THE RADIOLOGICAL ACCIDENT IN SAN SALVADOR

A REPORT PREPARED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
IN CO-OPERATION WITH THE
PAN AMERICAN HEALTH ORGANIZATION OF THE
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FOREWORD

By the Director General

Technologies that make use of radiation continue to spread around the world: millions of people are employed in radiation related occupations and hundreds of millions of people benefit from these applications. The use of intense radiation sources for purposes such as the sterilization of medical products requires special care in the design and operation of equipment to prevent radiation injury to workers or to the public. Experience has shown that such technology is generally safely used, but controls have on occasion been circumvented and serious radiological accidents have ensued.

To the extent that reports on such accidents are incomplete or are unavailable to the scientific community, potentially valuable information is lost. Although the causes of accidents may be highly case specific, review of the circumstances in which they happen may yield generally applicable lessons that can be of help in preventing accidents in the future or in improving the response to those that do occur. Thus, the IAEA's review of the radiological accident in Goiânia, Brazil, in 1987, in which the misuse of an abandoned medical teletherapy source led to radiation injuries resulting in four deaths and to widespread contamination, has been found useful by the international radiation protection community in seeking to ensure the safety of major radiation sources.

The accident at an industrial irradiation facility in San Salvador was quite different from that in Goiânia, being limited to the external irradiation of workers. However, it did result in a fatality, as had similar accidents in Italy in 1975 and in Norway in 1982. There are more than 160 industrial irradiation facilities around the world that are as large as or larger than the one in San Salvador, and some of these are in countries that lack adequate infrastructures for radiation protection. An international review was undertaken to document the facts of the accident and to define generic lessons for the benefit of those having safety responsibilities for such facilities.

The report was prepared in co-operation with the Pan American Health Organization of the World Health Organization.

CONTENTS

1. **INTRODUCTION** 1

2. **THE BACKGROUND IN EL SALVADOR** 1

3. **THE IRRADIATION FACILITY** 3

3.1. History of the irradiation facility and description of the Model JS6300 Gamma Sterilizer 3
3.2. The radioactive source 5
3.3. The source hoist mechanism 7
3.4. The product transport mechanism 7
3.5. Safety interlocks and access control 10
3.5.1. The control panel 10
3.5.2. Radiation monitoring 10
3.5.3. Automatic safety features 14
3.5.4. Administrative controls 15
3.6. Maintenance 16
3.7. Operation 16
3.8. Supervision and radiological training 17

4. **THE ACCIDENT** 18

4.1. Overview 18
4.2. Initial exposures: the first event 19
4.2.1. The initiating events 19
4.2.2. The first entry 20
4.2.3. The second entry 20
4.3. Further exposures at the facility: the second event 26

5. **THE RESPONSE TO THE ACCIDENT** 28

5.1. The medical response in San Salvador 29
5.1.1. Patient A 29
5.1.2. Patient B 29
5.1.3. Patient C 30

5.2. Securing the facility 30
5.3. The response of the authorities in El Salvador 31
5.4. International participation 33
5.5. Dosimetric analyses 34
5.6. Further medical treatment in Mexico City 35
5.6.1. Patient A 35
5.6.2. Patient B 36
5.6.3. Patient C 37
5.7. Medical follow-up in San Salvador 37
5.7.1. Patient A 37
5.7.2. Patient B 37
5.7.3. Patient C 38

6. FACTORS CONTRIBUTORY TO THE ACCIDENT 38

7. GENERIC LESSONS LEARNED 40

A. Operating organizations 41
B. National authorities 42
C. Irradiator suppliers 44
D. The medical community 45
E. International organizations 45

ADDENDUM 47

PHOTOGRAPHS 49

APPENDICES 65

Appendix I: DOSIMETRIC ANALYSIS 65
AI.1: Initial estimates 65
AI.2: Dose profiles from biological effects 66
AI.3: Cytogenetic analysis 66
AI.4: Reconstruction of the accident 69
AI.5: Other dose estimation techniques 75

Appendix II:
MEDICAL TREATMENT 76
AII.1: Initial diagnosis and treatment at the Primero de Mayo Hospital in San Salvador 76
AII.2: Treatment in the Angeles del Pedregal Hospital in Mexico City 77
AII.3: Further treatment in San Salvador 83

ANNEXES 85

Annex I: PATIENT A: A NUTRITIONAL REPORT BY THE ANGELES DEL PEDREGAL HOSPITAL IN MEXICO CITY 85
Annex II: PATIENT B: A NUTRITIONAL REPORT BY THE ANGELES DEL PEDREGAL HOSPITAL IN MEXICO CITY 88

LIST OF PARTICIPANTS 91

LIST OF CONTRIBUTORS 93

1. INTRODUCTION

On 5 February 1989, a radiological accident occurred at an industrial irradiation facility near San Salvador, the capital of the Republic of El Salvador (see Fig. 1). Prepackaged medical products are sterilized at the facility by irradiation by means of an intensely radioactive cobalt-60 source in a movable source rack. The accident happened when this source rack became stuck in the irradiation position. The operator bypassed the irradiator's already degraded safety systems and entered the radiation room with two other workers to free the source rack manually.

The three workers were exposed to high radiation doses and developed the acute radiation syndrome. Their initial hospital treatment in San Salvador and subsequent more specialized treatment in Mexico City were effective in countering the acute effects. However, the legs and feet of two of the three men were so seriously injured that amputation was required. The worker who had been most exposed died six and a half months after the accident, his death being attributed to residual lung damage due to irradiation, exacerbated by injury sustained during treatment.

The report details the events leading up to the accident, the circumstances of the accident itself and the response to it. From the facts established, lessons are derived for operators and suppliers of irradiators, national authorities, medical staff and international organizations. Detailed information on dosimetric and medical aspects of the accident for the specialist reader is presented in the appendices and annexes.

2. THE BACKGROUND IN EL SALVADOR

El Salvador has been in a state of civil war since 1979. The national economy has been disrupted by armed attacks on transport links, military targets and economic targets such as factories and installations of the electricity generation and distribution system. The danger of being identified as an economic target has led to a tendency in managers of enterprises to divulge information relating to the security of commercial operations (including safety aspects) on a 'need to know' basis only, particularly for technical installations such as the irradiation facility at which the accident occurred. The commercial and economic isolation of the country because of the civil war was a factor in the accident.

The Ministry of Labour and Social Security in El Salvador is responsible for the administration of matters under the Labour Code. The Labour Code covers the responsibilities of managements and of workers in respect of hygiene and safety

FIG. 1. Central America, showing the locations of San Salvador and Mexico City.

measures in the workplace. However, neither the Code nor any of the sets of regulations derived from it makes any provisions for the use of ionizing radiations. Within the Ministry, under the General Directorate for Social Security, there is a Department of Occupational Hygiene and Safety; however, this Department has no expertise in radiological protection.

The Institute of Social Security (ISSS) of El Salvador is an autonomous institution affiliated to the Ministry of Labour and Social Security. One of its main functions is to collect social security payments from employers and employees, and from the proceeds to make social security provisions and to provide health care. In respect of health care, the ISSS runs its own hospitals. After the accident the three injured workers were treated at the Primero de Mayo Hospital of the ISSS in San Salvador. This has both an emergency department and radiotherapy facilities. The ISSS Department for Occupational Hazard Prevention is located on the same premises.

There is no regulatory control of nor any appropriate infrastructure for radiological protection in El Salvador. The country's only resources in this field are two persons in the Department of Nuclear Medicine of the Rosales Hospital, run by the Ministry of Health. This 'team', which has no permanent staff and receives no funding, presently consists of a professor of physics at a local university who works unpaid at the Rosales Hospital and a non-technical member of the hospital staff who assists him. Donated equipment is used to provide a personnel monitoring service. However, it may take a long time to effect the repair or replacement of an item of equipment, and this monitoring service is intermittent.

In 1986 the IAEA funded the visit of an expert to El Salvador to help in the drafting of proposals for the regulatory control of sources of ionizing radiations. Owing to the civil war, the proposals were not given a high priority in the regulatory programme. Nevertheless, some enabling provisions were included in Decree 955 of 1988, Articles 191 and 192 of which gave the Ministry of Health the responsibility for controlling the use of radiation sources and the authority to promulgate regulations. At the time of the accident no regulations existed, but new proposals were being drafted.

3. THE IRRADIATION FACILITY

Note: *Observations on factors contributory to the accident are presented in italic script.*

3.1. HISTORY OF THE IRRADIATION FACILITY AND DESCRIPTION OF THE MODEL JS6300 GAMMA STERILIZER

The accident occurred at an industrial irradiation facility near San Salvador, El Salvador, that was built in 1974 and commissioned in 1975. The facility has a Model JS6300 Gamma Sterilizer designed, manufactured and installed by Atomic Energy of Canada Limited, which now trades as Nordion International Inc., hereinafter referred to as 'the supplier'. In irradiators of this design, the product packages to be sterilized are loaded into large product boxes and moved by pneumatic cylinders (pistons) around a centrally located, vertical rectangular source rack. The source rack contains cobalt-60 gamma source elements in the form of rods contained in 'source pencils'. The source is shielded when not in use by lowering it into a pool of water, making it a Category IV irradiator under the international classification[1].

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Safety Aspects of Gamma and Electron Irradiation Facilities, IAEA, Vienna (in preparation).

The Model JS6300 was designed for relatively small product throughputs, having a maximum source capacity of 9.25 to 18.5 PBq (250 to 500 kCi) using cobalt-60. However, the initial loading of the irradiator was only 4.0 PBq (108 kCi). The source was never replenished, and by the time of the accident its radioactivity had decayed to approximately 0.66 PBq (18 kCi).

The irradiation facility is owned by a company that manufactures intravenous solutions and blood dispersion sets. The sets are sterilized by irradiation or with autoclaves. At the time of commissioning of the facility in 1975 the company was owned by a Mexican–Salvadorian–Costa Rican consortium. Later that year it was sold to a consortium in the United States of America. It returned to Salvadorian ownership in December 1987.

During the facility's building and commissioning stages, the supplier trained three operators in operational and radiological protection aspects. However, these three trained operators left the company after it changed ownership in 1975. From this time onwards any training of operators was informal and oral only.

In 1975 an incident occurred in which the product boxes obstructed the movement of the source rack. The rack was deformed, allowing the pencils to fall out. However, the installed safety systems and the operators' training were sufficient to prevent any occupational exposure. The supplier was informed and sent staff to the plant to effect repairs.

The civil war in El Salvador has exacerbated the economic problems of the country, engendering a 'make do and mend' attitude at the plant, as elsewhere. One result of this was that the company did not seek to replenish the source material within the normal time period. Eventually, in 1981, the owner of the plant negotiated with the supplier for the replenishment of the source. A representative of the supplier travelled to San Salvador, only to turn back at the airport in consequence of the escalating civil war. In 1982 and 1984, the owner of the plant again communicated with the supplier about replenishing the source. However, because of the security situation, the supplier did not send a representative to El Salvador. The owner of the plant had kept up telephone contact with the supplier over the fourteen years since 1975. However, the facility had not had the benefit of the radiological safety audits that normally accompany any replenishment of the source by the supplier.

The key factors from the description here and in Section 2 are that over the fourteen year period from 1975:

(a) there was no regulatory control of radiological protection matters nor any readily available expertise in El Salvador;

(b) operators trained by the supplier of the irradiator had left at an early stage and subsequent training was only oral and informal;

(c) there was no direct access other than by telephone to the supplier and the supplier's radiological expertise.

One result of these shortcomings was a serious loss of understanding over the years of the functions of the installed safety systems and of what was important for radiological safety. The remainder of this section describes the facility and its operation at the time of commissioning and at the time of the accident. For clarity, the changes are shown in italic type. To supplement the description in the text of the design and layout of the facility, three detailed drawings have been included at the end of the report. (Figs 2–4: *see inside back cover.*)

3.2. THE RADIOACTIVE SOURCE

Radioactive cobalt-60 metal is the radiation source in the JS6300 Gamma Sterilizer. The cobalt-60 source elements are contained in doubly encapsulated stainless steel source pencils approximately 45 cm long, with solid stainless steel end caps approximately 1 cm in diameter (see Fig. 5). Each source pencil is identified by a

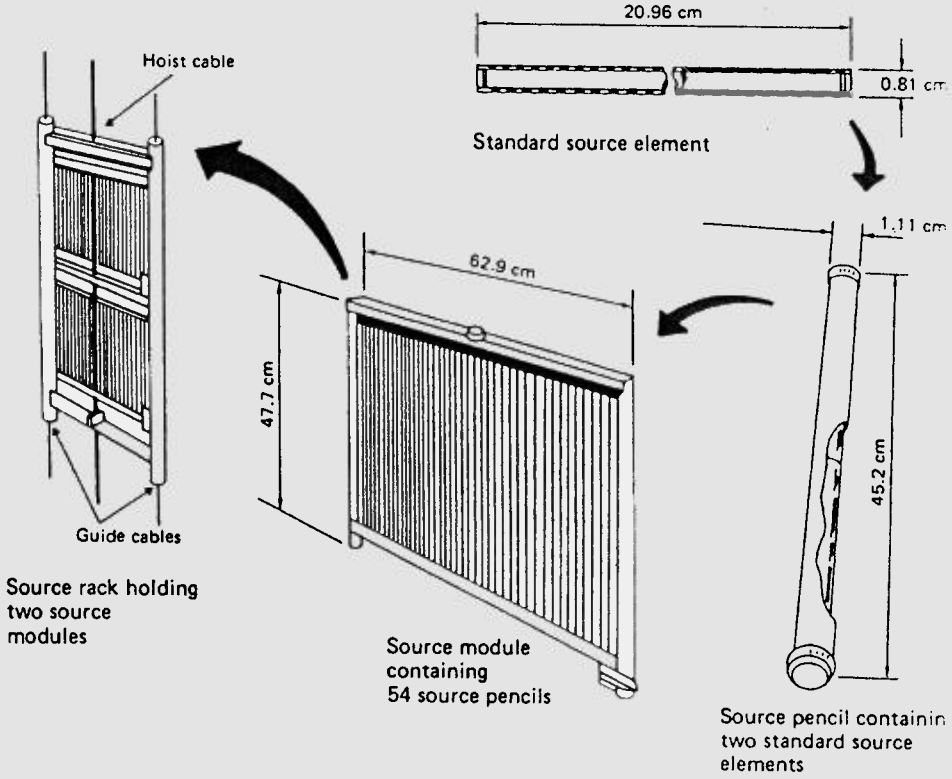

FIG. 5. The source rack with two source modules, each containing up to 54 source pencils with two standard source elements in each pencil. (By courtesy of Nordion International Inc.)

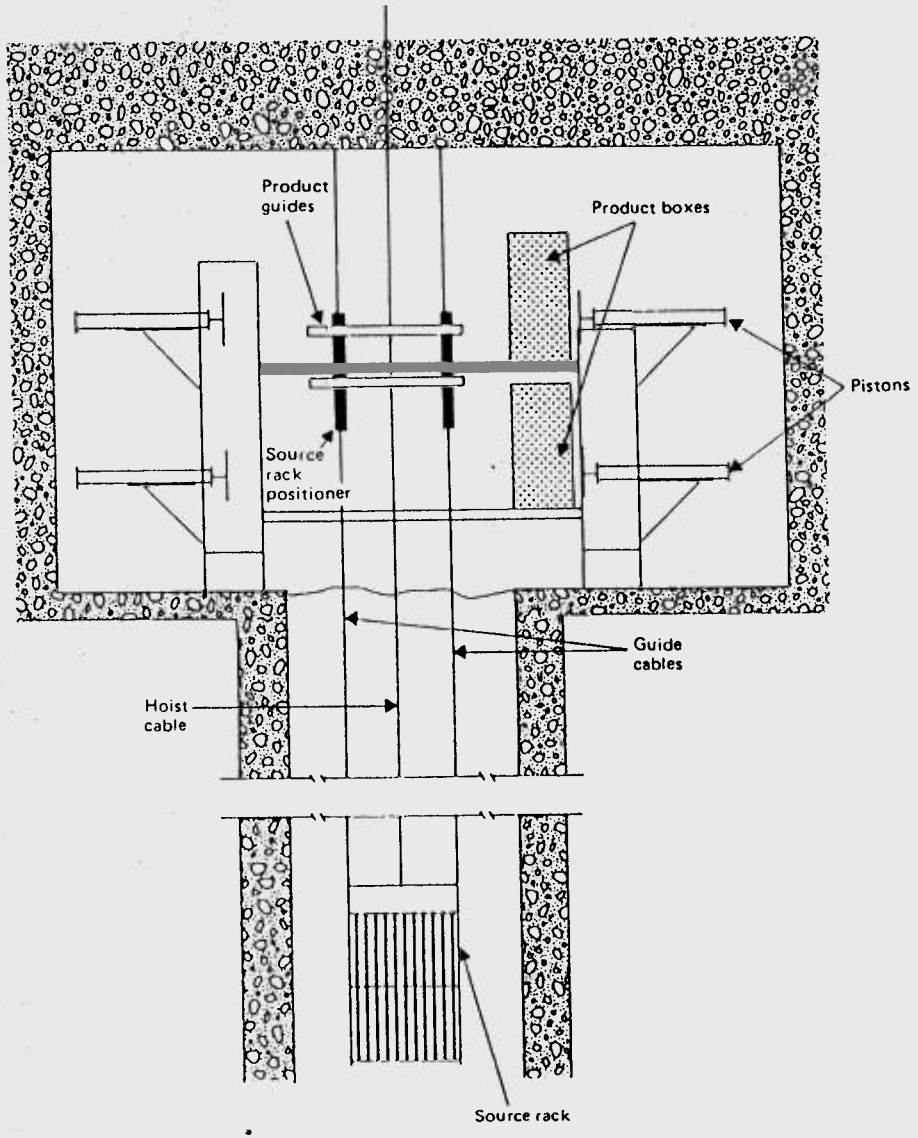

FIG. 6. Cross-sectional diagram of the source rack, hoist mechanism and transport mechanism. (By courtesy of Nordion International Inc.)

serial number engraved on an end cap. Fourteen active source pencils and 40 inactive dummy pencils (stainless steel spacer rods) were loaded into each of two source modules. The source pencils and dummy pencils are held in place in channels at the top and bottom of the source modules. The two source modules are placed one above the other in a flat, vertical source rack to give a uniform radioactivity over an area approximately 0.60 m by 0.90 m. When the source was installed in June 1975 the total radioactivity of the cobalt-60 gamma source was 4.0 PBq (108 kCi). By the time of the accident (5 February 1989) its radioactivity had declined to 0.66 PBq (18 kCi).

3.3. THE SOURCE HOIST MECHANISM

The source rack, when not in use, is stored near the bottom of a 5.5 m deep storage water pool and is raised to the irradiation position by a pneumatic hoist mounted on the roof of the facility above the radiation shield (see Figs 3 and 4). A stainless steel hoist cable attached to the source rack passes through the shield and the roof to two sets of sheaves in the hoist cylinder. When air pressure is applied to the hoist, the sheaves separate and the source rack is lifted. The movement of the source rack is guided by two taut guide cables, one at each end of the rack. In the raised position the source rack (see Fig. 6) actuates a microswitch to indicate that the source is up.

When air is exhausted from the source hoist, the source rack is returned under gravity to the safe storage position in the water pool. The weight of the source rack pulls the sheaves in the hoist cylinder back together, deactuating a microswitch mounted on the hoist cylinder to indicate that the source is down.

3.4. THE PRODUCT TRANSPORT MECHANISM

In the JS6300 irradiator, the products to be sterilized are loaded into fibreglass product boxes 0.40 m square and 0.90 m high. These boxes on stainless steel trays are irradiated in 29 positions, between which they are moved by pistons of the product transport mechanism (see Fig. 7). The boxes are moved backwards and forwards past the source rack along four rows, two on each side of the source rack, on each of two levels (shown schematically in Fig. 8), and are raised from the lower to the upper level by a pneumatic elevator. Steel product guides restrict the movement of the boxes to the path around the source and provide some protection to the source rack. Limit switches monitor the locations of the boxes and control the sequence of operation of the pistons.

The length of time for which a product box remains in each irradiation position (by 5 February 1989, the day of the accident, this had been increased to 140 min) is controlled by a master timer. When the time set on the master timer has elapsed,

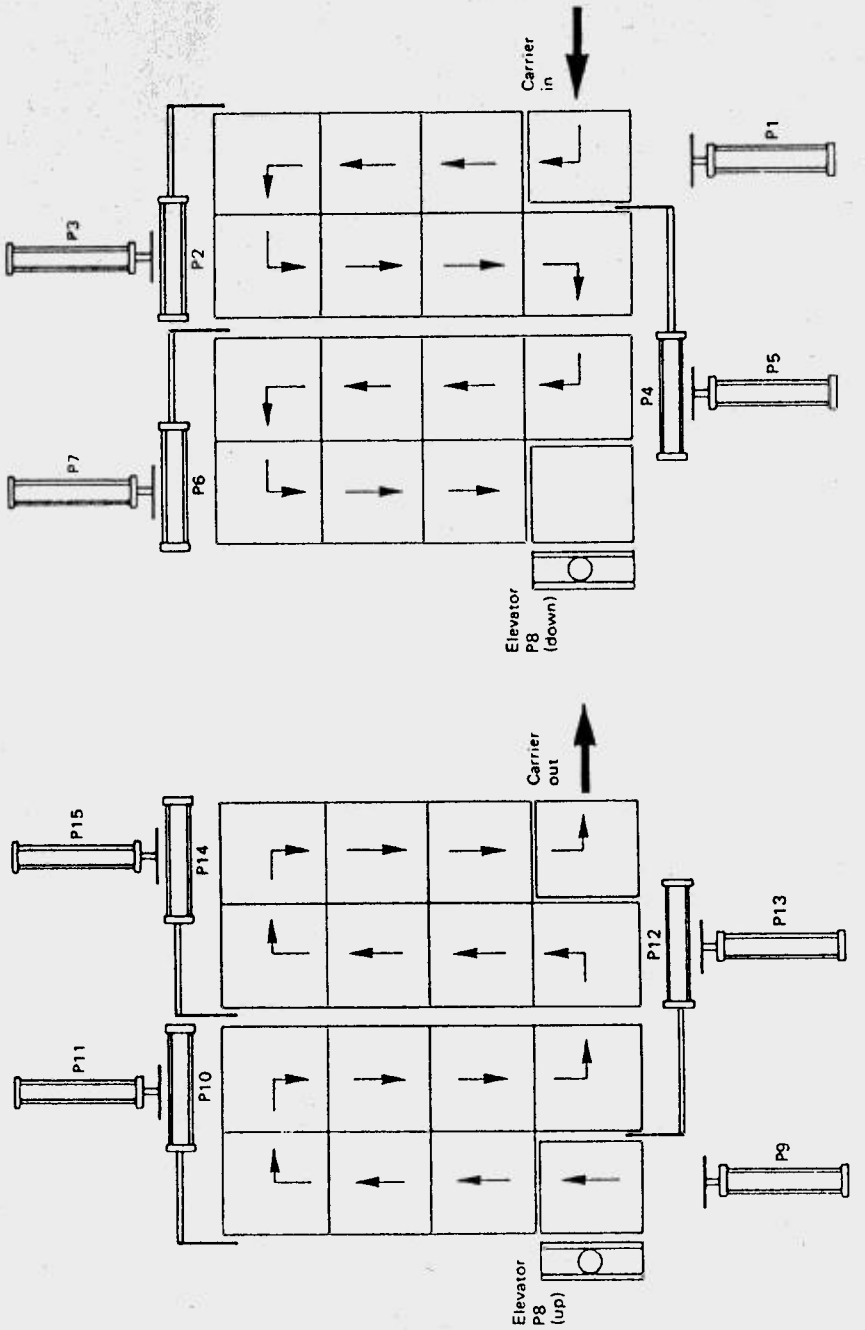

FIG. 7. Plan of the two levels of the transport mechanism of the JS6300 irradiator. (By courtesy of Nordion International Inc.)

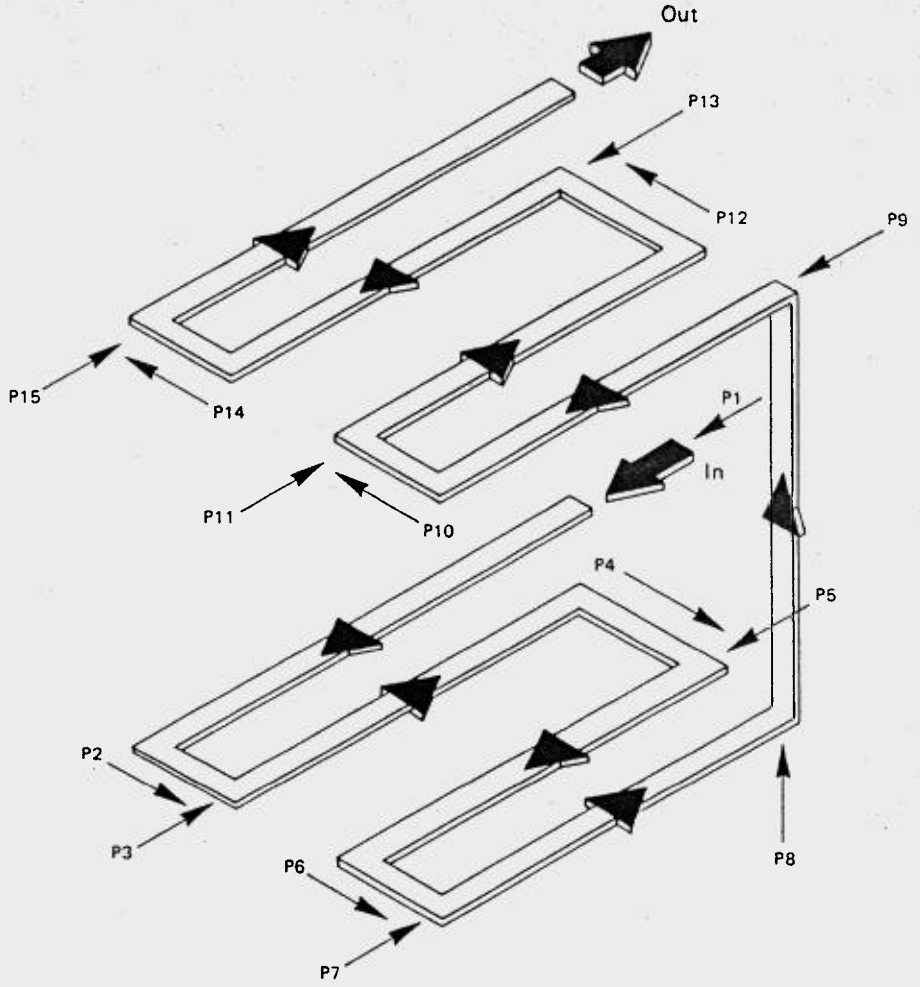

FIG. 8. Schematic diagram of the transport of product boxes in the irradiator. (By courtesy of Nordion International Inc.)

a sequential movement of the pistons is initiated. This advances each product box by one position and shifts one completely processed product box to the upper shelf of a product carrier which transports it from the irradiator.

Between 1975 and 1981, a number of incidents occurred at irradiators from the same supplier, in the USA and elsewhere (including the incident in San Salvador in 1975) in which damaged product boxes obstructed the source rack and caused it to jam. Consequently, in 1981, the supplier distributed *Warning Notice IND-81-1,*

in which it recommended that a steel source shroud be fitted around the irradiation position. It was also recommended that the condition of the boxes be routinely checked and that boxes in marginal condition be replaced.

The owner of the plant received this warning notice but never had its recommendations implemented owing to their cost and the increase in the exposure time that would be necessary to compensate for the shielding effect of the shroud. By the time of the accident in February 1989, the product boxes had been in use for a number of years. Many were in extremely poor condition and had been repaired with adhesive tape.

3.5. SAFETY INTERLOCKS AND ACCESS CONTROL

The following is a description of how the intact system as installed was intended to function.

3.5.1. The control panel

The wall mounted control panel (Fig. 9) has power and machine key switches and display lights for machine ready, machine on, source up and source down. A master timer, an overdose timer (which shuts down the irradiator in the event of a malfunction of the master timer) and a cycle counter are also mounted on the control panel.

Although Fig. 9 shows the panel as having illuminated legends, at the time of the accident the panel had no markings to indicate the significance of the controls or the warning lights. (However, the workers interviewed who were responsible for operating the controls were familiar with their functions.) In addition, a skylight above made it difficult to see whether the warning lights were on in the daytime.

3.5.2. Radiation monitoring

An L118 radiation monitor is interlocked with the personnel access door to prevent access to the radiation room if there are abnormal radiation levels inside when the source should be in the storage position. The L118 radiation monitor (see Fig. 10) is mounted on the wall in the radiation room and detects background radiation with a high sensitivity by means of an array of nine Geiger–Müller tubes. The monitor is designed to give an alarm condition for exposure rates in the range from the equivalent of about eight times that due to natural background radiation to greater than 10 000 $Sv \cdot h^{-1}$ (10^6 $rem \cdot h^{-1}$). Figure 11 is a schematic representation

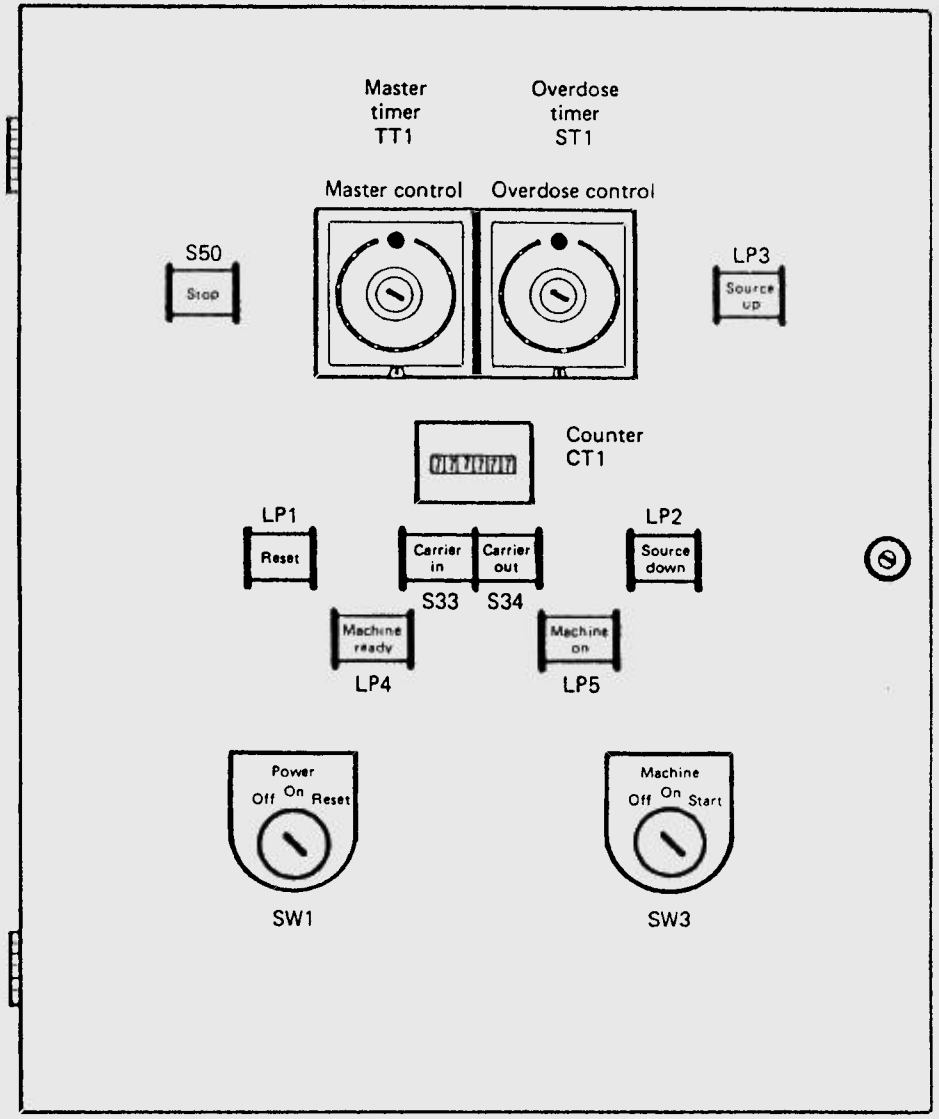

FIG. 9. The control panel of the JS6300 irradiator. (By courtesy of Nordion International Inc.)

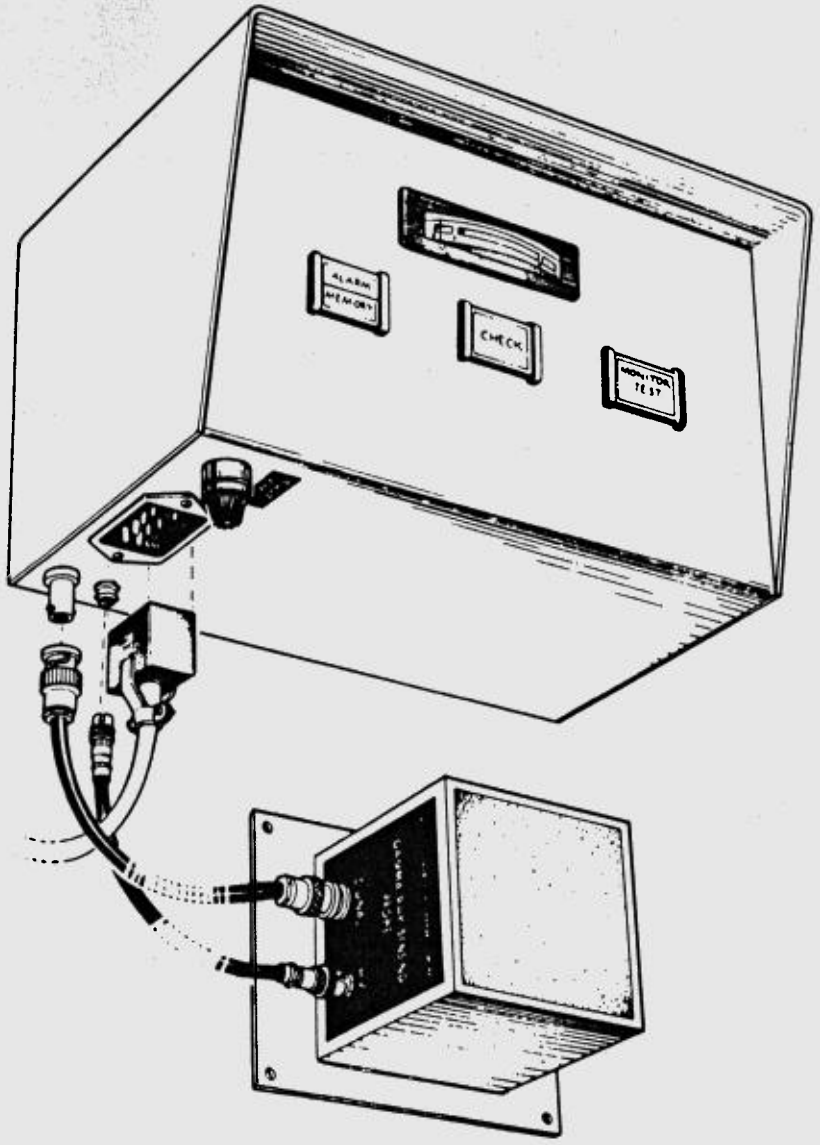

FIG. 10. The L118 wall mounted single probe monitor system. (By courtesy of Nordion International Inc.)

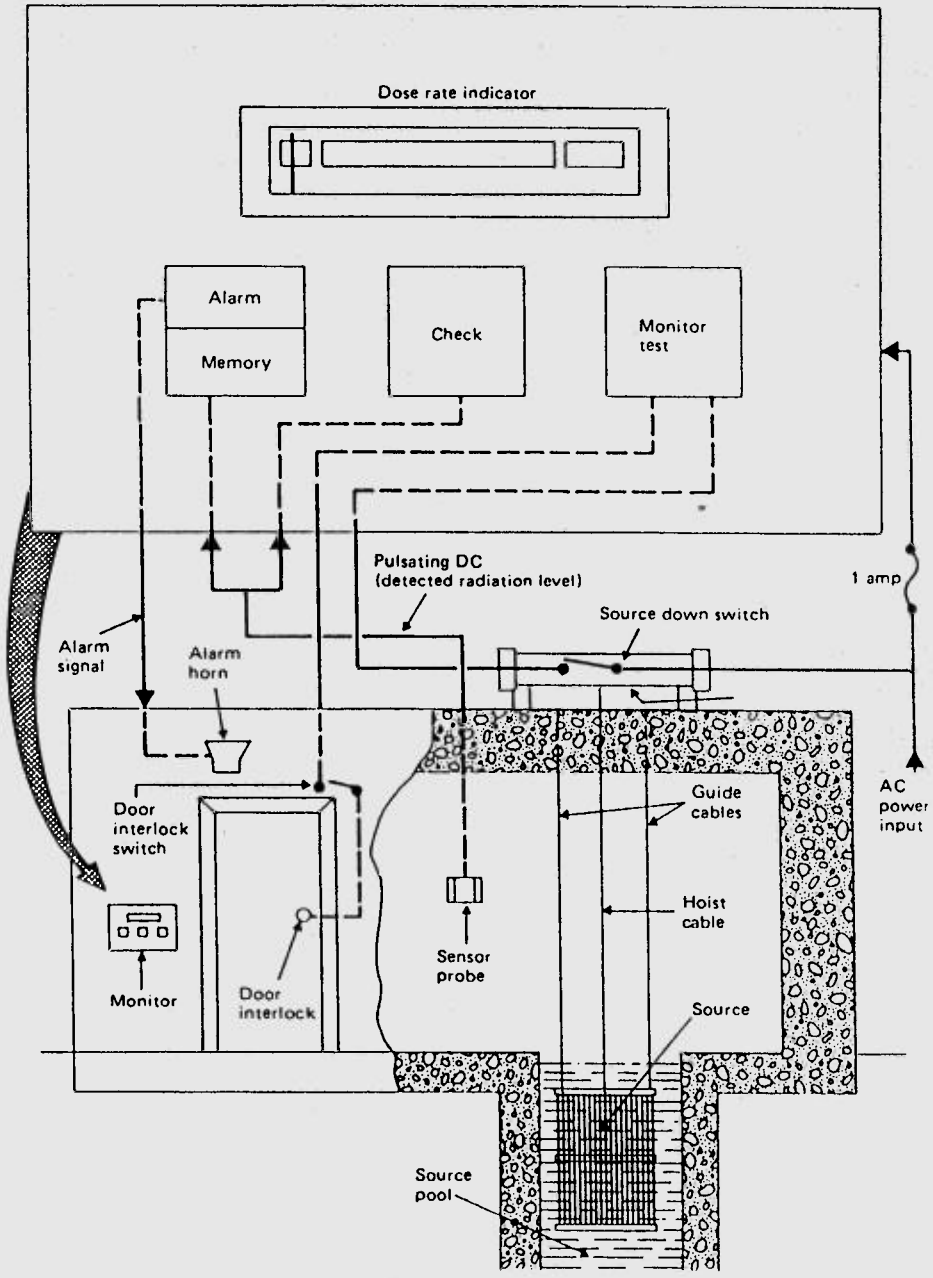

FIG. 11. Schematic diagram of the circuits for the monitor in the radiation room. (By courtesy of Nordion International Inc.)

of the monitor's main features and shows how they are integrated with other safety features.

In order to enter the radiation room, the operator must first press the monitor test button. The counting circuitry in the monitor then causes pulses from the monitor probe as it registers natural background radiation to give a test alarm indication. The test cannot be performed if the monitor is already showing the alarm condition. When the monitor test button is released, the monitor must again indicate normal background radiation before power can be supplied to the key switch that operates the door lock solenoid.

The radiation monitor is also interlocked with the source down microswitch. When the source rack is not fully down (in the storage position), power to the monitor is shut off. This also cuts off power to the key switch that operates the door lock solenoid, thus disabling the access control system and preventing access to the radiation room.

More than five years before the accident, the monitor probe had failed and the probe assembly had been removed. Its cabling remained. Removal of the monitor probe should have disabled the irradiator. However, 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. The access door had not been maintained and had become badly fitting, with the result that it could also be opened by force or by using the blade of a knife to slip the catch (see Photographs 5 and 6). Thus one major safety feature of the design was bypassed.

3.5.3. Automatic safety features

The JS6300 Gamma Sterilizer has automatic safety features for the protection of personnel and the products for sterilization. Safety interlocks require the operator to enter the radiation room and actuate a switch and to close the door before raising the source rack.

The personnel access door can only be opened if the source rack is in the storage position and there are not high radiation fields in the radiation room. If the door is forced open when the source is up, a microswitch behind the door will shut down the irradiator and lower the source.

In the radiation room there is a key switch with a time delay operated by the machine key, to oblige the operator to enter the room before raising the source. The operator is then to make an inspection to ensure that there is no one in the room and that the transport mechanism is in order. When the delay timer is set, a buzzer sounds to warn personnel that the source rack is about to be raised. The operator then has

90 seconds to leave the radiation room, close the door and start the operation of the irradiator from the control panel.

The electricity generation and distribution system in El Salvador has been a common target of attack and power failures have been frequent. In order to reduce the startup time after power cuts and other stoppages, the time delay switch in the radiation room had been replaced with a switch at the control panel.

The radiation room door can be opened from the inside so that personnel cannot be locked in. In addition, an emergency pull cable mounted along the walls of the radiation room and the entrance maze actuates a stop switch that lowers the source or stops the startup operation.

Turning the machine key switch to the off position or pressing the stop button on the control panel will also stop the irradiator and lower the source.

If the irradiator malfunctions or a safety device is actuated, the irradiator is shut down, the source rack is lowered, the red stop light on the control panel lights up and the source transit alarm sounds until the source is in the fully down storage position. Possible causes of an irradiator shutdown include loss of air pressure to the source hoist cylinder, too high a temperature in the radiation room, failure of the source rack to reach the irradiation position in the allotted time, delay in completing the sequence of actions of the pistons, a power failure, or expiry to zero of the overdose time. (The overdose timer should be set to elapse about five minutes after the master timer.)

3.5.4. Administrative controls

In addition to the automatic safety features, there should be administrative controls to ensure that the facility is operated only by trained, authorized operators in accordance with the procedures given in the instruction manual.

In operating the facility, a single machine key is used for resetting faults, operating the irradiator, opening the door and actuating the time delay in the radiation room. A portable radiation monitor should always be attached to this key to ensure that the operator never enters the radiation room without a monitor. This radiation monitor should be checked before each entry of the room with a small test source mounted in the door key switch.

There was no portable radiation monitor attached to the key of the facility and no one knew where the test source was. As is discussed later, there are doubts whether the portable radiation monitor was always used and whether it was used correctly.

3.6. MAINTENANCE

A regular preventive maintenance programme is prescribed in the instruction manual for the irradiator. The number of irradiator shutdowns can be kept to a minimum by following this preventive maintenance programme. A monthly test of all emergency shutdown devices is included in the maintenance programme.

This preventive maintenance programme had not been implemented.

A warning is given in the instruction manual for the JS6300 Gamma Sterilizer that any attempt to modify the installed mechanical, pneumatic or electrical systems of the facility may prove hazardous to personnel and cause extensive damage to the machinery, and that any such modifications must have the written approval of the supplier.

No approval had ever been sought from or given by the supplier for any modifications to the facility.

3.7. OPERATION

The facility should be operated only by trained, authorized personnel in accordance with the operating rules and procedures and emergency procedures given in the instruction manual.

The English language instruction manual provided by the supplier had been translated at the plant; however, the Spanish version was inaccurate and incomplete.

To restart the irradiator after a shutdown, the operator first turns the machine key switch on the control panel to the off position and removes the machine key. Lights on the control panel will indicate the status of the irradiator and whether a fault has occurred. The following procedure should then be followed:

(a) The operator presses the monitor test button on the L118 radiation monitor panel next to the personnel access door and holds it until the monitor alarm sounds. When the monitor test button is released, the alarm stops and the monitor test light remains on, indicating that radiation levels in the radiation room are normal and that the door can be opened with the machine key.

(b) The operator checks the operation of the portable radiation monitor attached to the machine key with the small test source mounted in the door key switch. He (or she) then opens the door with the machine key, enters with the portable radiation monitor, carries out an inspection of the entrance maze and radiation room and corrects any fault that may have caused the shutdown.

(c) To start the irradiator, the operator actuates the 90 second delay timer in the radiation room with the machine key, ensures that no one is in the room and leaves through the entrance maze. The door must be closed and the machine key inserted into the machine key switch and turned to the on position. This raises the source and starts the irradiator.

Each of these operating procedures given in the instruction manual had been circumvented or adapted at the facility, as described in the foregoing sections.

To shut down the irradiator and lower the source, the machine key switch is turned with the machine key to the off position. The machine key can be removed from the machine key switch only when the key switch is in the off position.

3.8. SUPERVISION AND RADIOLOGICAL TRAINING

Initial training in radiation safety, operation of the irradiator, preventive maintenance and maintenance 'troubleshooting' was provided by the supplier at the time of installation of the irradiator. The supplier's normal practice is to train operators during the time taken to install the irradiator in order to familiarize them with its construction, operation and maintenance. Three operators were initially trained to operate the irradiator.

The in-facility course on irradiator operations included instruction in the following:

(a) the purpose of industrial irradiation;
(b) familiarization with the facility (with a tour);
(c) the monitoring system;
(d) the control panel;
(e) auxiliary equipment;
(f) operating procedures;
(g) administrative procedures;
(h) emergency and safety procedures;
(i) maintenance procedures;
(j) contamination detection procedures.

No one at the plant had been given responsibility for radiological protection matters. After the departure, within a year of the facility's commissioning, of the operators who had been trained by the supplier, relevant training was given only orally and informally as part of the instruction of operators in how to operate the facility. There were no effective written local rules. Over the years, awareness of the nature and effects of radiation seems to have dwindled to the point that no one working at the plant appreciated the potential hazards or their scale.

This was the situation in February 1988 when Worker A joined the staff as a maintenance technician. He also became a shift operator of the irradiation facility in September 1988 and received oral training in its operation. He was regarded as showing initiative and resourcefulness in solving the frequent maintenance problems at the facility.

The safety systems at the facility had thus become degraded in several vital respects and the employees did not appreciate the dangers. This state of affairs might be characterized as amounting to 'an accident waiting to happen'. On 5 February 1989, the potential for an accident was fulfilled.

4. THE ACCIDENT

4.1. OVERVIEW

The accident comprised two distinct but associated events. In the first event, on Sunday 5 February (Day 1), three persons were exposed to radiation from the cobalt-60 source elements while manipulating the source rack, receiving potentially lethal doses. Throughout the following week, the management of the plant remained unaware of the seriousness of the accident and the facility continued to be operated normally.

It is believed that the source rack was damaged in this first event, which led to the second event at some time later in the week, in the course of which all the pencils were 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. Although the consequences of this second event were not as great as those of the first, they could potentially have been much more serious, and there are lessons to be learned from both events.

The elevated radiation level in the radiation room (due to the active source pencil) was detected on Day 6 (Friday 10 February). In response to the company's consequent request for help, the supplier sent two of its personnel, who were eventually able to locate the active source pencil and remove it to 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 investigation of the accident indicated that four workers had received doses in excess of generally applied worker dose limits. The second event is described in Section 4.3.

The investigation of the accident included interviews with the workers and other people involved. As might be expected, there were some minor inconsistencies between the various accounts. The description in the following sections seems to be the most plausible and consistent account of what happened.

4.2. INITIAL EXPOSURES: THE FIRST EVENT

4.2.1. The initiating events

At 18:15 on Saturday 4 February 1989, Worker A began a night shift as operator of the facility. That evening, as usual, he had to deal with a number of power failures and problems with the pistons, but he managed to restart the operation each time. At about 02:00 on Sunday 5 February (Day 1), while he was taking a coffee break, a fault condition occurred which caused the source rack to be lowered automatically from the irradiation position. On returning from his coffee break, he heard the source transit alarm ringing, indicating that the source was neither fully up nor fully down.

He went to the control panel and followed the reset procedure. When this failed to stop the alarm and release the door, he left the control point, walked around through two gates to the other side of the facility and climbed the ladder to the roof where the source hoist is mounted. There, he followed the 'usual' procedure (not that recommended by the supplier) adopted at the facility in such circumstances to return the source to the fully down storage position. He detached the normal regulated pressurized air supply and applied an overpressure to force the source into the fully raised position, in the hope that this would free the source rack and permit its descent to the storage position.

This attempt was also unsuccessful. Since the source transit alarm continued to sound and the hoist cable was still not under tension, he forcibly pulled the slack cable fully out of the hoist mechanism by hand and then fed it back down through the shield. This had the same effect on the microswitch of the hoist cable as though the source rack were in the fully down storage position and finally stopped the alarm.

Worker A descended and returned to the control panel. He found that the (red) general failure light and the source up light were on. He went back to the roof and managed to manipulate the source down microswitch so that when he returned to the control panel he found the (green) source down light on.

In its original design, the facility had a fixed radiation monitor in the radiation room which would have detected radiation from the (still raised) source rack and prevented unlocking of the personnel access door. However, this monitor probe had been removed more than five years before and had not been replaced. To unlock the door, Worker A followed another 'usual' procedure at the facility (not recommended by the supplier) of rapidly cycling the buttons on the L118 radiation monitor panel (which simulated the detection by the fixed monitor of normal background radiation in the radiation room) while turning the key in the door switch (see Fig. 10). At about 02:30 he succeeded in opening the door. Established practice then required waiting for some minutes for ozone to be ventilated from the radiation room. He did so and then switched off the power supply to the facility.

Worker A seems to have been aware that he had not solved the problem of the stuck source rack but not to have appreciated the nature or magnitude of the danger of entering the room. His statements indicated that his impression was that radiation, like ozone, would dissipate and that, as with unpowered X ray equipment, there would be no continuing radiation.

4.2.2. The first entry

Having switched off the power supply, Worker A entered the radiation room with a torch. He did not check the radiation level with the portable radiation monitor. He examined the pistons around the lower of the two levels of the product transport mechanism, noticing nothing out of order. He then removed two fibreglass product boxes from normal positions on the product entry side of the lower level. In the second row, adjacent to the source rack, he found five boxes jammed into the space for four; that is, a nominal total length of boxes of 2.00 m in a floor length of 1.90 m.

Earlier in the shift, when repairing one of the pistons for this second row, he had found that two boxes had cracks, but since they could still hold the products he had not removed them. These deformed boxes may subsequently have disrupted the system for detecting the positions of the boxes, causing the five boxes to be squeezed into the space for four. The deformation of these boxes probably buckled the metal product guides on the conveyor (see Fig. 6), preventing the source rack from being lowered.

Working by torchlight, Worker A removed two of the five boxes, one of which was wedged against the lower of the two source modules in the source rack (see Fig. 5). This took several minutes. The left side of the source rack then became visible. He noticed that the slack cable that he had paid through from the roof was draped over the fixed product guide just above the upper floor level and was obstructing the descent of the source rack.

Unable to free the rack by himself, Worker A left the radiation room about five minutes after his initial entry. He switched the electrical power back on. The failure light (red) was on and the source down light (green) was intermittent. There was no alarm sounding. He then went to seek help.

4.2.3. The second entry

Shortly afterwards, at about 03:00, Worker A returned with Workers B and C, from another department, who had no experience of the irradiation facility. On being asked about any hazard, Worker A assured the others that there was no danger since the machine was switched off. The three men entered the radiation room and proceeded to remove product boxes from the third row on the upper level (adjacent to the source) so that the source rack could be freed from above (see Figs 12 and 13).

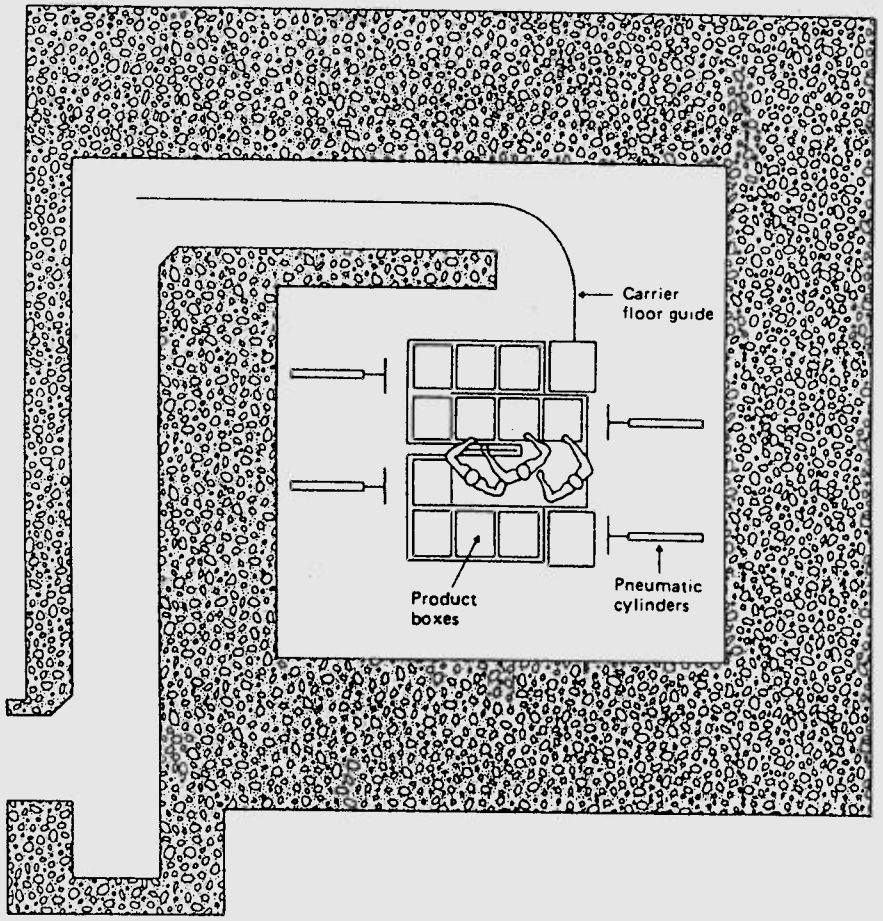

FIG. 12. Plan view of the positions of Workers A, B and C in the radiation room during the accident. (Source: REAC/TS.)

The next phase of the accident was probably when the three workers sustained the largest share of their doses. They would have been moving, but the positions and dose rate contours shown in Figs 13–15 can be taken as indicative of the patterns of exposure. In order to free the source rack they first had to raise it (a mass of about 60 kg) by all three pulling on the hoist cable. Eventually the three men were standing broadly in line on the upper level (Fig. 16). Worker A was in a crouching position with his legs slightly apart and his right leg forward directly in front of the rack. To his right, Worker B had his left leg nearer the source. (The leading leg of each man

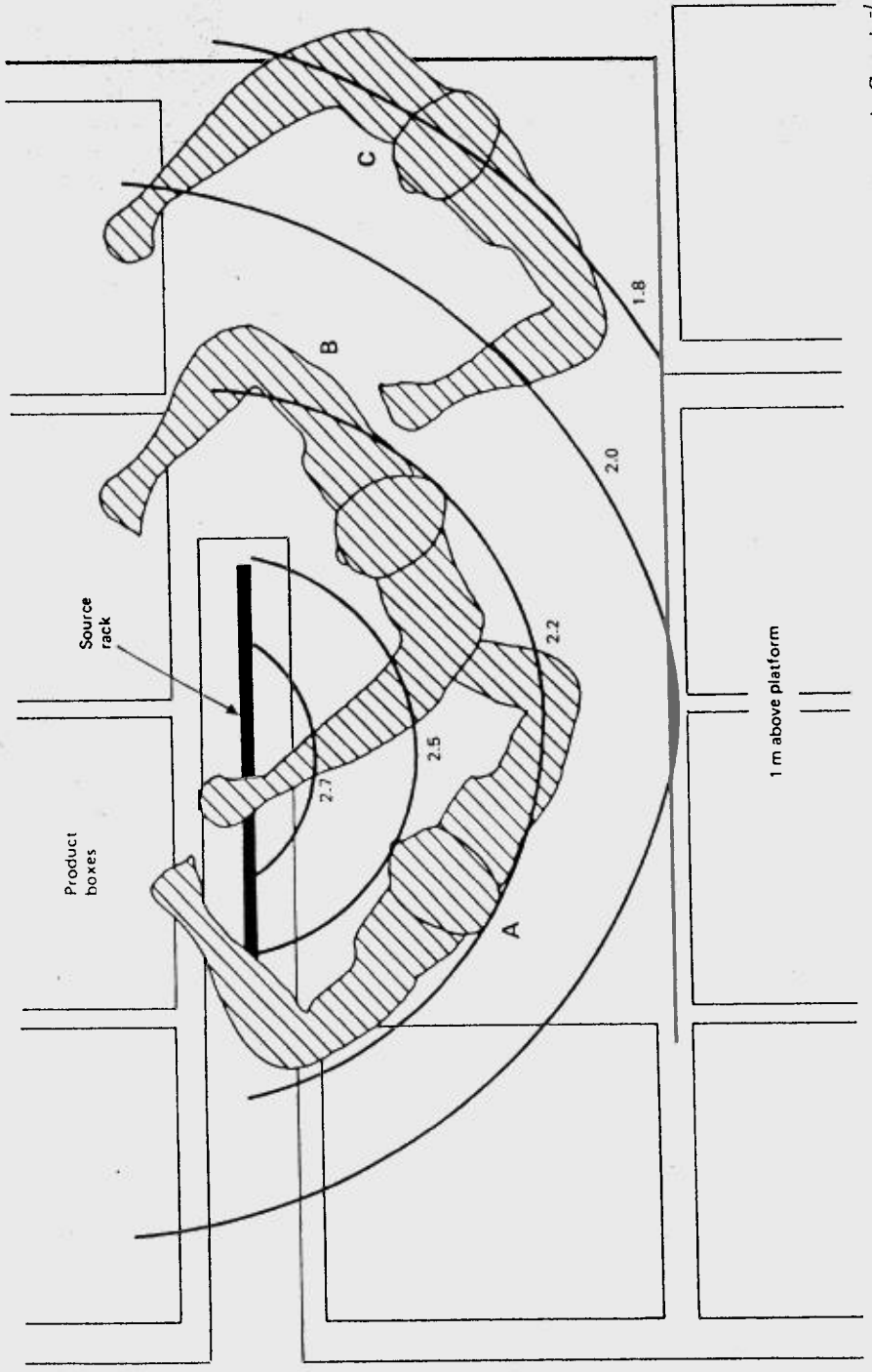

FIG. 13. Plan view of the positions in relation to the source rack of Workers A, B and C during the accident with dose rate contours in Gy·min^{-1}. (Source: REAC/TS.)

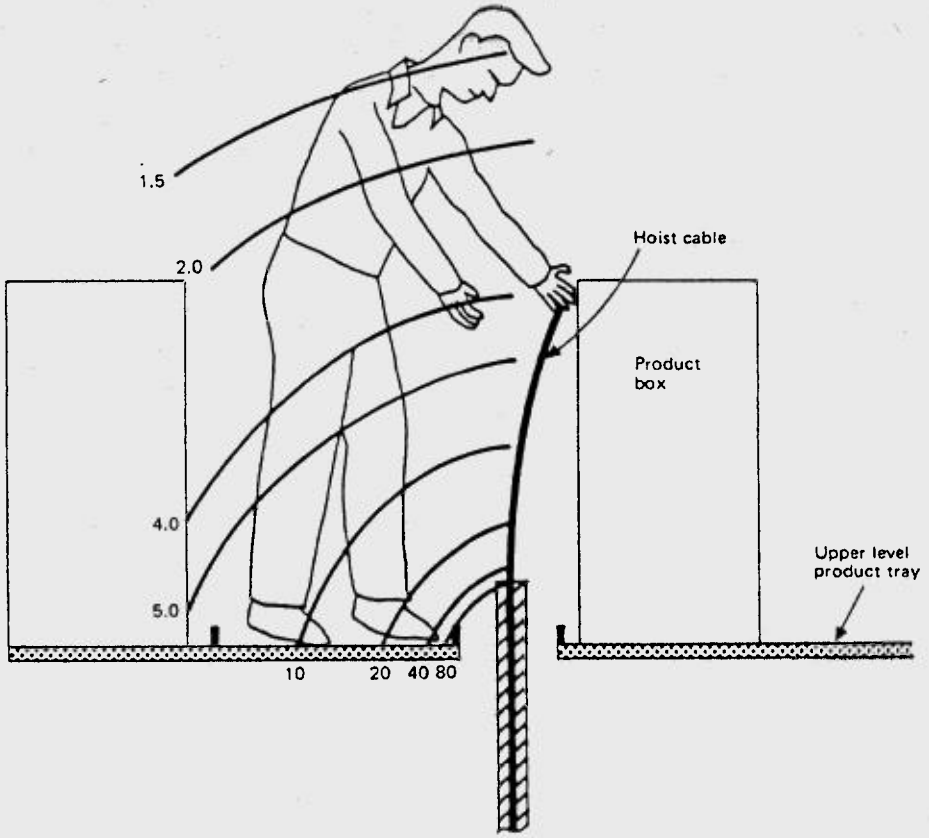

FIG. 14. Dose rate contours for a standing figure: rates in Gy·min^{-1}. (Source: REAC/TS.)

was subsequently amputated first.) Worker C was standing with his left foot on the upper product level and his right foot on a piston. He pulled the hoist cable free while Workers A and B raised the rack.

The three men then paid out the cable over the top of the source rack framework to lower the source rack into the pool. After about two metres of cable had been paid out, the source rack reached the surface of the water, and the men saw the blue glow due to Cerenkov radiation. Worker A was surprised at this and, on fully lowering the source rack, he told his helpers to withdraw quickly. At this point, apparently, he began to suspect that there was some kind of hazard, but not how lethal it was. On leaving the radiation room, Worker B noticed the portable radiation monitor some distance away from the irradiator and asked what its purpose was.

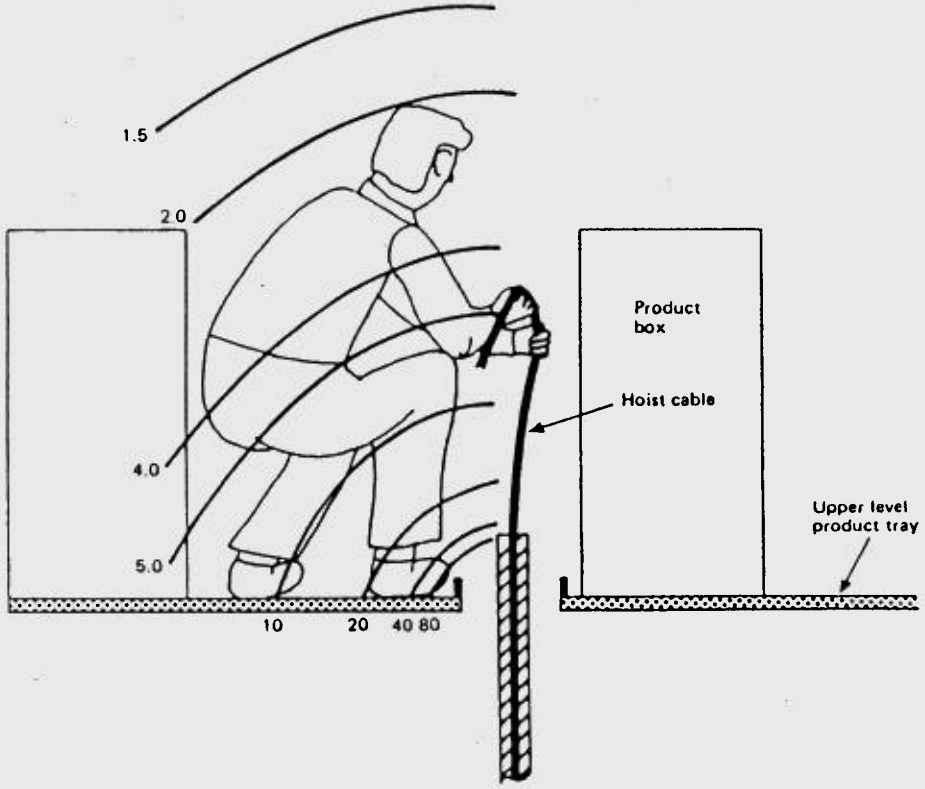

FIG. 15. Dose rate contours for a squatting figure: rates in Gy·min^{-1}. (Source: REAC/TS.)

Worker A replied that it was used for measuring radiation, but that this had not been necessary.

Worker A began vomiting within minutes of leaving the radiation room with the others, having been initially exposed about an hour earlier and being the most exposed of the three. They went outside the building and sat down. He felt increasingly ill. At about 03:30 he began to vomit blood and they went to seek medical help. Since the guard at the gate to the facility was not permitted to leave his post, Worker B helped Worker A about 100 metres to the main road, where they took a taxi to the emergency unit of the Primero de Mayo Hospital. Worker B then began vomiting. Worker C also began to vomit after returning to his work area, and he too went to the Primero de Mayo Hospital. Details of the subsequent medical treatment of Workers A, B and C are given in Section 5.

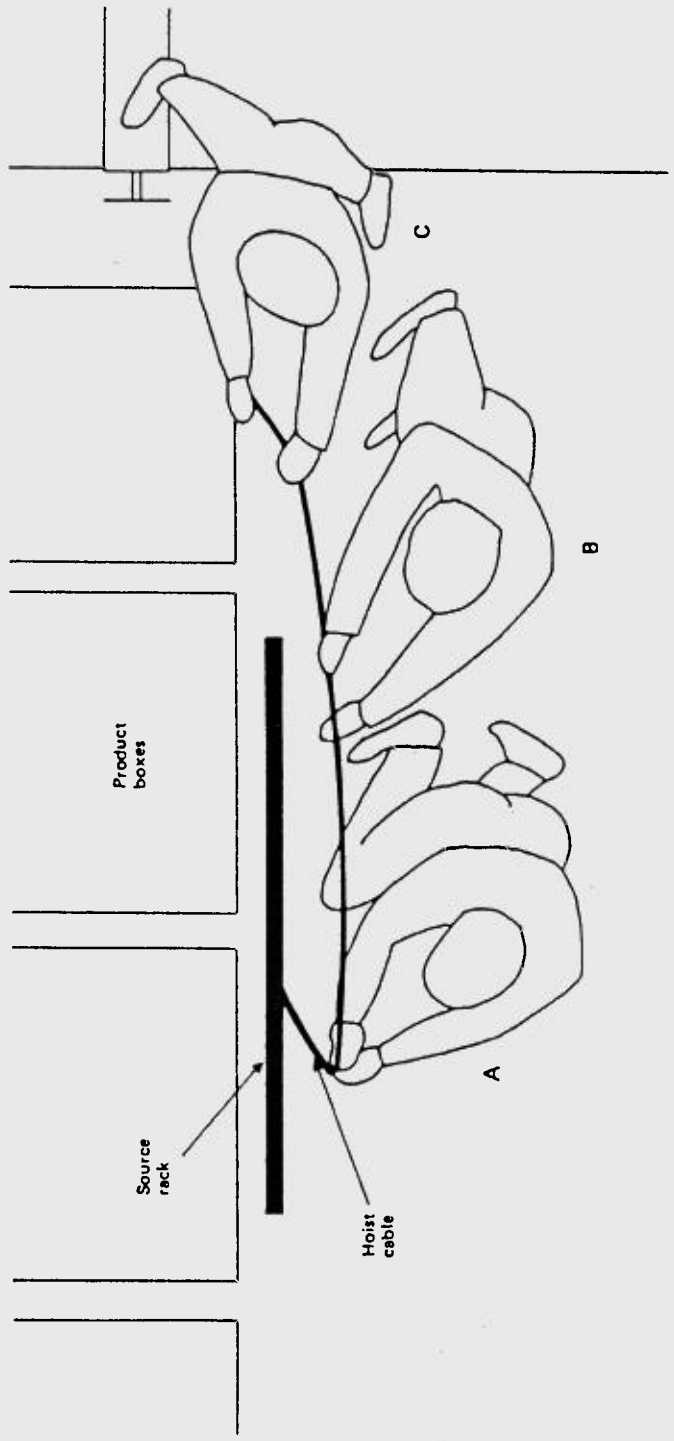

FIG. 16. Plan view of the positions in relation to the source rack of Workers A, B and C while attempting to free the source rack. (Source: REAC/TS.)

4.3. FURTHER EXPOSURES AT THE FACILITY: THE SECOND EVENT

At 06:00 on Day 1 (Sunday 5 February), Worker D reported for duty on the day shift at the facility. He found the main door open, the facility shut down and the product boxes in disorder, with no sign of Worker A. Worker D straightened the boxes and started up the facility. When Worker A did not arrive for duty on the night shift at 18:00, Worker D remained and operated the facility for another shift. On Day 2 (Monday 6 February) at 06:00, he reported the matter to the maintenance manager.

The company was aware of the receipt of sick notes for the absent workers; however, these notes stated that the men were suffering from food poisoning. The company remained unaware that the accident on Sunday 5 February had caused any radiological injury to workers until contacted by medical staff of the Primero de Mayo Hospital on Day 4 (Wednesday 8 February). However, the significance of the injuries was then still not appreciated. For the rest of the week the facility was operated more or less normally; that is, with a typical number of shutdowns for repairs, usually requiring entry of the radiation room. A notable exception was on Day 4 (Wednesday 8 February) at 13:55, when the source rack became stuck but was released by the 'usual' overpressure technique.

Subsequent examination by representatives of the supplier showed a downward bending of the top and bottom horizontal bars of the lower source module and of the bottom bar of the upper module. This deformation had probably occurred in the accident on Day 1 (Sunday 5 February), and may have worsened when the source rack again became stuck on Day 4 (Wednesday 8 February). At some point, probably on Day 5 or 6 (Thursday 9 or Friday 10 February), some of the pencils fell from the upper source module into the pool.

The absence of some pencils was discovered on Day 6 (Friday 10 February) after quality assurance dosimetry had indicated that the doses to the irradiated products that had left the radiation room that morning were substantially lower than required. Upon learning this, the maintenance manager and the quality assurance specialist entered the radiation room at 12:00. They observed from the Cerenkov glow that some source pencils were missing from the upper source module and were lying on the bottom of the pool, and that two of the remaining pencils in the centre of the upper source module had become crossed. In all probability this meant that at least one of the pencils was protruding from the rack. However, it seems that at the time it was not appreciated that a projecting pencil might catch on one of the cross-pieces of the fixed rack positioner when the rack was raised. Since the ambient radiation level in the radiation room was normal, it was decided to continue operation but with longer exposures to compensate for the reduced source strength.

At 16:00 that afternoon (Day 6: Friday 10 February), operation of the irradiator was halted by an 'electromechanical' failure. The operator was unable to return the source rack to the storage position, and called on the head maintenance technician, Worker X, to help. They checked the radiation level with the portable radiation monitor (a 'beeper' type of monitor) outside the door and concluded, on the basis of an increase in the 'beep' rate, that the source rack must be stuck in the raised position. The two workers somehow managed to lower the source rack (probably by the overpressure method), as indicated by the source down light and a fall in the 'beep' rate of the portable monitor, again used *outside* the personnel access door. In the course of lowering the source rack, they heard a noise. This was probably when the remaining pencils were knocked out of the upper module of the source rack.

Workers X and Y opened the door with the key in the 'usual' way (see Section 3.5.2), under the impression that all the source pencils were safely in the pool since the 'beep' rate (as measured outside the door) was low. Worker X and two of his staff, Workers Y and Z, entered the radiation room without further checking the radiation level and, it seems, without a monitor. Not finding anything wrong, they requested the maintenance manager to make an inspection.

The maintenance manager observed that the source rack was indeed in the pool, but that the upper source module was empty of pencils. He left the radiation room to fetch the monitor and, on holding it in the maze entrance, he found that the dose rate was above normal. He closed the personnel access door and had the source rack raised and lowered to see whether this made any difference. It moved without difficulty. He again checked the level of radiation and found it still to be elevated.

TABLE I. RESULTS OF CYTOGENETIC ANALYSES MADE BY THE NATIONAL ATOMIC ENERGY COMMISSION OF ARGENTINA THROUGH THE WHO COLLABORATING CENTRE ON RADIATION EMERGENCIES: DOSES RECEIVED BY OTHER WORKERS ON DAY 6 IN THE SECOND EVENT

Worker	Dose estimate (Gy)	95% confidence interval (Gy)
Maintenance manager	0.22	0.0–0.38
Worker X	0.09	0.0–0.26
Worker Y	0.16	0.0–0.33
Worker Z	0.16	0.0–0.33

After repeating this process twice more with the same results, he concluded that something was amiss beyond their normal experience, and at 16:35 he ordered the facility to be closed and sent the staff to other parts of the plant. Four of the pencils from the top module, one active source pencil and three dummy pencils, were subsequently found to have fallen into the radiation room; the others had fallen into the pool.

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 of at least four more workers: the maintenance manager and Workers X, Y and Z. The dose rate outside the door would have been at least 30 times lower than the dose rate just inside the entrance maze. Thus 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 was only 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 made on all workers who might have been exposed as a result of the accident. These tests indicated that these four persons probably received doses beyond generally applied worker dose limits. (See Table I.)

Had the elevated radiation level in the radiation room due to the active source pencil remained undetected, operating personnel could have accumulated much higher, possibly even lethal, doses through continual uncontrolled exposure.

5. THE RESPONSE TO THE ACCIDENT

Section 5 presents a summary of the response to the accident. Sections 5.1 to 5.4 describe related events that are for convenience considered grouped as the initial medical treatment of the patients, the repairs made to the facility, the response of the authorities in El Salvador and the international participation in the response. Sections 5.5 to 5.7 give summaries of the dosimetric analyses made and of the medical treatment of the patients in the Angeles del Pedregal Hospital in Mexico City and after returning to San Salvador. For specialists, the appendices and annexes to this report describe in greater detail the dosimetric analyses and the medical management of the patients.

Workers A, B and C are from now on also referred to as Patients A, B and C.

5.1. THE MEDICAL RESPONSE IN SAN SALVADOR

On Day 1 (Sunday 5 February) at 03:55 Patients A and B arrived at the emergency room of the Primero de Mayo Hospital in San Salvador. Later, Patient C, who had initially returned to work, also arrived. All three were vomiting. The radiation source at the facility was mentioned; however, no further symptoms of radiation exposure were then manifest. The misdiagnosis was made of food poisoning, and the men were given three-day sick leave certificates and discharged at about 06:00 the same morning.

5.1.1. Patient A

On Day 3 (Tuesday 7 February) Patient A returned to the Primero de Mayo Hospital with nausea and vomiting and also strong general erythema and burns to his legs and feet. In consequence of his statements about the incident at the facility, he was hospitalized as having "radiation burns" from "acute exposure to cobalt". (Apparently, the medical staff then had in mind exposure to a cobalt medical teletherapy source. Their information on and experience of radiation effects derived from cancer radiotherapy.) They consulted by telephone the senior radiotherapist of ISSS, who concurred with their diagnosis and intended treatment.

Patient A was placed in improvised reverse isolation in an annex to the hospital to reduce the possibility of infection. This regime was apparently effective, since no symptoms of severe infection (such as sepsis or septicaemia) appeared. Blood tests and other appropriate tests were performed and symptomatic supportive treatment was begun, including transfusions of blood components (thrombocytes, erythrocytes and plasma) and administration of antibiotics.

The treatment initially appeared to combat the symptoms, but enteritis (inflammation of the gastrointestinal tract) set in on Day 9 (Monday 13 February) with recurrence of vomiting and diarrhoea and the onset of pain and fever. Although mouth lesions made it difficult for Patient A to eat, the medical team did not institute tube feeding. These factors, together with declining blood counts and worsening of the burns to the extremities, led to a deterioration in his general condition.

On Day 11 (Wednesday 15 February) the haematology staff decided that preparations should be made to transfer Patient A as soon as possible from San Salvador to better facilities elsewhere with staff experienced in bone marrow transplant surgery. (The medical staff also recommended that the senior staff of the Occupational Hazard Prevention Department of ISSS investigate the irradiation facility.)

5.1.2. Patient B

When Patient B returned to the facility on Day 4 (Wednesday 8 February), his supervisor released him from work until Day 9 (Monday 13 February) on grounds

of his ill health. On Days 5 and 6 (Thursday 9 and Friday 10 February) he played football with only some discomfort in his feet, but by Day 7 (Saturday 11 February) they were itching and painful. On Day 9 (Monday 13 February) he went back to work but, unable to carry a heavy load because of the pain in his feet, he returned to the Primero de Mayo Hospital and was admitted immediately.

5.1.3. Patient C

Patient C returned to the Primero de Mayo Hospital on Day 2 (Monday 6 February) when nausea and vomiting continued. He was admitted to the hospital, still with a diagnosis of food poisoning. Although radiation injury was diagnosed for Patient A on Day 3 (Tuesday 7 February), Patient C refused to remain in hospital and, since he was not so sick, he was discharged on Day 5 (Thursday 9 February). He returned again on Day 8 (Sunday 12 February) and was readmitted. Again, however, since he was markedly less ill than the other two patients and preferred not to remain in hospital, he was discharged three days later on Day 11 (Wednesday 15 February).

The account of the medical treatment of Patients A, B and C is resumed in Section 5.6.

5.2. SECURING THE FACILITY

Although the company had been informed of the admission of the workers to hospital (see Section 5.3), it seems that the significance of the information was not appreciated. On Day 6 (Friday 10 February) it was discovered at the facility that the pencils had spilled from the source rack in the irradiator. Once apprised of this, the plant manager immediately requested the supplier to send a representative to San Salvador to effect repairs to the facility. Two experts from the supplier duly arrived at the plant on Day 9 (Monday 13 February). They succeeded in determining, by means of a remote television camera and an ion chamber device sent into the radiation room attached to a product carrier, that there was an active source pencil on the upper level.

On the following day the two experts drilled a hole through the approximately 1.6 m thick concrete roof of the radiation room and were able to view remotely two pencils on the upper level. These two pencils were inadvertently moved out of reach in manipulating them with a remote source handling tool in an attempt to determine which was the active one. On Day 11 (Wednesday 15 February), after devising another remotely controlled tool, they succeeded in picking up one pencil and lowering it into the pool. At 19:30 the experts confirmed that the radiation in the radiation room was at the normal background level. They then entered the radiation room and found three inactive dummy pencils on the lower level.

The experts from the supplier were unaware of any overexposure of personnel and had been assured that the radiation monitor had always been used before entry into the radiation room. On Days 12 and 13 (Thursday 16 and Friday 17 February) they made follow-up examinations of the facility and in view of the poor state of the equipment, particularly of the safety systems, they disabled the irradiator to prevent further operation and discussed with plant staff its possible refitting. They carried out a radiation survey of the entire plant in an attempt to confirm that no active source pencil had fallen into a product box and remained on the premises.

As a result of the drilling of the concrete roof, there was too much dust in the water in the pool below for a definitive inventory of the pencils to be made visually. The experts told the plant staff how to obtain a portable pool filtration system for filtering the water to permit the inspection of the pool's contents. Instructions were also given for repairing the existing filtration system, for the upgrading of product boxes and for the manufacture of a source shroud. Since these actions would take some time, the two experts from the supplier returned home. It was not until Day 24 (Tuesday 28 February), on telephoning the plant for a progress report, that the supplier was informed of the accident on Sunday 5 February and the admission of Workers A, B and C to hospital.

The existing pool filtration system was not repaired; however, in a few weeks the water had cleared sufficiently for a visual inspection to be made in an attempt to count the active source pencils by means of their Cerenkov radiation. Although this preliminary check indicated that the full complement of source pencils was present in the pool, their disarray left an element of doubt.

A definitive count of the source pencils was made photographically in November 1989 at the request of the owner of the plant. The results showed that all fourteen active source pencils dislodged from the upper module of the source rack in the second event, clearly distinguishable by their Cerenkov radiation, were on the floor of the storage pool. The photograph also showed that the lower source module containing a further fourteen source pencils was intact. Copies of the photograph were sent to the supplier and forwarded to the IAEA (see photograph).

This confirmed evidence gained previously from an inspection made with a remote television camera by the two experts from the supplier, and also during the IAEA mission, when the lower module was removed from the source rack to the floor of the storage pool. Thus all the source pencils were satisfactorily accounted for in the pool and no further exposure could ensue.

5.3. THE RESPONSE OF THE AUTHORITIES IN EL SALVADOR

On Day 4 (Wednesday 8 February), ISSS staff for internal medicine asked the plant management about the radiation illness of the three workers. They were told that everything at the plant was operating normally.

Because of the worsening condition of the patients, two specialists in occupational medicine from the ISSS went to the plant to investigate on Day 12 (Thursday 16 February). The plant manager had left on a business trip after the experts from the supplier had secured the source pencils, and the medical staff were met by the maintenance and personnel managers. The managers indicated that the company was aware of some kind of accident to three workers in which safety systems had been overridden and that the facility, although temporarily out of operation, was then secure. The ISSS staff did not inspect the facility. They reported the interview to the deputy director of the ISSS.

On the basis of reports by staff of the ISSS and consultants, the deputy director of ISSS initiated a series of actions. On Day 17 (Tuesday 21 February) arrangements were made (including obtaining visas for the patients and for family members who could serve as bone marrow donors) to transfer the patients to a hospital in Mexico City with better facilities and more experienced staff. On Day 18 (Wednesday 22 February) the Ministers of Health and of Labour were briefed and on Day 19 (Thursday 23 February) officials from the ministries of Health and of Labour and representatives of the ISSS met to discuss further steps.

On Day 20 (Friday 24 February) this group met again, and a Salvadorian physicist from the Ministry of Health also attended. After a briefing by the ISSS on the conditions of the three patients, the attendees went to visit the plant immediately. At the plant, the plant manager and staff briefed them and the physicist surveyed radiation levels. They then viewed the intact source rack and the sources in the pool and concluded that the situation was under control. Thermoluminescent detectors were placed in various positions around the facility. When they were read on Day 26 (Thursday 2 March), radiation levels were found to be acceptably low.

Later on Day 20 (Friday 24 February) the Salvadorian physicist contacted Worker C at his home to arrange for his admission to hospital. Worker C was by this time evidencing some hair loss as a result of the radiation exposure, and agreed to be admitted to hospital for the third time. He remained there from Day 23 (Monday 27 February) until his transfer to Mexico City on Day 33 (Thursday 9 March).

The first news that the public had of the accident was a report on late evening television in El Salvador on Day 27 (Friday 3 March). Since the weekend editions of the newspapers had by then already gone to press, the first press accounts appeared on the morning of Day 30 (Monday 6 March). The television news on the Monday evening included an interview with the Salvadorian physicist. On Day 31 (Tuesday 7 March) government officials met and then gave a press conference, after which officials and journalists visited the plant. At this point the public had been informed of the events as they were then understood.

5.4. INTERNATIONAL PARTICIPATION

International participation began after Day 20 (Friday 24 February) at about 15:00 (23:00 Central European time (CET) in Vienna), when the deputy director of the ISSS telexed the IAEA to report a case of "radioactive contamination", requesting experts and equipment and help to determine the effects. The telex message, which was in Spanish and lacked the appropriate codeword for an emergency and whose significance was thus not appreciated by the duty officers on their rounds, did not reach staff of the IAEA's twenty-four hour emergency response system (ERS) until Day 23 (Monday 27 February) at 16:45.

Upon receiving the message, the staff of the emergency response unit informed the responsible IAEA staff and sought, through the office of the United Nations Development Programme (UNDP) in San Salvador, more details from the authorities in El Salvador of the type of help needed. The UNDP became a major communication link between the authorities in El Salvador and the IAEA, since El Salvador is not a signatory of the Convention on Early Notification of a Nuclear Accident (the Notification Convention) or the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the Assistance Convention) and has no designated point of contact in San Salvador or representative in Vienna.

On Day 24 (Tuesday 28 February) at 16:00 CET the Salvadorian physicist responded to the IAEA's enquiry, informing the Agency that medical assistance was needed for three persons in serious condition owing to overexposure to radiation in an accident at an industrial irradiator three weeks previously. He estimated that the doses received were between 4 and 6 Gy, and added that there had been no contamination. On the basis of the information available, the ERS staff contacted the Radiation Emergency Assistance Center/Training Site (REAC/TS) of the United States Department of Energy at Oak Ridge to ascertain whether a team could participate in a mission to San Salvador to assist in the medical treatment of the exposed workers. REAC/TS later suggested that a representative of the Pan American Health Organization (PAHO) of the World Health Organization (WHO), based in Washington, D.C., also participate. This request was endorsed by the IAEA, and the Mission of the USA in Vienna was informed of the IAEA's intentions.

In view of the serious exposures, the IAEA emergency decision making group approved on Day 25 (Wednesday 1 March) the dispatch of two persons (one each from REAC/TS and PAHO) to render medical assistance for two weeks. Subsequently, REAC/TS volunteered a third person and then a fourth. The support of authorities in the USA was obtained through the Mission of the USA in Vienna and the authorities in El Salvador were notified. However, the mission was delayed while the patients were transferred to Mexico City, and the REAC/TS medical assistance team did not arrive in Mexico City until Day 32 (Wednesday 8 March). The group included a health physicist from the Oak Ridge Institute of Nuclear Studies who was

to make more accurate theoretical dose estimates after interviewing the three patients.

On Day 36 (Sunday 12 March) the expert team returned to the USA, and on Day 37 (Monday 13 March) the Mexican medical team sent word through the Mission of Mexico in Vienna that all three patients were expected to survive.

In the mean time, from Day 31 to Day 38 (Tuesday 7 to Tuesday 14 March), the physicist from PAHO and the Salvadorian physicist visited the plant in San Salvador and interviewed staff about the accident. From Day 39 to Day 43 (Wednesday 15 to Sunday 19 March), the PAHO physicist interviewed the three patients in Mexico City. These interviews formed a major element in the subsequent reconstruction of events. The PAHO physicist requested that blood samples be taken of all those staff who might have been exposed and sent through the WHO Collaborating Centre on Radiation Emergencies in Argentina to the National Atomic Energy Commission of Argentina for cytogenetic dose assessment. As stated in Section 4.3, the results indicated that at least four more workers had been exposed significantly over the dose limit for occupational exposure, probably as a result of the incident with the active source pencil on Day 6 (Friday 10 February).

On Day 196 (Saturday 19 August) the IAEA received an urgent request for medical help from the authorities in El Salvador, in response to which an IAEA staff member who had directed the treatment of patients with radiation injuries after the accident at Chernobyl went to San Salvador to render further assistance.

5.5. DOSIMETRIC ANALYSES

From Day 32 to Day 36 (Wednesday 8 to Saturday 12 March) the medical team at the Angeles del Pedregal Hospital in Mexico City worked together with the IAEA expert team from REAC/TS to assist in both medical and dosimetric aspects. Assessments of the patients' dose distributions were made on the bases of the onset and extent of epilation and dry and wet desquamation and early signs of necrotic lesions. These assessments, which did not substantially change afterwards, are presented in Fig. 17.

Blood samples for cytogenetic analysis were collected from the patients upon their admission to the Angeles del Pedregal Hospital: from Patient A on Day 24 (Tuesday 28 February), from Patient B on Day 26 (Thursday 2 March) and from Patient C on Day 33 (Thursday 9 March). Further samples were collected on Day 32 (Wednesday 8 March) for independent analysis by the specialist centres at REAC/TS and the Angeles del Pedregal Hospital. The results of the cytogenetic analyses at the two centres, presented in detail in Appendix I, were in very good agreement. The estimates of mean doses from these results were as follows:

Patient A: 8.1 Gy
Patient B: 3.7 Gy
Patient C: 2.9 Gy.

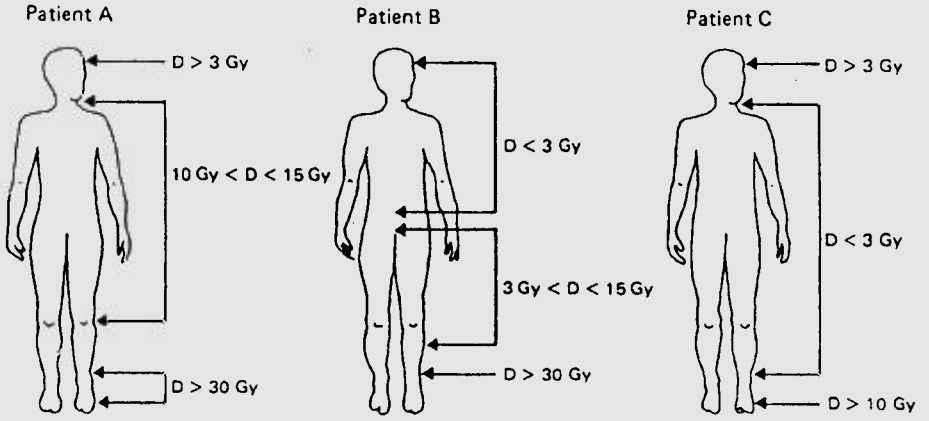

FIG. 17. Patients A, B and C: doses D incurred by different parts of the body. (Source: REAC/TS.)

5.6. FURTHER MEDICAL TREATMENT IN MEXICO CITY

5.6.1. Patient A

When admitted to the Angeles del Pedregal Hospital in Mexico City on Day 24 (Tuesday 28 February), Patient A was severely ill with gastrointestinal and haematopoietic radiation syndromes. He had general radiodermatitis, extensive burns to his legs and feet, and oedema in his hands. He continued to suffer nausea, vomiting and diarrhoea and was severely malnourished, having lost 20% of his (normally light) body weight. His blood and bone marrow were in extremely poor condition, but some effective bone marrow that could support recovery may have remained owing to the non-uniformity of his exposure.

Experienced medical and dosimetric teams were assembled and a complete range of tests were made (see Appendices I and II). The treatment regime for Patient A included strict protective isolation, blood transfusions and, to supplement his meagre oral nutritional intake, total parenteral feeding. In addition, on his arrival Patient A commenced a twenty day course of treatment with the experimental agent granulocyte macrophage colony stimulating factor (GMCSF), which may promote bone marrow recovery. (A supply of GMCSF was donated by a Swiss company through its Mexican subsidiary.) This treatment was preferred to bone marrow transplant surgery, which in this case was not considered appropriate. Although the drug was first given at a time (about 30 days after irradiation) when spontaneous bone marrow recovery might in any case have been expected, it nevertheless seemed to the Mexican medical staff for a number of reasons to have expedited recovery. The

use of GMCSF seemed not to be harmful, although it did cause side effects of tremors and weakness.

This regime led to a steady improvement. Patient A was removed from isolation on Day 47 (Thursday 23 March) but otherwise the regime was maintained. Although special attention was given to treating his leg burns, which were hindering his general recovery, gangrene appeared three months later. Consequently, on Day 132 (Friday 16 June) his right leg was amputated above the knee.

His prognosis was then guardedly for continued recovery; however, the danger of recurrent infections would persist; further blood transfusions would be necessary to combat anaemia; amputation of his left leg could become necessary; the probability of his subsequently developing cataracts was not insignificant; and there was a greater than normal possibility of his contracting acute leukemia. Nevertheless, by Day 173 (Thursday 27 July) his condition was considered to have improved sufficiently for him to be returned to the Medico-Surgical Hospital of the ISSS in San Salvador, where his nutritional, orthopaedic, physiotherapeutic and haematological condition was kept under close observation and where the more familiar surroundings were a positive psychological factor.

5.6.2. Patient B

Patient B was transferred to the Angeles del Pedregal Hospital in Mexico City on Day 26 (Thursday 2 March) with gastrointestinal and haematopoietic symptoms of acute exposure and severe burns to the legs and feet. He also was malnourished and had a severely depressed blood picture. As with Patient A, the non-uniformity of Patient B's exposure was a factor in his favour in that not all his bone marrow was severely irradiated.

Although the effects of Patient B's overexposure developed somewhat more slowly and to a lesser extent than for Patient A, who had received a much higher dose, the treatment regimes were similar. Patient B's treatment included the use of GMCSF, a ten day course of which was begun on his arrival and completed without notable side effects. After 11 days his blood picture had improved sufficiently to permit his removal from isolation. Again, the Mexican medical team considered that GMCSF was effective in promoting recovery. Psychological support was also an important element of the treatment.

The burns to Patient B's extremities were severe, and progressive necrosis of a toe eventually necessitated the amputation of his left leg above the knee on Day 161 (Saturday 15 July). After this, he also made sufficient general progress to be returned to San Salvador on Day 173 (Thursday 27 July), where he was kept under close medical supervision, particularly for the condition of his other (right) foot.

5.6.3. Patient C

Patient C was admitted to the Angeles del Pedregal Hospital on Day 33 (Thursday 9 March) with less severe haematopoietic symptoms and burns to his left foot. He required less intensive treatment. The medical staff followed a course of treatment similar to those for Patients A and B but to a lesser extent, including a nine day course of GMCSF begun on Day 34 (Friday 10 March) and tolerated without notable side effects. Since Patient C showed no other complications (with his extremities, for example), he was released from the Angeles del Pedregal Hospital on Day 55 (Friday 31 March) and transferred for continued medical supervision in San Salvador.

5.7. MEDICAL FOLLOW-UP IN SAN SALVADOR

5.7.1. Patient A

Patient A was returned to San Salvador on Day 173 (Thursday 27 July) and placed in a separate specially prepared room in the Medico-Surgical Hospital of the ISSS. Although he continued to make progress, his other (left) leg was not healing and a second amputation was likely to become necessary. On Day 187 (Thursday 10 August) his condition began to deteriorate. He had contracted pneumonia by Day 191 (Monday 14 August) and his condition was critical. At some time during this period, a lung was perforated when a catheter was placed in his neck (the condition of his limbs being too poor to permit the insertion of a catheter).

After a week in critical condition in intensive care, Patient A died at 07:00 on Day 197 (Sunday 20 August), six and a half months after the accident. His family did not permit a post-mortem examination. The cause of death cannot be stated with certainty, but it was attributed to residual radiation damage to the lungs complicated by traumatic perforation.

In response to an urgent request received from the authorities in El Salvador on Day 196 (Saturday 19 August), an IAEA staff expert who had directed the treatment of patients after the Chernobyl accident went to San Salvador. However, Patient A died shortly before the expert arrived in San Salvador the following day. The expert assisted in planning further treatment and follow-up for Patients B and C.

5.7.2. Patient B

Patient B was discharged from the Angeles del Pedregal Hospital and returned to San Salvador on Day 173 (Thursday 27 July). He also was admitted to the Medico-Surgical Hospital and placed in a separate room, and his condition continued to improve. However, progress was slow owing to the worsening condition of his other

(right) leg. After the right leg also had been amputated on Day 202 (Friday 25 August), his general recovery was more rapid. His need for psychological support then became the most important factor in his further progress. He was transferred on Day 221 (Thursday 14 September) to the Hospital for Rehabilitation. His prognosis is good except for the possibility of late effects such as cataracts.

5.7.3. Patient C

Patient C was returned to San Salvador on Day 55 (Friday 31 March), and had his next medical examination on Day 58 (Monday 3 April). He remained on sick leave from work until Day 199 (Tuesday 22 August). On Day 220 (Tuesday 12 September) further rehabilitation therapy was commenced to relieve residual chronic effects, particularly in his more exposed (left) foot, which was painful and caused him to limp. The prognosis is promising for his full recovery; however, the possibility of late radiation injury to the eyes remains.

6. FACTORS CONTRIBUTORY TO THE ACCIDENT

Section 6 presents a brief recapitulation of some significant factors that contributed to the accident.

The accident occurred after damaged fibreglass product boxes caused the irradiator's transport mechanism to jam, forcing five boxes into the space for four. The boxes were forced against a thin steel bar in the frame inside which the source rack is raised and lowered. The bowing of this bar was sufficient to cause the source rack to become stuck in a raised position. If this had occurred soon after the commissioning of the facility in 1975, any one of the multiple in-built safety systems together with the training of the operators should have sufficed to prevent access to the radiation room while radiation levels were potentially lethal. The problem in February 1989 might well have been solved had help been sought from the supplier, whether advice by telephone or direct assistance. Indeed, a similar event in 1975 was successfully dealt with. However, in the intervening fourteen years a combination of circumstances led to degradation in the safety features installed and in the level of staff training.

El Salvador's economy has been severely disrupted since 1979, fostering a make do and mend approach at the plant, as elsewhere, rather than a positive approach to maintaining and improving safety. This is exemplified by the following:

(1) The company continued to use significantly depleted source elements, even when it could have funded their replenishment. When the company could afford to invest in such replenishment in 1981, the supplier would not send personnel to El Salvador for personal security considerations.
(2) The company did not implement measures detailed in notices from the supplier designed to upgrade the safety of the facility.

One result of the financial difficulties and the security aspects of the civil war was that the only contact between the company and the supplier between 1977 and 1989 was by telephone. The supplier would normally expect to visit most facilities it had constructed once every two to three years to replenish the source, on which occasions it would be possible to detect any serious safety deficiencies and to instigate corrective actions.

The civil war also brought about a high level of security consciousness in El Salvador. The company regarded the irradiation facility as a high technology installation and a potential target for attack. The significance of this lay in the fact that the existence of the facility was therefore not publicized; moreover, there was a reluctance to commit any information on its operations to writing, even safety measures and operating procedures. Training in these matters was passed on orally from one operator to another.

Although proposals for the regulatory control of ionizing radiations were made in 1986 and enabling legislation was drafted, there have never been any regulations in El Salvador governing the use of ionizing radiations, nor has any organization acted as an official point of reference on the subject. The lack of regulatory control and the loss of contact with experts in radiation matters caused an information void that, coupled with the effects of the civil war, led to a fall in the standards of radiation protection.

This decline began with the departure from the company, within a year of the commissioning of the facility, of the three operators trained by the supplier. Their experience was passed on orally to their successors and from them to subsequent replacements, with a concomitant potential for corruption of information. The result was that at the time of the accident no one in the plant seemed to have a full appreciation of the potential hazards of the facility.

In the accident, Worker A, unaware of the extreme danger, entered the radiation room on his own initiative, as he had in the past, in an attempt to keep the facility operating. The installed safety systems, which would normally have prevented human error from leading to an accident, had degenerated or been bypassed over the years.

As in accidents elsewhere, the victims were initially diagnosed as having food poisoning and sent home. However, within a few days they had returned to hospital with more extensive and severe symptoms. A correct diagnosis was then made and appropriate treatment regimes were instituted.

After it had been confirmed that the three workers were suffering from the effects of overexposure to radiation, there was a significant delay before the source of the exposure was recognized and effective actions were instigated to verify that no further uncontrolled exposure was occurring. That there was a significant potential for further exposure was demonstrated by the subsequent spill of pencils from the upper source module in the second event, which gave rise to doses in excess of generally accepted worker dose limits to four other persons. The elevated radiation level in the radiation room due to a spilled active source pencil was detected before more serious doses were incurred (see Section 4.3).

When the management of the plant realized that dealing with this second event was beyond its competence, it contacted the supplier for help. The following week, two experts from the supplier located an active source pencil in the radiation room and succeeded in removing it to the pool. They also disabled the source hoist mechanism in view of the degraded condition of the safety systems at the facility. It was only then, almost two weeks after the first event, that the facility could be considered to have been 'made safe'.

7. GENERIC LESSONS LEARNED

The information that was made available to the IAEA, as presented in this report, is a basis for reaching conclusions about the causes of the accident and how it was dealt with. These conclusions lead to generally applicable recommendations to those responsible for the safe operation of irradiation facilities on actions designed to prevent accidents in the future or to make the response to those that do occur more effective.

Many of the recommendations cover procedures and practices already widely considered to be essential to safe operation. Action on others, particularly those relating to international aspects, would enhance and reinforce present safety practices. The lessons necessarily concern irradiation facilities; however, many of the recommendations apply to radiation safety in other areas.

Conclusions and (in italic type) recommendations which follow from them are presented for the major groups concerned with the safety of such facilities: operating organizations, national authorities, source suppliers, the medical community and international organizations.

A. OPERATING ORGANIZATIONS

(1) The physical integrity of the irradiation facility, particularly its safety features, was allowed over a long period to degrade significantly and the supplier's recommendations for upgrading safety were not heeded.

The operating organization should, as a minimum, ensure:

(a) that safety systems conform to the supplier's current recommendations;
(b) that preventive maintenance is part of the operating plan;
(c) that recommendations by the supplier for upgrading safety are promptly considered, and that the reasons for any non-implementation are fully documented and the supplier and national authorities are informed of them.

(2) Safety procedures at the facility and training in their observance had deteriorated to the point of inadequacy. Not only did this contribute to the accident, it also meant that the initial exposures went unrecognized, as did the damage to the source rack, which led to further overexposures.

The operating organization should ensure:

(a) that operators have initial and continuing training in radiological safety that is separate and distinct from training for production operations;
(b) that training is based on the up to date and official written operating, maintenance and emergency procedures and on practical exercises;
(c) that the operating manual, operating rules and procedures and emergency procedures are available at the control panel in an accurate local language version;
(d) that staff are trained to recognize situations that call for implementing such arrangements;
(e) that written emergency procedures detail effective arrangements for notifying the authorities of radiological accidents and for initiating actions to limit residual hazards;
(f) that operators and maintenance staff wear personal dosimeters and dosimetric records are kept.

(3) The management of the facility failed to maintain a corporate awareness of the acute danger inherent in the unauthorized or improper operation of such an irradiation facility.

The management of such facilities should manifest continuing recognition of the primary responsibility of the operating organization for safety by at a minimum:

(a) *participating fully in radiological protection matters, especially in providing continuity regardless of changes in ownership, management or staffing;*
(b) *emphasizing to personnel the primary importance of safety for themselves and, ultimately, for continued productivity;*
(c) *appointing two radiation safety officers with full authority in such matters, of whom one should be available at all times;*
(d) *seeking periodic independent safety review by recognized experts.*

(4) Production concerns overrode any safety concerns that the sole operator on duty may have had.

The radiation room of an irradiation facility must on no account be entered unless someone assigned sole responsibility for radiation protection is on call.

(5) The immediate cause of the accident (the jamming and deforming of product boxes which in turn obstructed the descent of the source rack) would have been prevented had earlier recommendations by the supplier been heeded.

A metal shroud should be installed in such irradiators to protect the source rack from obstruction; product boxes should be inspected regularly and marginal boxes replaced.

B. NATIONAL AUTHORITIES

(6) The lack of a national infrastructure for overseeing radiological safety, despite earlier proposals, was a major factor in the failure to identify and remedy deficiencies in radiological protection at the facility and to respond more expeditiously and effectively to the accident.

There should be in place in all countries with irradiation facilities as a minimum infrastructure for overseeing radiological safety:

(a) *enabling legislation, a central regulatory authority and simple, specific implementing regulations;*
(b) *an organization with adequate resources and expertise to ensure that essential safety services such as personnel monitoring and training are provided;*
(c) *a comprehensive national inventory of all man-made sources of ionizing radiation;*
(d) *a system for the registration and inspection of sources;*

(e) *a widely disseminated emergency response plan to ensure the prompt notification of any accident to the authorities, the transmission of adequate information to the public and follow-up to determine causes and to take corrective action.*

(7) Although the need for more experienced medical staff and better facilities than those available in El Salvador was recognized, there was a significant delay in effecting the transfer of the patients to a suitable hospital elsewhere.

In countries where applications of radiation are widespread, the national emergency plan should identify at least one central medical unit capable of treating victims of a radiological accident. There should be plans for transferring any seriously overexposed patients for more specialized treatment, possibly in another country. Plans should also be in place for the speedy fulfilment of administrative requirements such as obtaining passports and visas.

(8) Once the accident had come to attention and caused concern, prompt steps were taken fully to inform representatives of the media and, through them, the public.

National emergency plans should expressly recognize the need to provide timely, factual information to the public on the nature, extent and significance of a radiological emergency.

(9) The reporting of the accident to the IAEA and hence the provision of assistance would have been facilitated had the government of El Salvador been party to the Notification and Assistance Conventions.

The governments of all countries in which major radiation sources are in use should consider subscribing to the Convention on Early Notification of a Nuclear Accident or the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency[2] *and setting in place the necessary infrastructure for the implementation of their provisions.*

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Convention on Early Notification of a Nuclear Accident and Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, Legal Series No. 14, IAEA, Vienna (1987).

C. IRRADIATOR SUPPLIERS

(10) The English language instruction manual provided by the supplier was not available in a local language version. The manual had been translated at the plant; however, the Spanish version was inaccurate and incomplete. Safety aspects were covered in the instruction manual only under production aspects and not separately.

It should be ensured that the instruction manual, including operating rules and procedures and emergency procedures, is available at all facilities in an accurate local language version. To help managers and operating and maintenance staff to appreciate the safety significance of their actions, operating manuals should cover radiation safety separately from production aspects.

(11) The supplier did not send representatives to the plant for personal security reasons, and was thus unable to detect the serious safety deficiencies and instigate corrective actions.

In the absence of regular, full communication with the operating organization, suppliers of irradiators should use all possible channels, formal and informal, to alert national authorities or appropriate international organizations in a timely manner to identified or suspected safety deficiencies at irradiation facilities. (See also Recommendation (17).)

(12) Confirmation of the preliminary visual inventory of source pencils in the pool to demonstrate that no further exposures beyond those already sustained were possible was significantly delayed.

The emergency procedures of the supplier should emphasize the need to make a prompt inventory to demonstrate (normally to the national competent authority) that all source pencils have been accounted for.

(13) Although assessment of the facility was made difficult by the long history of practices in circumvention of the systems of protection, no fundamental design flaws were identified.

Design, operation and emergency procedures for irradiation facilities should be reviewed after an emergency response so that practical lessons can be identified, documented and acted on, as in this case. Probabilistic safety assessment might be of use in such a review.

D. THE MEDICAL COMMUNITY

(14) Once acute radiation exposure had been diagnosed after two days, the medical staff in San Salvador carried out a generally effective treatment strategy despite their lack of experience in treating radiation injuries.

Further efforts should be made to acquaint medical practitioners with the symptoms and treatment of acute radiation syndrome (such as by including synopses of typical accidents in initial and continuing training) in order to facilitate prompt recognition and initial treatment.

(15) The post-initial treatment by the medical team in Mexico City was especially effective; for example, in the use of parenteral nutrition, in forgoing bone marrow transplantation, in scheduling amputation, in providing physiotherapeutic and psychotherapeutic support, and, above all, in haematological analysis.

The post-initial treatment of seriously exposed persons should be undertaken at specialized facilities by experienced medical staff, assisted as necessary by specialists from elsewhere.

(16) The medical team in Mexico City considered that granulocyte macrophage colony stimulating factor (GMCSF) was effective in expediting bone-marrow recovery, although the evidence was not unambiguous (it was administered at a time when spontaneous recovery might in any case have been expected).

The timely use of GMCSF in treating the victims of radiological accidents should be considered.

E. INTERNATIONAL ORGANIZATIONS

(17) Although it was not the case for this facility, major radiation sources have been provided with the financial assistance of other countries or international organizations to countries in which the supervision of radiological safety by national authorities is inadequate.

Governments or international organizations that have facilitated the provision of major radiation sources should investigate with suppliers and national authorities possible means of continuing co-operation to ensure that there is adequate radiation protection. (See also Recommendation (11).)

(18) The co-operation between several governments and intergovernmental organizations in the rendering of expert assistance to El Salvador in medical treatment, physical dosimetry and investigation of the accident was hindered because normal administrative procedures were followed rather than special procedures appropriate to an emergency.

The tasks and responsibilities of participants in the emergency response to a radiological accident should be well defined to facilitate the response of governmental and intergovernmental organizations in extraordinary circumstances.

(19) The UNDP office in San Salvador was a key communication link that facilitated the provision of assistance and the follow-up.

Official points of contact should be identified in all countries, even those whose adherence to the Notification Convention or the Assistance Convention has not yet been effected.

ADDENDUM

In February 1990, the IAEA was informed of plans to refit the irradiator in San Salvador to extant irradiator safety standards and to recommission it for operation. New cobalt-60 source elements and new parts will be shipped and installed and the original source elements will be returned to the supplier. Requirements for the import of radioactive source elements into El Salvador and for the use of the irradiator are set out in a licence issued by the ministry now designated as responsible for the control and use of radiation sources and by the newly appointed competent authority.

- *Instruction manual.* The manual will be revised for the refitted unit and will include a section on radiation safety and the danger to health of misuse of the equipment. The revised manual will be sent to the company for translation into Spanish and personnel from the supplier will verify the translation by rehearsing the operating and maintenance procedures with it.
- *Training of personnel.* The training of operation and maintenance personnel by the supplier will be fully certified, their competence must be demonstrated and the competent authority must be so informed. The danger of neglecting maintenance and of circumventing interlocks and other safety features will be emphasized.
- *Safety systems.* The safety systems will be demonstrated to the competent authority by plant personnel, overseen by the supplier, by means of a 'cold' check before installation of the new cobalt-60 sources.
- *Radiation survey.* The supplier will make a radiation survey of the shielding and send the results to the company and the competent authority.
- *Periodic safety audits.* The results of periodic safety audits by the supplier and any deficiencies found will be reported to the company. The competent authority will be informed if action is not taken to remedy any deficiencies.
- *Safety checklist.* The competent authority will be given the supplier's safety checklist and will be informed how to perform a safety audit and to assess the competence of authorized operators in case personnel from the supplier are unable to inspect the plant.

When the facility has been refitted and company personnel have been trained, the safety systems will be demonstrated to the competent authority and the facility will be recommissioned.