place is not sufficient in itself to ensure the required level of radiation safety. A safety culture needs to be fostered and maintained by management to encourage a positive attitude to safety and to discourage *complacency [BSS, para. 2.38]. Further details regarding the development of radiation protection programmes are given in the* Safety Guide on Occupational Radiation Protection *[3].*

The supervision of the iridium source and the measures to ensure its security were not adequate.

Work involving occupational exposure needs to be adequately supervised [BSS I.26 (d)] and radiation sources need to be kept secure to prevent unauthorized persons from accessing them [BSS, para. 2.34]. Mobile devices such as radiography cameras must never be left unsupervised.

The person responsible for carrying out the radiography was not a fully trained and qualified radiographer.

Radiation protection and safety in industrial radiography, especially site radiography, rely heavily on human intervention and the correct implementation of procedures. Persons carrying out such work have high demands placed on them and they must, therefore, be fully trained and qualified. Employers need to provide suitable and adequate human resources and appropriate training in protection and safety. Periodic retraining can help to ensure the required degree of competence is maintained [BSS, para. I.4. (h)].

The welder was unaware of the radiation hazards, even though he was left to work unsupervised close to the radiography camera.

Persons not directly working with radiation sources, but working nearby, should be given appropriate information and may require training. Co-operation between licensees/employers and exchange of information can help to ensure that all relevant persons are aware of the hazards and understand the protection and safety measures to be taken.

7.2. NATIONAL AUTHORITIES

The accident occurred even though the radiography company had been granted a licence and had been inspected by the regulatory authority.

The assessment of licence applications and the inspection of premises needs to be undertaken by trained and experienced staff. National authorities are invited to use the IAEA publication Safety Assessment Plans for Authorization and Inspection of Radiation Sources *[18]. The use of practice specific regulations*[1] *or national*

[1] The IAEA is currently preparing practice-specific regulatory guides, including one on industrial radiography.

guidance can provide additional support for regulatory inspections and the assessment of licence applications. Regulatory authorities may wish to consider more frequent inspections of high risk applications, such as industrial radiography, especially in cases where there is a history of non-compliance by licensees.

During the accident investigation, IPEN reported that it was to possible to use a screwdriver to remove the locking mechanism on the radiography camera, allowing the source to be removed. It was also reported that the method for attaching the source to the drive cable was not very secure.

The design and construction of radiography cameras need to be considered by national authorities at the licence application stage. ISO 3999 [19] specifies the international standards for apparatus used for gamma radiography.

7.3. EQUIPMENT MANUFACTURERS/SUPPLIERS

The lock on the radiography camera was reportedly easy to dismantle, allowing the source to be readily removed without a key. It was also reported by IPEN that the particular type of connector used to attach the source to the drive cable was not considered to be very secure.

Radiography cameras need to be designed and constructed in a way that prevents unauthorized access to the radioactive source. As mentioned above, ISO 3999 [19] specifies the international standards for apparatus used for gamma radiography.

7.4. MEDICAL COMMUNITY

There are uncertainties associated with physical dose estimates based on the observed biological effects. These uncertainties could have been diminished if histopathological and electron spin resonance studies had been carried out on the tissue from the amputated leg. Unfortunately, the amputated tissue had been discarded and was unavailable for study.

Amputated tissue from highly exposed persons can provide an additional source of dose information that could help in the subsequent treatment of the patient. Care needs to be taken to ensure that such samples are kept until it is certain that they are no longer required.

Hemipelvectomy was considered several weeks post-exposure and prior to involvement of the perianal region, but a decision was made to delay the procedure and to graft over the lesion in an attempt to save the irradiated limb. The grafting techniques failed and the limb was amputated a few months later. While it is not possible to know whether early hemipelvectomy would have prevented involvement of tissues of the perianal region, physicians in charge of patient care in any similar accidents in the future should give careful consideration to extensive surgical therapy, taking into account physical and biological dosimetry and consulting experts with experience in localized radiation injuries.[2]

Dexametazone proved to be effective in diminishing the severity of the radiation effects such as oedema and pain.

[2] A medical peer review group is currently being established by the IAEA.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Bottollier-Depois, J.F.	Institut de protection et de sûreté nucléaire, France
Berger, M.E.	REAC/TS, Oak Ridge Institute for Science and Education, Oak Ridge Associated Universities, USA
Caceres, E.	Instituto de Enfermedades Neoplásicas, Peru
Chau, Q.	Institut de protection et de sûreté nucléaire, France
Gaillard-Lecanu, E.	Institut de protection et de sûreté nucléaire, France
Goans, R.	REAC/TS, Oak Ridge Institute for Science and Education, Oak Ridge Associated Universities, USA
Gourmelon, P.	Institut de protection et de sûreté nucléaire, France
Heredia, A.	Instituto de Enfermedades Neoplásicas, Peru
Leon, L.	Instituto de Enfermedades Neoplásicas, Peru
Marquina, J.	Instituto de Enfermedades Neoplásicas, Peru
Medina Gironzini, E.	Instituto Peruano de Energía Nuclear, Peru
Mettler, F.	University of New Mexico, Albuquerque, New Mexico, USA
Moscol, A.	Instituto de Enfermedades Neoplásicas, Peru
Nogueira de Oliveira, C.	International Atomic Energy Agency
Ortiz Lopez, P.	International Atomic Energy Agency
Picón, C.	Instituto de Enfermedades Neoplásicas, Peru
Pinillos Ashton, L.	Instituto de Enfermedades Neoplásicas, Peru
Ramirez, R.	Instituto Peruano de Energía Nuclear, Peru
Ricks, R.	REAC/TS, Oak Ridge Institute for Science and Education, Oak Ridge Associated Universities, USA
Roux, A.	Institut de protection et de sûreté nucléaire, France
Stephanazzi, J.	Percy Hospital, Paris, France
Toohey, R.	REAC/TS, Oak Ridge Institute for Science and Education, Oak Ridge Associated Universities, USA
Trompier, F.	Institut de protection et de sûreté nucléaire, France
Turai, I.	International Atomic Energy Agency
Vizcardo Lama, C.	Instituto Peruano de Energía Nuclear, Peru
Wheatley, J.	International Atomic Energy Agency
Wrixon, A.	International Atomic Energy Agency
Zaharia, M.	Instituto de Enfermedades Neoplásicas, Peru

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