The Radiological Accident in Cochabamba

IAEA
International Atomic Energy Agency

IAEA SAFETY RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish standards of safety for protection against ionizing radiation and to provide for the application of these standards to peaceful nuclear activities.

The regulatory related publications by means of which the IAEA establishes safety standards and measures are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety, and also general safety (that is, of relevance in two or more of the four areas), and the categories within it are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides.**

Safety Fundamentals (blue lettering) present basic objectives, concepts and principles of safety and protection in the development and application of nuclear energy for peaceful purposes.

Safety Requirements (red lettering) establish the requirements that must be met to ensure safety. These requirements, which are expressed as ‘shall’ statements, are governed by the objectives and principles presented in the Safety Fundamentals.

Safety Guides (green lettering) recommend actions, conditions or procedures for meeting safety requirements. Recommendations in Safety Guides are expressed as ‘should’ statements, with the implication that it is necessary to take the measures recommended or equivalent alternative measures to comply with the requirements.

The IAEA’s safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA.

Information on the IAEA’s safety standards programme (including editions in languages other than English) is available at the IAEA Internet site

www-ns.iaea.org/standards/

or on request to the Safety Co-ordination Section, IAEA, P.O. Box 100, A-1400 Vienna, Austria.

OTHER SAFETY RELATED PUBLICATIONS

Under the terms of Articles III and VIII.C of its Statute, the IAEA makes available and fosters the exchange of information relating to peaceful nuclear activities and serves as an intermediary among its Member States for this purpose.

Reports on safety and protection in nuclear activities are issued in other series, in particular the **IAEA Safety Reports Series**, as informational publications. Safety Reports may describe good practices and give practical examples and detailed methods that can be used to meet safety requirements. They do not establish requirements or make recommendations.

Other IAEA series that include safety related publications are the **Technical Reports Series,** the **Radiological Assessment Reports Series,** the **INSAG Series, the TECDOC Series**, the **Provisional Safety Standards Series**, the **Training Course Series,** the **IAEA Services Series** and the **Computer Manual Series**, and **Practical Radiation Safety Manuals** and **Practical Radiation Technical Manuals**. The IAEA also issues reports on radiological accidents and other special publications.

THE RADIOLOGICAL ACCIDENT
IN COCHABAMBA

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BANGLADESH
BELARUS
BELGIUM
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BULGARIA
BURKINA FASO
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHILE
CHINA
COLOMBIA
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LATVIA
LEBANON
LIBERIA
LIBYAN ARAB JAMAHIRIYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITIUS
MEXICO
MONACO
MONGOLIA
MOROCCO
MYANMAR
NAMIBIA
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
PAKISTAN
PANAMA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
SAUDI ARABIA
SENEGAL
SERBIA AND MONTENEGRO
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIETNAM
YEMEN
ZAMBIA
ZIMBABWE

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

Printed by the IAEA in Austria
July 2004
STI/PUB/1199

THE RADIOLOGICAL ACCIDENT IN COCHABAMBA

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2004

IAEA Library Cataloguing in Publication Data

The radiological accident in Cochabamba. — Vienna : International Atomic Energy Agency, 2004.
p. ; 24 cm.
STI/PUB/1199
ISBN 92–0–107604–5
Includes bibliographical references.

1. Radiography, Industrial — Cochabamba Valley (Bolivia). 2. Radiography, Industrial — Exposure. I. International Atomic Energy Agency.

IAEAL 04–00368

FOREWORD

In April 2002 an accident involving an industrial radiography source containing ^{192}Ir occurred in Cochabamba, Bolivia, some 400 km from the capital, La Paz. A faulty radiography source container had been sent back to the headquarters of the company concerned in La Paz together with other equipment as cargo on a passenger bus. This gave rise to a potential for serious exposure for the bus passengers as well as for the company employees who were using and transporting the source. The Government of Bolivia requested the assistance of the IAEA under the terms of the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. The IAEA in response assembled and sent to Bolivia a team composed of senior radiation safety experts and radiation pathology experts from Brazil, the United Kingdom and the IAEA to investigate the accident.

The IAEA is grateful to the Government of Bolivia for the opportunity to report on this accident in order to disseminate the valuable lessons learned and help prevent similar accidents in the future. In particular, the IAEA wishes to express its gratitude to the Bolivian Institute of Nuclear Science and Technology, the Bolivian Institute of Standardization and Quality, and the Caja Nacional de Salud (National Health Insurance Bureau).

The IAEA wishes to thank the experts of the IAEA team for their participation and their dedication in carrying out their tasks, and for their contributions to the preparation and review of this report. The IAEA wishes to acknowledge the contributions of the Communications Department of the National Radiological Protection Board, United Kingdom, and the Laboratory of Radiological Sciences of the University of Rio de Janeiro, Brazil.

The IAEA officer responsible for the preparation of this publication was E. Buglova of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

On 28 June 2002, the Bolivian authorities informed the IAEA's Emergency Response Centre of three events that involved radioactive material:

(1) In April 2002 an accident involving an industrial radiography source containing ^{192}Ir occurred in Cochabamba, Bolivia, some 400 km from the capital, La Paz. The source, in a remote exposure container, remained exposed within a guide tube, although this was not known at the time. The container, the guide tube and other equipment were returned from Cochabamba to the headquarters of the company concerned in La Paz as cargo on a passenger bus. This bus carried a full load of passengers for the journey of about eight hours from Cochabamba to La Paz. The equipment was subsequently collected by company employees and transferred by taxi to their shielded facility. Routine radiation measurements made there established that the source was still exposed and actions were then taken to return the source to its shielded container.

(2) In May 2002, on the basis of information supplied by the Argentine authorities, the Bolivian authorities were able to detect and follow up the unauthorized import of four ^{192}Ir sources for industrial radiography.

(3) In June 2002 a soil moisture probe incorporating an americium/beryllium source was stolen in transport.

The first of these three events is the primary focus of this report. It was a serious radiation accident that resulted in significant exposures of workers and members of the public, and there are lessons to be learned from it.

A number of actions were taken by the Bolivian authorities to investigate the circumstances of the accident and to address the issues arising from it. The exposure of those persons involved in the accident, particularly the passengers on the bus in which the radiography source was transported, had become a matter of growing concern among the authorities. The Government of Bolivia formally sought the assistance of the IAEA under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. In response, a mission under the auspices of the IAEA was conducted in La Paz from 11 to 16 August 2002. The objectives of the IAEA mission were achieved with the collaboration of the Bolivian authorities and the cooperation of the individuals involved in the accident. In pursuing these objectives, it was necessary to investigate the circumstances and the causes of the accident in terms of both root causes and contributory factors.

1.2. OBJECTIVE

For a number of years the IAEA has provided support and assistance under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, and has conducted follow-up investigations upon request in the event of serious accidents involving radiation sources. Reports have been published on the follow-up investigations of such accidents in El Salvador [1], Israel [2], Belarus [3], Vietnam [4], the Islamic Republic of Iran [5], Peru [6] and Panama [7].

The accidents in Gilan, Islamic Republic of Iran [5], and Yanango, Peru [6], are the only two of these events that involved industrial radiography sources. However, there have been many other accidents with such sources. The UNSCEAR 2000 Report noted that "The data compiled indicate that most of the accidents occurred in the industrial use of radiation and that most of them involved industrial radiography sources..." ([8], paragraph 321). In this connection the IAEA has published a compilation of lessons learned from accidents in industrial radiography [9]. In the accident reported here, the initiating industrial radiography accident followed a familiar pattern. However, the subsequent transport of the exposed source on a passenger bus was highly unusual.

The objective of this report is to describe details of the accident in Bolivia, how it was dealt with, its consequences and the lessons to be learned by those persons directly or indirectly involved in γ radiography operations. The information is intended for national authorities and regulatory bodies, emergency planners and a broad range of specialists, including physicists, technicians, medical specialists and persons responsible for radiation protection, and is intended to enable them to take steps to prevent similar accidents occurring in the future and to put in place arrangements to limit the consequences of such accidents if they do occur. This report also contains information relevant to licensees and operating organizations using radioactive sources.

1.3. SCOPE

This report describes the circumstances of the accident in Bolivia, the subsequent management of the investigation and the follow-up actions, the methods used in the dose assessments and their results, and how the dose assessments complemented the medical assessments. Uncertainties remain concerning details of the event, particularly the durations of the exposures, the dose distributions in the bodies of the persons exposed, and the separations between the persons involved and the source. Nonetheless, sufficient information is now available to provide broad estimates of the doses received, to analyse the main causes of and contributory factors in the accident, and to identify the lessons to be learned.

1.4. STRUCTURE

Background information about the regulatory and radiation protection infrastructures in Bolivia, the radiography company and the equipment involved in the accident is given in Section 2. A chronology of the various stages of the accident is given in Section 3, while Section 4 details the subsequent actions taken by various organizations once the accident had been recognized. Section 5 describes the work undertaken in the IAEA's emergency assistance mission, covering the investigation of the circumstances of the accident, the physical dose reconstruction undertaken, the medical assessments made of the persons exposed and the measures that were taken for purposes of reassurance. Section 6 summarizes the lessons to be learned and the recommendations. The Annex presents the medical form that was used to gather information from the workers involved in the accident and from some of the passengers on the bus in which the radiography source was transported.

2. BACKGROUND INFORMATION

2.1. REGULATORY INFRASTRUCTURE

2.1.1. Competent authority

The Bolivian Institute of Nuclear Science and Technology (IBTEN) was established by Supreme Decree (SD) No. 19583 of 3 June 1983 as successor to the Bolivian Nuclear Energy Commission (COBOEN), the regulatory body created in 1960.

IBTEN is the competent authority for all applications of nuclear energy and radioactive materials in Bolivia, as well as the national point of contact for all conventions and international cooperation in this field. In accordance with SD No. 24253 of 21 March 1996, IBTEN is a 'decentralized dependence' of the Ministry for Sustainable Development and Planning. This means that IBTEN is a separate and autonomous organization, setting its own work programme and determining its structure to meet its legal responsibilities. Its budget derives from a grant from the Treasury of Bolivia and income from technical services rendered, such as services for individual dosimetry. The director is directly answerable to the Minister for Sustainable Development and Planning.

In addition to being the regulatory body responsible for the implementation of regulations relating to the safe use of ionizing radiation, IBTEN has a function in contributing to improving the management of natural resources through the use of nuclear technologies in agriculture, chemistry, environmental protection and hydrology. As the national contact point for nuclear and radiation related matters, IBTEN provides the channel for all international technical cooperation (such as that provided by the IAEA) nationwide, and it sets priorities as needed.

Figure 1 depicts the organizational structure of IBTEN. Altogether IBTEN has a staff of 35, of which seven employees with the relevant expertise work in radiological protection. Although IBTEN has an enforcement function under Bolivian regulations, there is no legal expertise within IBTEN.

In order to meet its objectives, IBTEN is legally bound to the National Environmental Authority, the National Health Authority, the National Customs Bureau, the Civil Defence Authority and Centre for Risk Reduction, the National Police and other governmental authorities.

2.1.2. Legal framework

Legal controls on the use of ionizing radiation were introduced in 1982 with the Law of Radiological Protection and Safety (Decree Law No. 19172). This was based on the recommendations of the International Commission on Radiological Protection (ICRP) in its Publication 26 of 1977 [10] and the associated IAEA publication, Safety Series No. 9[1]. However, this legislation was not supported by any regulations to give it practical effect. Although over the years some effort had been made to draft regulations, it was not until 1997

---

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Basic Safety Standards for Radiation Protection (1982 Edition), Safety Series No. 9, IAEA, Vienna (1982).

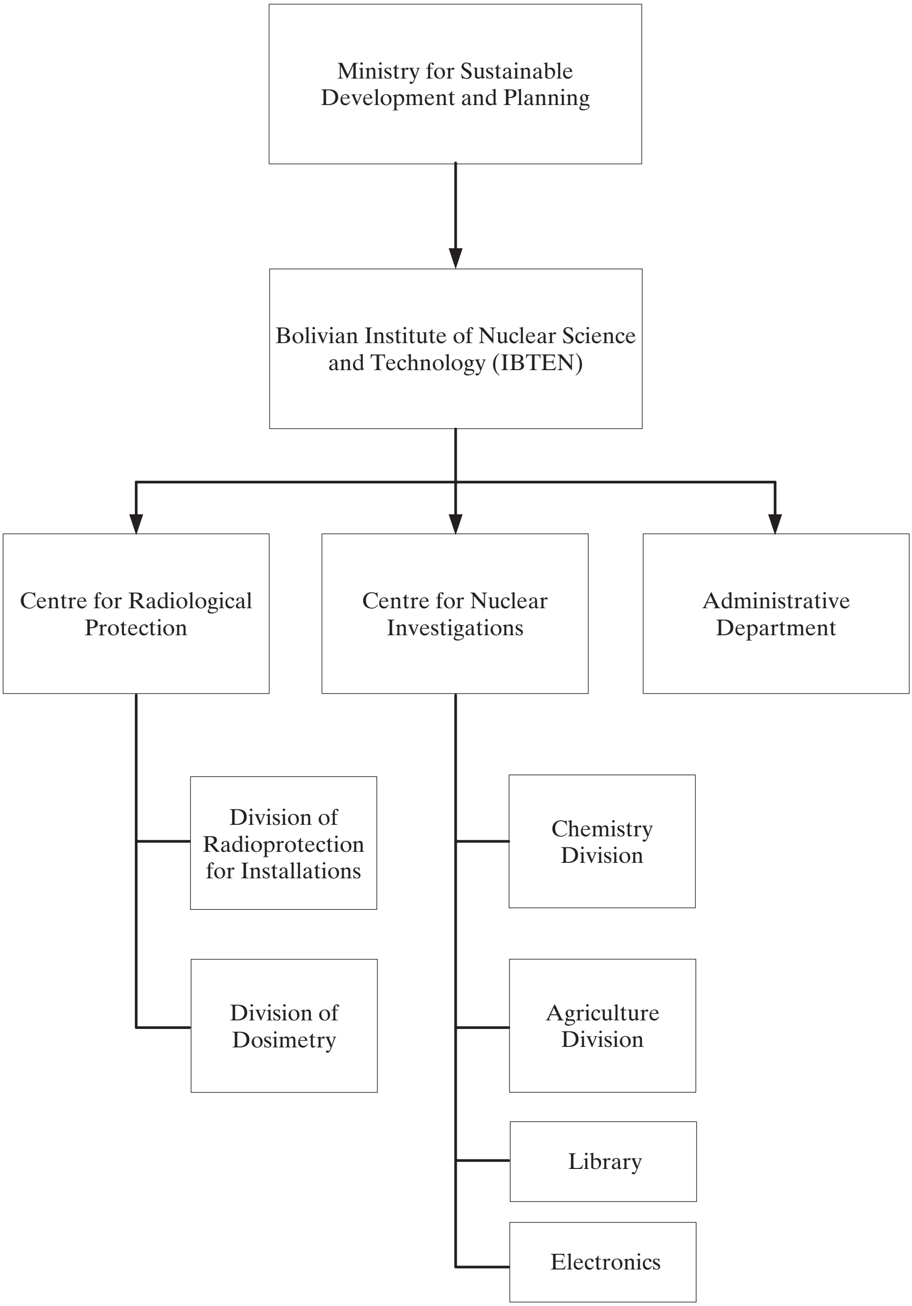

FIG. 1. Organizational chart for IBTEN.

that this effort came to fruition. One of the major driving forces for this was Bolivia's commitment in 1996 to participate in the Interregional Model Project on Upgrading Radiation Protection Infrastructure (INT/9/143).

In April 1996 the Government of Bolivia agreed to participate in the project, nominating a national counterpart and approving a work plan including, among other activities, the development and approval of a legal and regulatory framework, and the establishment of a national regulatory body and a national system of notification, registration, inspection, licensing and enforcement. The work plan considered the establishment of a national system for monitoring occupational exposure.

In 1997 SD No. 24483 was enacted; this provided the regulatory basis necessary to implement most of the International Basic Safety Standards [11], which are based on the 1990 Recommendations of the ICRP [12]. These regulations enhanced the regulatory function of IBTEN. In particular, the regulations established requirements for the licensing of all organizations and individuals working with radiation sources, as well as for authorization to transport radioactive material, for the use of radiotherapy equipment, for activities involving radioactive material, for the control of radiation installations, for response to emergencies and for the conduct of decontamination processes.

Of particular relevance to this accident are the regulations concerning the licensing of organizations and individuals and authorization for the transport of radioactive material. The licensing of organizations and individuals is covered in Section 2.1.3. The transport of radioactive material is governed by Regulation 5 of SD No. 24483, the key elements of which are as follows:

(a) The transport of radioactive material is subject to special agreement from IBTEN.
(b) The transport of radioactive material must meet the requirements of the current edition of the IAEA's Regulations for the Safe Transport of Radioactive Material [13], hereinafter referred to as the Transport Regulations.
(c) The consignee is responsible for compliance and must keep a record of all transports of radioactive material.

2.1.3. Implementation of the regulations

Supreme Decree No. 24483 introduced a requirement for a comprehensive system of licensing covering organizations and individuals. For organizations, the licensing process was designed to ensure that all the necessary arrangements and capabilities were in place to comply with the regulations.

This was a new process to most organizations working with sources of radiation, and significant efforts had to be made on their part to bring their radiation protection measures up to the appropriate standards. Similarly, review of the evidence and inspections also required a significant effort by IBTEN. It was recognized that some time would be necessary to achieve full compliance with the regulations nationally.

Some 490 radioactive sources have been identified in about 50 organizations. No time limit for transitional arrangements was specified in the regulations and licensing is still in process. Where appropriate progress is being made towards fulfilling the standards but they have not yet been fully met, the granting of licences has been deferred and recommendations have been made for the necessary actions. Whenever organizations are found not to be in compliance with the regulations, IBTEN has the power, by issuing an Administrative Resolution:

— To impose fines of up to ten minimum monthly salaries (about US $500);
— To suspend or cancel licences;
— To seize sources and equipment and decommission them;
— To temporarily or permanently close parts or all of a facility.

For instance, one of the six radiotherapy centres in Bolivia was closed by IBTEN following inspections. There are other examples of sanctions imposed by IBTEN.

At the time of this accident, three organizations in the industrial radiography sector had been licensed to operate. Eight other organizations were operating with licence applications in various stages of progress. One element of pressure that IBTEN can exercise with respect to radiography organizations is that IBTEN must authorize the import of radioactive sources. For IBTEN to issue an authorization, the requesting organization must have a licence or must be making suitable progress towards obtaining one. However, radiography organizations might as a consequence seek to carry out unauthorized import of sources.

Licences are mandatory for all workers. The requirements for obtaining a licence vary from one profession to another, but industrial radiographers are obliged:

— To attend a radiation protection course (run by IBTEN);
— To pass an examination on the training material;
— To show supporting documents from their employer.

The numbers of training courses provided by IBTEN for industrial radiographers are shown in Table 1.

The individuals who attended the courses and passed the examination were able to apply for a licence. A total of 32 individuals obtained their licence from IBTEN between 1998 and 2002: 5 in 1998, 1 in 1999, 23 in 2001 and 3 in 2002. No licences were granted in 2000.

2.1.4. Occupational health

In Bolivia the Health Code, which is issued by the Health Ministry, and the Industrial Safety and Health Law of the Labour Ministry are the sets of rules that deal with occupational health and safety. These two pieces of legislation contain only general considerations on the medical evaluation of workers, including those exposed to radiation.

Health insurance coverage in Bolivia is provided by the 'cajas', which are state insurance organizations. Each of the main production and service sectors of the economy, such as the oil industry, the banks, commercial companies and other businesses, has a coverage agreement with one of the cajas. The most important of these state insurance companies is the Caja Nacional de Salud (National Health Insurance Bureau), which provides insurance coverage for about 30% of the Bolivian population.

Both the Bolivian Institute of Standardization and Quality (IBNORCA) and IBTEN have contracted for health insurance coverage for their employees with the Caja Nacional de Salud. In recent years, this state insurance organization has not conducted medical examinations of workers within a health surveillance programme to assess the initial and continuing fitness of workers for their intended tasks.

TABLE 1. TRAINING IN INDUSTRIAL RADIOGRAPHY UNDER THE AUSPICES OF IBTEN IN BOLIVIA

Year	Number of courses	Number of organizations participating	Number of individuals attending
1998	1	1	6
2000	3	2	39
2001	3	3	27
2002	2	2	18
Total	**9**	**8**	**90**

2.2. RADIOGRAPHY COMPANY

Pursuant to SD No. 23489 of 28 April 1993, IBNORCA was created on 5 May 1993 to replace the Government run General Direction for Industries. IBNORCA employs a staff of 40 and is a private, not-for-profit association with the following primary activities:

(a) The development of national technical standards through committees. IBNORCA has issued more than 100 standards in such diverse areas as food production, metrology, environment, textiles and information technology.
(b) Certification in areas such as quality control and environmental control.
(c) Training courses in most of the above mentioned areas.

IBNORCA is the official organization in Bolivia that drew up the Bolivian System for Standardization, Metrology, Accreditation and Certification (SNMAC). SNMAC was established by SD No. 24498 of 17 February 1997. IBNORCA is also a service company offering physical–chemical analysis for food oils, cereals, beef, milk and other food products. The National Centre for Welding, which provides services of non-destructive testing by means of industrial radiography and ultrasonic analysis, is a part of IBNORCA.

The head of this centre ('the Supervisor') and three of the centre's staff ('Worker 1', 'Worker 2' and 'Worker 3') were the persons who were involved in the accident. The company had a single ^{192}Ir source and container which was used both for on-site work at various locations around Bolivia and for work in a shielded radiography facility on Avenue Camacho in La Paz. The company had been performing radiography for many years before the promulgation of the 1997 regulations, but it was not until 2001 that it applied for a licence. This application was unsuccessful for the following reasons:

(1) None of the radiographers had attended the radiography training course.
(2) Deficiencies had been identified in the material supplied with the licence application: the company's local rules still referred to the dose limits of earlier regulations rather than the limits set out in the 1997 regulations.
(3) An inspection of the radiography facility on Avenue Camacho had also identified deficiencies.

Following the inspection, the regulatory body made the following recommendations:

(i) It was mandatory for the company to make available a vehicle specifically for the transport of radioactive sources.
(ii) Appropriate arrangements were to be made for compliance with the Transport Regulations. This included having the appropriate signs on the vehicle.
(iii) The vehicle had to carry appropriate equipment to be able to deal with a radiography accident such as an accident with a decoupled source.
(iv) An appropriate preventive maintenance programme for the radiography equipment was to be undertaken. In particular, this was to include routine checks that the drive cable and 'source pigtail' connections were within tolerances.
(v) During all aspects of radiography work, individual dosimeters were to be worn. As a minimum this was to include a dosimeter approved by IBTEN and a direct reading dosimeter such as a quartz fibre electrometer.
(vi) The calibration of the dose rate meter was out of date and had to be tested.

2.3. RADIOGRAPHY EQUIPMENT

The radioactive source involved in the accident was an ^{192}Ir special form sealed source (serial number 140.101) housed in a model 660 remote exposure container (serial number 4110) manufactured by AEA Technology/QSA Inc. in the USA (Fig. 2).

Figure 3 shows a schematic view of the remote exposure container and ancillary equipment [14]. The principal components of the model 660 container are an outer steel shell, polyurethane foam around a depleted uranium shield in which there is an S tube, and end plugs.

At the time of the accident the activity of the source was 0.67 TBq (18 Ci). The container weighs about 22.5 kg in total.

The radioactive pellet is 3.0 mm × 2.5 mm in size and is twice encapsulated. The source capsule is attached to a Bowden cable about 15 cm long known as the source pigtail. When locked in the safe position, as it should be when not in use, the source capsule end of the source pigtail resides in the middle of the S bend in the source tube running through the depleted uranium shield. In this position a metal ball near the connector end of the source pigtail is held fixed by a mechanical interlock as described below. This safety feature prevents movement during transit, as does a shipment plug at the other end of the source tube.

When in use the source pigtail is connected by a male–female ball and spring loaded socket joint to a drive cable some 20 m long attached to a crank

FIG. 2. Industrial radiography container involved in the accident in Cochabamba.

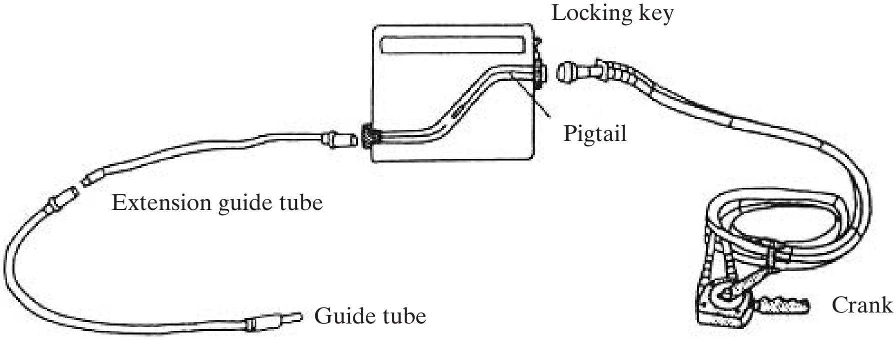

FIG. 3. Schematic view of the remote exposure container and ancillary equipment involved in the accident in Cochabamba.

handle. This allows the radiographer to be at a safe distance when exposing the source. For radiography a guide tube (2 m long, though extension lengths can be added) is attached to the front of the container and the 'snout end' is located where the radiography exposure is to take place. The source is then wound out to the snout end using the crank handle, left for the appropriate exposure time and then fully rewound.

Over the years there have been a number of radiation accidents with various types of remote exposure container. In these accidents the source or source pigtail has become disconnected from the drive cable, giving rise to the exposure of the radiographer and others. This can happen when the guide tube is bent into a sharp radius of curvature or when there is an obstruction in the guide tube and undue force is used on the drive cable to overcome friction. This can cause shearing in parts of the drive train. Another possible cause is an obstruction in the guide tube that prevents the source from being fully wound back into the safe position. Such accidents are well documented, for example in Ref. [9]. The principal lesson from such accidents is that it is imperative after each single radiography exposure to use a dose rate meter close to the front end of the source container to verify that the source is in its proper position.

When the source pigtail is fully in the safe position, the female connector end just protrudes through the locking ring on the back of the container, thus making it available for connection to the drive cable. When the radiography equipment is being transported, the female connector is covered by a captive screw on a protective metal cap. By pulling back on the spring loaded catch on the female connector, the shank and ball of the male connector can be inserted. Releasing the spring holds the male connector fixed. Figures 4–6 show the mechanism that couples the source pigtail with the drive cable. The two parts of a tubular clamp join lengthwise around the source pigtail and the drive cable. The clamp itself is secured by a metal ring with two protruding lugs that can be slid forward so that the lugs engage with the locking ring on the back of the source container. Figures 4–8 show the sequence of actions needed to connect the drive cable to the source pigtail and to secure the connection.

This is part of the mechanical interlock that allows the locking ring to be rotated, thus releasing the ball on the source pigtail and allowing the source to be wound out. The reverse sequence, i.e. to disconnect the drive cable, cannot be carried out until the ball on the source pigtail is in the safe position.

Wear and tear can cause components of the mechanism, particularly the ball and socket joint, to deteriorate in such a way that they no longer conform to the manufacturers' tolerances. This gives rise to the possibility of the coupling separating or of the male connector to be merely pushing against the female connector but still allowing the locking ring connection to be made. For this reason, the manufacturers of this connector specify a maintenance schedule and provide feeler gauges for testing key components.

For transporting the source container and in order to accommodate normal source activities, the manufacturers now supply an overpack, type OPL 660. This has been tested by the United States Nuclear Regulatory Commission and has a Type B(U) certificate (USA/9283/B(U)-85). The overpack is a 20 mm

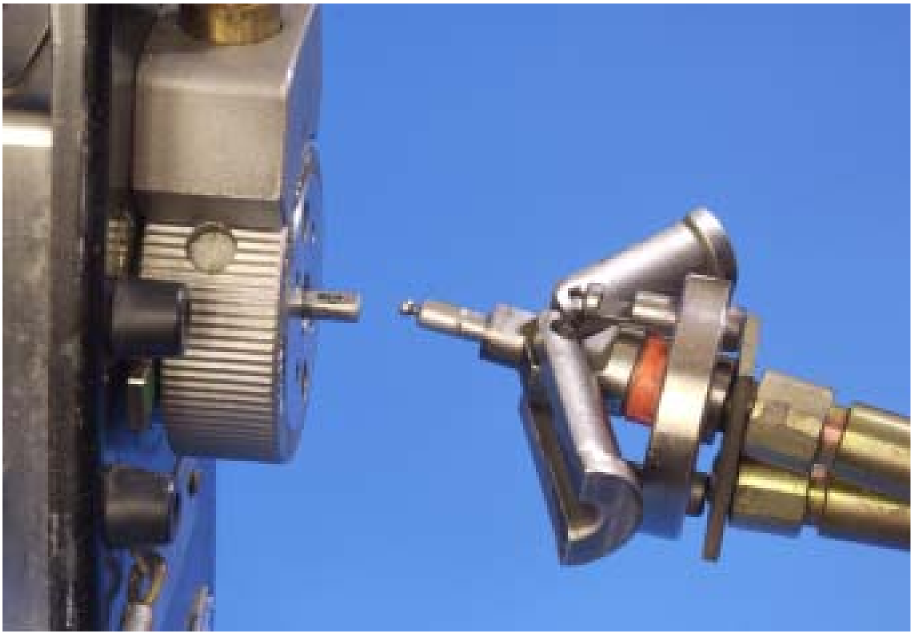

FIG. 4. Male connector on the drive cable (on the right) and female connector on the source pigtail.

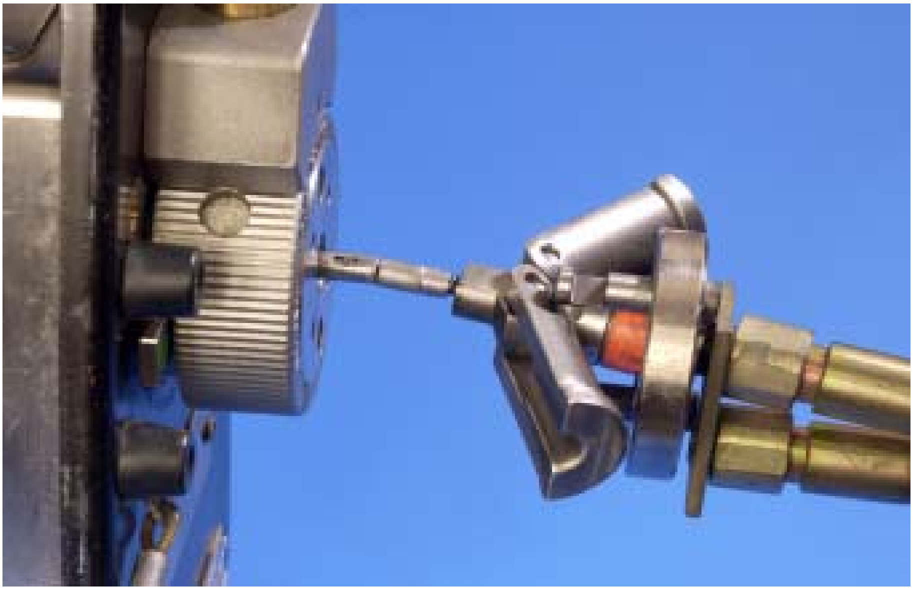

FIG. 5. Drive cable connected to the source pigtail. The two parts of the cylindrical metal collar are in the open position.

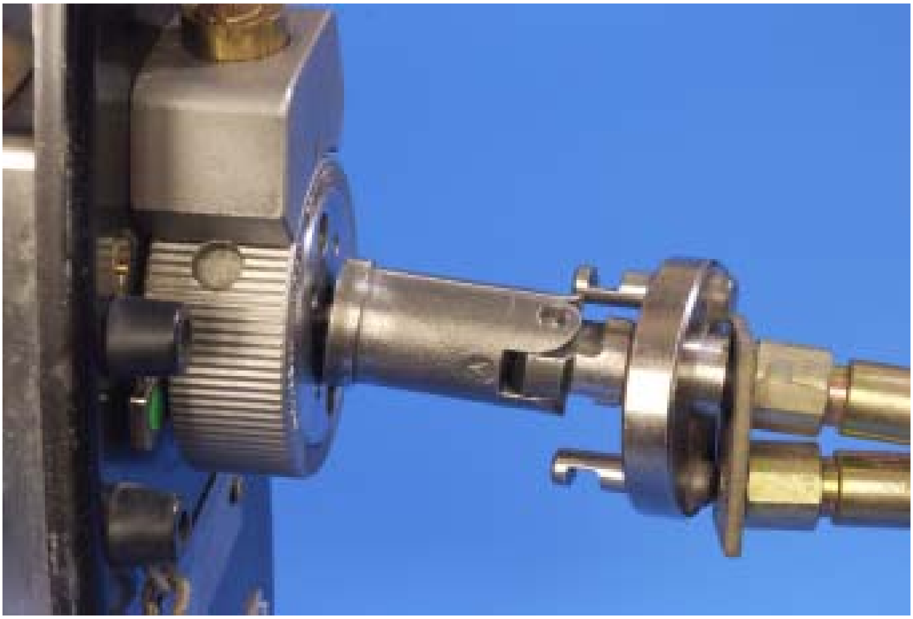

FIG. 6. The two parts of the cylindrical metal collar are closed over the connector (to the right of the connector is a disc with keyed metal lugs).

FIG. 7. The metal lugs enter the locking ring.

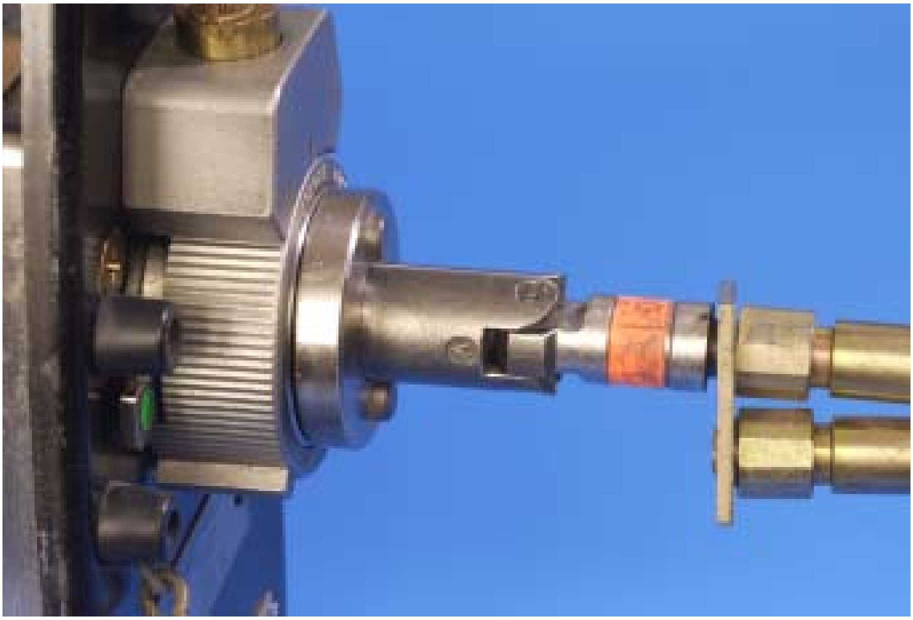

FIG. 8. The lugs are fully engaged and the locking ring is rotated to hold the drive cable captive.

cartridge shipping and storage box of military design. It is of welded steel construction (Fig. 9).

The protective container is fitted with foam and wood inserts and its lid is secured by latches. The model 660 container fits in the centre of the foam inserts.

3. CHRONOLOGY OF THE ACCIDENT

3.1. IN COCHABAMBA

IBNORCA had been contracted to carry out radiographic inspections of welds on a 51 mm (2 inch) natural gas pipeline near the airport at Cochabamba. Worker 1, who had worked for IBNORCA as a radiographer for 12 years, had made arrangements for the radiography equipment to be sent to Cochabamba from the city of Oruro, where it had been used in work done under another contract. It was sent by what was the company's normal means of transport, as

FIG. 9. Overpack for the source container.

cargo on a passenger bus. The bus arrived at 09:30 on Saturday, 13 April 2002, and the type 660 remote exposure container housing a 0.67 TBq ^{192}Ir source was collected immediately by Worker 1, who was working alone. He had an ND 2000 radiation dose rate meter and an individual dosimeter but he was not wearing the dosimeter. The only times that the dose rate meter was used was when Worker 1 first collected the container and at the beginning of the radiography session. The first of these readings was normal and it is understood that the radiographs from the work done for the previous contract were normal, indicating that the source was in the safe position during the journey to Cochabamba from Oruro.

Between 10:00 and 11:30 Worker 1 carried out ten radiography exposures in the trench containing the pipeline. Worker 1 did not use the dose rate meter after each exposure to check that the source had been returned to the safe position, as required by the company's local rules. Upon finishing his work, Worker 1 wanted to pack up his equipment by disconnecting both the drive cable and the exposure guide tube. He found that he could not turn the locking ring on the mechanical interlock in order to disconnect the drive cable.

Because of the dirty environment in which he had been working, he thought that some dirt may have entered the source tube in the container, preventing the source pigtail from being pulled fully into its safe position and thus preventing the disconnection of the drive cable. It was subsequently shown that the drive cable had been fully wound back, but that the source pigtail, with the ball that releases the locking mechanism, was not connected to it. The source pigtail was at that point lying somewhere in the guide tube. As mentioned in Section 2.3, this disconnection could have occurred for two reasons:

(a) Wear and tear on the components of the ball and socket joint could have allowed excessive movement of the components so that tensions caused by the frictional forces of winding the cable back through tight curves caused the ball to pop out of its socket. This could have occurred at any point during the movement of the source throughout the ten exposures.

(b) With worn equipment it is possible to connect the drive cable tube with the ball not in the socket. The consequence is that the drive cable will push the source pigtail out at the start of an exposure but, not being connected, cannot retract it at the end of the exposure. In this accident the source would have remained in the guide tube from the first exposure, probably near the exposure end that Worker 1 would have had to handle to reposition it for each radiograph.

Worker 1 did not consider these possibilities and was convinced that the source pigtail was in the container. However, crucially, he did not use his dose rate meter to check that the source was in the shielded position. He worked until 12:00 trying to solve the problem and then contacted the company's office in La Paz, explaining the situation as he saw it. It was agreed that the container and equipment should be sent back to La Paz as cargo on a scheduled long distance passenger bus. For the purpose of transporting the equipment he arranged two physically connected packages (Fig. 10).

To meet the requirements of the Transport Regulations, the source container on its own is usually placed into an overpack steel carrying case marked with transport labels for radioactive material. In this case the source container was placed at an angle in the carrying case with the attached drive cable protruding. The winding crank end was placed in a large, strong cardboard box with a hole cut in it to accommodate the drive cable (taped into position), which was still connected to the exposure container. The guide tube with the source inside it was also placed in the cardboard box.

FIG. 10. Industrial radiography equipment prepared for transport in the bus.

Throughout the morning Worker 1 would have handled the guide tube on a number of occasions, giving rise to a high probability that his hands would have been in close proximity to the source.

3.2. BUS JOURNEY TO LA PAZ

Between 13:15 and 13:30 Worker 1 took the connected packages to the cargo handling depot for the bus line. Here some as yet unidentified employees would have handled it, first to put it on the storage shelves and then at 15:30 to put it on the bus itself.

Plan and elevation views of the bus are shown in Fig. 11.

There were three storage areas in the bus underneath the passenger deck. The forward area could be used by the off-duty driver, in cases when there are two drivers, for sleeping. For this trip to La Paz there was only one driver. The middle compartment was used for passenger baggage and the rear compartment for cargo. Where the radiography equipment and source were placed in the cargo compartment on the day of the accident is unknown. Likewise it is not known what other cargo that might have partially shielded the source was stowed in the compartment (see the assessments in Section 5.3).

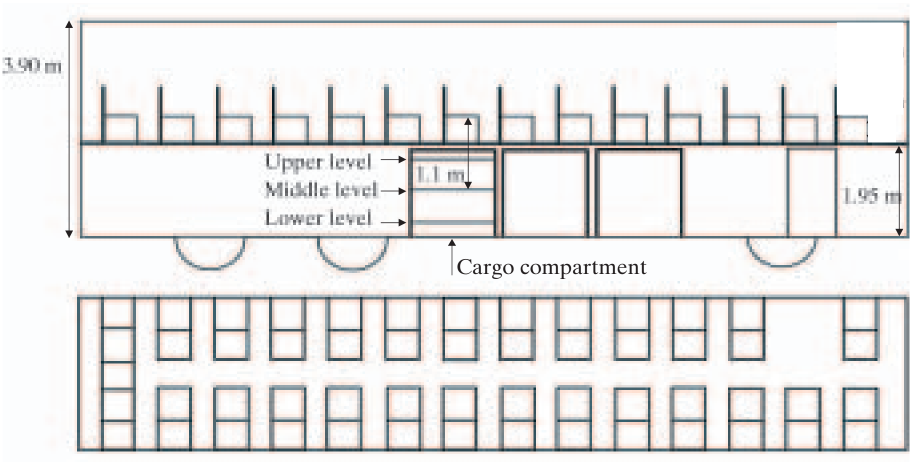

FIG. 11. Plan and elevation views of the bus in which the radiography equipment was transported.

The base of the cargo compartment was some 2 m below the level of the thorax of an adult in the nearest seat above.

The bus had seating for 55 passengers. Records show that upon its arrival in La Paz the bus was carrying a full load of 55 passengers. Thirty-three passengers had been on the bus when it departed from Cochabamba. All 33 passengers made the full eight hour journey to La Paz. They were joined by another 22 passengers in Quillacollo, 30 minutes from Cochabamba. Although the names of 30 passengers are known from booking details, only 15 passengers have been identified. The bus left Cochabamba at 16:00 and arrived at the La Paz bus terminal at midnight. The radiography equipment stayed in the cargo compartment of the bus overnight. The cargo was unloaded on the morning of the following day and an unknown bus station employee moved the packages to the cargo storage area.

3.3. IN LA PAZ

On the following day (Sunday, 14 April 2002) at 10:00, two employees of IBNORCA, the Supervisor and Worker 3, went to collect the packages from the cargo terminal. However, as the packages were addressed to a colleague, Worker 2, they were not allowed to take them. The Supervisor and Worker 2 returned at 14:00, claimed the packages and carried them for about three minutes to a taxi. The packages were placed in the boot (trunk) of the vehicle and for the ten minute journey in the taxi the Supervisor sat in the front passenger seat and Worker 2 in the back. It has not been possible to find the taxi driver.

The Supervisor and Worker 2 went to the shielded radiography facility on Avenue Camacho. Here they were met by Worker 3, who followed behind the Supervisor and Worker 2 as they carried the packages to the radiography facility (a walk of approximately two minutes). None was wearing an individual dosimeter or direct reading dosimeter.

Once in the bunker, they used a dose rate meter and immediately realized that the source was exposed. The dose rates were too high for them to use the meter to determine where exactly the source was. At first it was thought that the source was in the source tube of the container but not fully shielded. Attempts were made to free the drive cable coupling but these were unsuccessful and it was eventually concluded that the source was in the guide tube. To find where the source was, the guide tube was pushed through a cable duct hole in the shielding wall of the bunker until the reading on the dose rate meter suddenly dropped. This indicated that the source was close to the snout end. The Supervisor shook the source pigtail out onto the floor without using any handling tools (Fig. 12).

The drive cable was wound out through the cable duct and, while Worker 3 used a 40 cm handling tong to hold the active end of the source

FIG. 12. Re-enactment of shaking the source pigtail out of the guide tube. It should be noted that, to leave the tube, the source must necessarily have passed very close to the Supervisor's fingers.

pigtail, the Supervisor coupled it to the drive cable and it was rewound fully into the safe position in the source container (Fig. 13).

The work in the bunker took between 30 and 45 minutes, during which time Worker 2 stood some 3 m away from his two colleagues. The Supervisor had to depart for Santa Cruz that day and from there, on the following day (Monday, 15 April 2002), he reported the accident to the director of IBNORCA.

4. FOLLOW-UP ACTIONS

4.1. OVERVIEW OF FOLLOW-UP

The notification of IBTEN about the accident was not immediate, nor were the circumstances of the accident made clear in the early communications. The first notification that an accident of some kind had occurred was made by the Supervisor by telephone. At IBTEN's request, he confirmed this in writing on 17 April 2002. This notification gave details of the source that had been in

FIG. 13. Returning the source to the safe position.

use in Cochabamba but suggested that Worker 1 alone had been exposed for 8 hours at a distance of 1 m from the source. IBTEN was requested to estimate the dose and to advise on any actions to be taken. IBTEN replied on the same day giving a dose estimate of 0.72 Gy and recommending haematological examinations. IBNORCA arranged examinations for all four of its staff members who were involved (see Section 4.4).

Over the next fortnight, discussions were held between the two organizations and more information about the accident emerged. IBNORCA was requested to provide further details in writing and responded on 2 May 2002. The focus of the response was on the exposure of the radiography staff. It included an assessment of their times of exposure and resulting doses, and provided the results of the haematological examinations. On 22 May IBTEN was provided with full details of the accident in writing, including the report from the radiographers. It was only at this stage that the possibility of significant exposure of the passengers became clear.

On 10 June 2002 IBTEN made arrangements for IBNORCA to contact the Argentine Nuclear Regulatory Authority to carry out chromosomal aberration tests on the four radiographers. The results became available on 10 July 2002 (see Section 4.4).

In early July IBTEN made assessments of the doses likely to have been received by the bus passengers. These assessments are described in more detail in Section 4.2. The assessments indicated the possibility of doses of up to about 2.5 Gy. In the course of the month of July both IBNORCA and IBTEN waged an extensive media campaign directed at the public at large that provided particulars of the accident and urged those who may have been among the passengers on the bus to come forward. The news media also covered two unrelated incidents involving the unauthorized import of radiography sources and the theft of a neutron moisture probe. These developments heightened concern in Bolivia over radiation protection issues.

On 1 July 2002 IBTEN issued an Administrative Resolution that came into force on 8 July 2002. This measure penalized IBNORCA for failure to comply with the regulations and included the following sanctions:

- A maximum fine of 10 minimum standard monthly salaries (approximately $500);
- The seizure and decommissioning of the radiography source and container;
- The temporary suspension of all radiography work by IBNORCA;
- The obligation to identify and locate people involved in the accident;
- The re-export of the radioactive source to the supplier.

On 28 June 2002 IBTEN reported the accident to the IAEA (see Section 5).

4.2. INITIAL DOSE ASSESSMENT

On the basis of the initial information provided by IBNORCA, IBTEN produced an internal report on 19 April 2002 that provided a rough estimate of the dose to Worker 1: 0.72 Gy. This was based on an exposure of 8 hours at a distance of 1 m. After more detailed information became available, the original estimate was replaced with an assessment based on six task periods, each with its own mean exposure distance and time of exposure (Table 2).

This approach gave an estimated dose of 0.92 Gy. A similar approach using common assumptions was taken for the Supervisor, Worker 2 and Worker 3, and this gave an assessed dose of 0.83 Gy (Table 3).

No physical reconstruction of the doses was undertaken by IBNORCA.

On 12 June 2002, blood samples were taken from all four IBNORCA employees involved in the accident (the Supervisor, Worker 1, Worker 2 and Worker 3) for cytogenetic analysis with an established protocol. Blood samples were shipped to the Argentine Nuclear Regulatory Authority, where they were received on 13 June. They were processed according to the protocols described in the IAEA manual on cytogenetic dosimetry [15]. Lymphocyte metaphases arising after first division were analysed for unstable chromosomal type

TABLE 2. DOSE ESTIMATES BY IBNORCA FOR WORKER 1

Task	Time (min)	Source distance (m)	Dose (Gy)
Tidying and sorting equipment	20	2.00	0.027
Disconnecting source	20	0.25	0.440
Calling La Paz	30	2.00	0.041
Buying petrol	20	No exposure	
Packing up equipment	15	0.25	0.330
Taking equipment to bus terminal	15	0.50	0.082
Total			**0.920**

aberrations. The frequency of dicentric aberrations was used as an indicator of radiation dose by reference to an in vitro γ ray dose–effect curve:

$$Y = 0.001 + 0.0318D + 0.0609D^2$$

where Y is the number of dicentrics per cell and D is the dose in Gy.

The results of this analysis, together with the estimated doses, are shown in Table 4.

The estimated doses were average whole body doses, rounded to the nearest 10 mGy, and included a small upward correction to allow for the delay of some three months between irradiation and blood sampling. These estimates were based on an assumed 3 year half-life for the persistence of peripheral blood lymphocytes [15].

TABLE 3. DOSE ESTIMATES BY IBNORCA FOR THE SUPERVISOR, WORKER 2 AND WORKER 3

Task	Time (min)	Source distance (m)	Dose (Gy)
Collecting equipment from bus terminal	10	0.25	0.22
Taxi trip	10	0.50	0.055
Walking to laboratory	5	0.25	0.110
Tidying and sorting equipment	20	0.25	0.440
Total			**0.830**

TABLE 4. RESULTS OF CYTOGENETIC DOSIMETRY BY THE ARGENTINE NUCLEAR REGULATORY AUTHORITY FOR THE IBNORCA EMPLOYEES

Individual tested	Cells scored	Dicentrics per cell	Estimated dose (Gy) and 95% CI[a]
Worker 1	510	0.008	0.19 (0.016–0.36)
Worker 2	503	0.006	0.16 (0–0.32)
Worker 3	500	0.002	<0.10
Supervisor	612	0.005	0.13 (0–0.28)

[a] CI: confidence interval.

IBTEN also produced estimates of the doses to the passengers on the bus. These were based on the relative locations of seats with respect to three possible heights at which the source may have been stowed in the cargo compartment of the bus.

The three heights represented the source container being: (1) on the cargo compartment floor, (2) at the middle elevation in the cargo compartment, or (3) close to the top of the cargo compartment, i.e. directly underneath the passenger deck. The calculations were based simply on the inverse square law and did not take account of possible shielding by other objects in the cargo compartment. In addition, the doses calculated were at the height of the passenger seats rather than at heights that would be representative of the whole body dose. The calculated doses to the passengers in the bus are given in Table 5.

From the results of the calculations shown in Table 5, it can be seen that the highest doses were received in seats 27 to 30, which were directly above the centre of the cargo compartment.

TABLE 5. ESTIMATES BY IBTEN OF DOSES (Gy) TO THE PASSENGERS IN THE BUS

Seat numbers	High	Medium	Low
1–4	0.02	0.02	0.02
5–6	0.03	0.03	0.03
7–10	0.04	0.04	0.04
11–14	0.07	0.07	0.06
15–18	0.14	0.12	0.09
19–22	0.38	0.24	0.16
23–26	1.64	0.52	0.24
27–30	2.77	0.52	0.24
31–34	2.29	0.52	0.23
35–38	0.52	0.29	0.17
39–42	0.17	0.14	0.11
43–46	0.09	0.08	0.07
47–50	0.05	0.05	0.04
51–55	0.03	0.03	0.03

4.3. INITIAL MEDICAL ASSESSMENT

On Wednesday, 17 April 2002, IBNORCA initiated arrangements for blood counts of the four employees, which was required by IBTEN. This was done at local laboratories in Cochabamba for Worker 1 and in La Paz for the Supervisor, Worker 2 and Worker 3.

Blood samples were taken for analysis starting on the fifth day after the accident and regularly up until 12 June 2002 for Worker 2, Worker 3 and the Supervisor. For Worker 1, one additional check was performed on a blood sample on 11 July 2002 (Figs 14–17, Table 6).

The blood counts performed for the four employees showed results within the normal range with regard to all parameters that were analysed (red and white cells and platelets). Some polycythaemia (increase in the number of red cells) could be observed from the blood analysis for Worker 2 and for the Supervisor, but this was a normal effect at the high altitude of La Paz. Some neutrophilia was observed in the blood counts of Worker 2. However, considered together with the other blood cell parameters, this neutrophilia did not indicate the effects of exposure. Local physicians did not undertake any medical examinations of the four IBNORCA workers until the IAEA team arrived in La Paz.

4.4. IDENTIFYING THE EXPOSED INDIVIDUALS

In view of the estimated doses, attempts were made, as requested by IBTEN, to find the bus passengers and the taxi driver who drove the Supervisor and Worker 2 with the source from the bus terminal in La Paz to Avenue Camacho. IBNORCA did this by advertising in newspapers, on television and on the radio (Table 7).

(a) From 7 to 21 June IBNORCA conducted a campaign in national newspapers (La Razón, La Prensa and Los Tiempos) in an attempt to find the bus passengers and the taxi driver and to provide background information on the accident. A total of nine articles were published.
(b) From 12 to 16 June IBNORCA covered this topic in a series of radio broadcasts.

The coverage on Bolivian television was comprehensive. Interviews with the head of IBTEN were broadcast on four occasions between 12 and 18 July. Questions on the circumstances of the accident were dealt with, listeners' questions were answered and the accident was discussed extensively. The theft

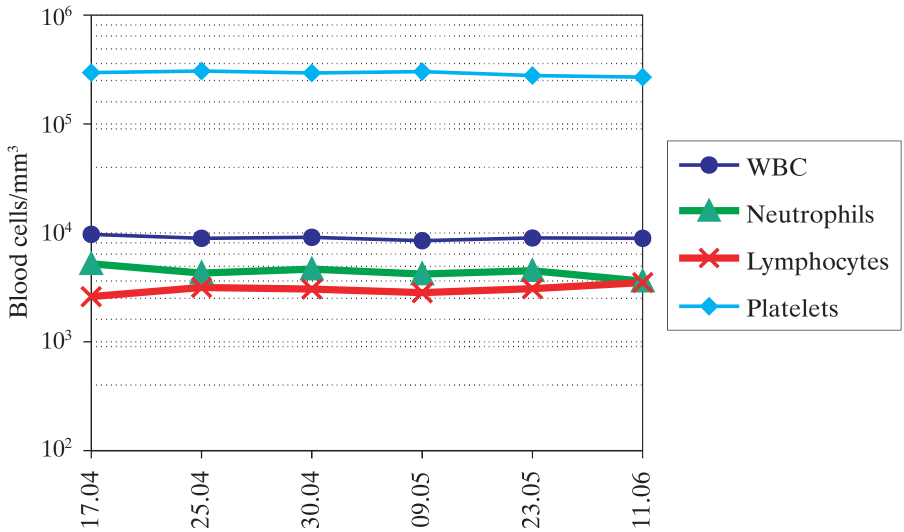

FIG. 14. Haematology chart for the Supervisor. WBC: white blood cells.

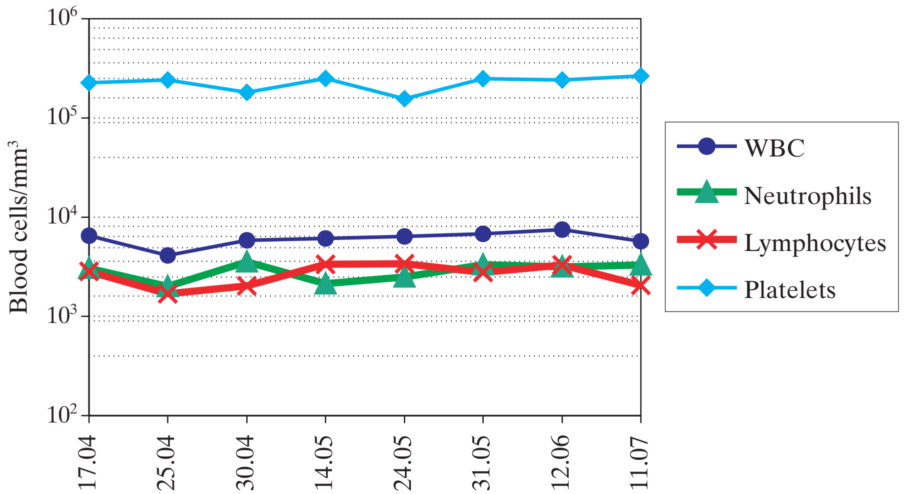

FIG. 15. Haematology chart for Worker 1. WBC: white blood cells.

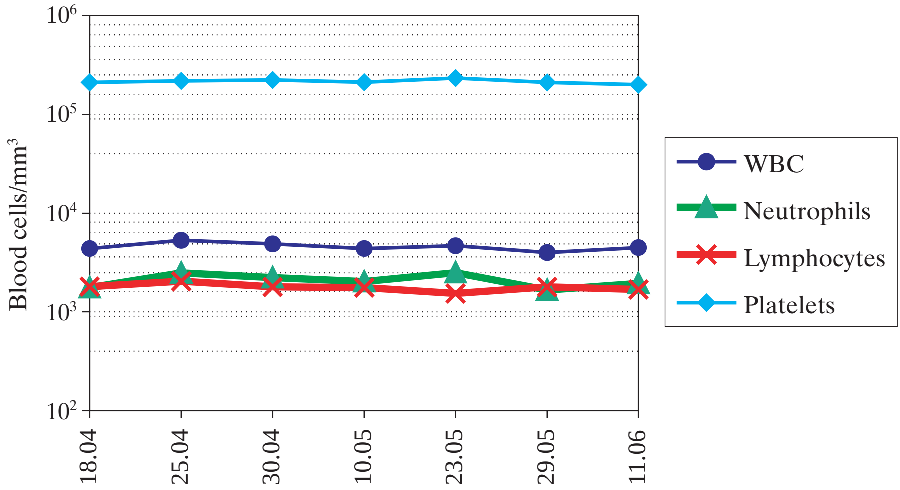

FIG. 16. Haematology chart for Worker 2. WBC: white blood cells.

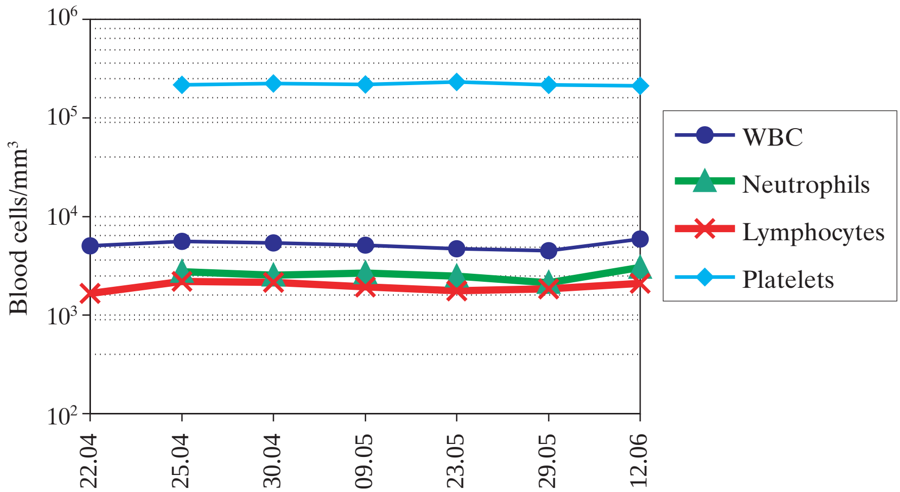

FIG. 17. Haematology chart for Worker 3. WBC: white blood cells.

TABLE 6. RESULTS OF BLOOD COUNTS FOR THE IBNORCA EMPLOYEES INVOLVED IN THE ACCIDENT

Individual tested	Date	WBC (10^3/μL)	Neutr. (10^3/μL)	Lymph. (10^3/μL)	Erythr. (10^6/μL)	PLT (10^3/μL)	Hb (g/dL)	Hct (%)
Normal range		4.0–11.0	2.0–8.0	1.0–5.0	4.0–6.2	150.0–400.0	11.0–18.8	35.0–55.0
Worker 1	17.04	6.5	3.1	2.8	5.3	227	16.8	47.3
	25.04	4.1	2.0	1.7	5.2	241	16.5	46.9
	30.04	5.8	3.6	2.0	4.9	182	14.8	46.0
	14.05	6.1	2.1	3.4	5.4	250	16.4	47.9
	24.05	6.4	2.5	3.4	4.8	156	14.5	45.0
	31.05	6.8	3.3	2.8	5.5	249	16.1	48.9
	12.06	7.5	3.2	3.3	5.5	241	15.0	46.8
	11.07	5.7	3.3	2.1	5.5	266	16.7	49.3
Worker 2	18.04	4.4	1.8	1.8	5.8	210	18.5	52.1
	25.04	5.3	2.5	2.0	6.0	218	19.0	53.9
	30.04	4.9	2.2	1.8	6.0	224	18.9	53.2
	10.05	4.4	2.0	1.8	6.4	212	17.5	55.1
	23.05	4.7	2.5	1.5	6.4	233	17.7	56.4
	29.05	4.0	1.7	1.8	6.2	211	16.8	53.8
	11.06	4.5	1.9	1.7	6.2	200	16.7	53.2
Worker 3	22.04	8.1	—	1.7	5.0	—	15.0	47.0
	25.04	5.6	2.8	2.2	5.5	217	17.6	50.4
	30.04	5.4	2.5	2.2	5.5	223	17.5	49.6
	09.05	5.1	2.7	1.9	5.9	218	16.0	50.8
	23.05	4.7	2.5	1.8	6.1	232	16.6	53.7
	29.05	4.5	2.1	1.8	5.8	216	15.7	51.3
	12.06	5.9	3.0	2.1	5.7	212	15.8	48.9
Supervisor	17.04	9.7	5.2	2.6	5.9	296	18.8	53.2
	25.04	8.9	4.3	3.1	5.8	306	18.3	51.6
	30.04	9.1	4.6	3.0	5.7	294	18.0	50.4
	09.05	8.5	4.2	2.8	6.4	303	17.1	53.5
	23.05	9.0	4.5	3.1	6.2	279	16.6	54.0
	11.06	8.9	3.6	3.5	6.0	268	16.1	51.6

Note: WBC: white blood cells; Neutr: neutrophils; Lymph: lymphocytes; Erythr: erythrocytes; PLT: platelets; Hb: haemoglobin; Hct: haematocrit; —: data not available.

TABLE 7. ACTIONS BY IBNORCA TO FIND PERSONS WHO HAD BEEN INVOLVED IN THE ACCIDENT

Name of newspaper or programme	Time of publication or broadcast	Title or subject
	Newspapers	
La Razón	10 July	List of passengers; search for taxi driver
La Razón	11 July	Search for taxi driver
La Prensa	17 July	Search for bus passengers
La Razón	18 July	Search for bus passengers
Los Tiempos	18 July	Information to the public
La Razón	18 July	Information to the public
La Prensa	18 July	Information to the public
La Prensa	21 July	Unauthorized shipment of four sources from Argentina since 21 May
La Razón	21 July	IBNORCA reprimanded in relation to handling of radioactive material
	Radio	
La Razón	12–16 July	Programmes running daily for five days
	Television	
PAT 39: PAT news	12 July 20:00	IBNORCA takes responsibility for inappropriate transport of radioactive material
UNITEL 2: Tele Country	16 July 20:00	Unsafe handling of radioactive material
UNITEL 2: Waking up	17 July 07:00	Search for bus passengers inadvertently exposed to radiation
UNITEL 2: Waking up	18 July 07:00	Bus passengers exposed to radiation

of a neutron probe was also covered in this campaign. A photograph of the probe was aired several times on television and viewers were alerted to the danger of handling it. The public were requested to volunteer any information they might have on the whereabouts of the source.

As a result of the extensive media campaign, 30 bus passengers were identified by name and 15 individuals out of the 30 identified were found. All of these persons were invited to attend a briefing by the physicians of the IAEA mission on the possible health consequences of proximity to the radiography source.

5. IAEA RESPONSE

5.1. INITIAL ACTIONS

The Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the 'Assistance Convention') and the Convention on Early Notification of a Nuclear Accident (the 'Early Notification Convention') are the prime legal instruments that establish an international framework to facilitate the exchange of information and the prompt provision of assistance in the event of a nuclear accident or radiological emergency, with the aim of minimizing the consequences. Along with States Parties to these conventions, the Food and Agriculture Organization of the United Nations (FAO), the World Health Organization (WHO) and the World Meteorological Organization (WMO) are full Parties to these agreements.

The IAEA has specific functions allocated to it under these conventions, such as the responsibility to inform States Parties, Member States and other States of a nuclear or radiological emergency. It receives reports of an emergency from a designated competent authority in a State and verifies any unconfirmed reports of an emergency. It establishes primary functional links with the reporting State and any potentially affected States as appropriate, providing direct communication with national coordinating structures for emergency response. It also establishes functional links with the FAO, the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), WHO, the WMO and other organizations as appropriate.

In order to meet its responsibilities under the Assistance Convention and the Early Notification Convention, the IAEA established in 1986 a 24 hour warning point and operational focal point in its Secretariat, the Emergency Response Centre (ERC). The ERC is located at the IAEA Headquarters in Vienna. It is administratively under the supervision of the Emergency Preparedness and Response Section in the Division of Radiation, Transport and Waste Safety.

On 28 June 2002, the ERC was informed by the Executive Director of IBTEN of three incidents involving radioactive material. According to the information reported, it appeared at that time that none of the incidents constituted an emergency that would necessitate an emergency response by the IAEA within the framework of the Assistance Convention. However, a radiation safety and security mission of the IAEA to La Paz from 29 July to 2 August 2002 found that one of the events had become a matter of growing concern to the Bolivian authorities and that prompt action might be necessary.

In relation to this event, on 9 August 2002 the ERC received a request from the Permanent Mission of Bolivia in Vienna for emergency assistance under the terms of the Assistance Convention. The request from the Permanent Mission of Bolivia specifically called for consultative expertise to evaluate the possible radiation doses incurred by those people who may have been exposed in the accident and to assist in their diagnosis, prognosis and possible treatment.

Preliminary discussions took place between the ERC and the Bolivian authorities to arrange for the IAEA team to have, at the time of the IAEA mission, access to all the relevant data and to the personnel and patients involved. The Bolivian counterpart agreed to make the following available to the IAEA team:

— All relevant records relating to the accident;
— All the medical personnel involved;
— All necessary means to permit a physical reconstruction of the accident.

The outline of the circumstances of the accident as understood before the IAEA mission gave rise to the possibility that the exposed workers and the bus passengers may have received radiation doses that could have caused deterministic health effects. In the light of this possibility, the preliminary specific objectives of the IAEA mission to Bolivia were:

(a) To advise the Bolivian Government on the steps to be taken to find those people who may have been overexposed to radiation;
(b) To recommend medical assistance if necessary;
(c) To assist in counselling people who feared that they may have been overexposed;
(d) To review and corroborate the existing assessment of doses in order to help meet the above three objectives.

In response to the request from the Permanent Mission of Bolivia, an international team was established that travelled to La Paz, arriving on Saturday, 11 August 2002. The IAEA mission to Bolivia was composed of: N. Valverde, a medical doctor from the Laboratory of Radiological Sciences of the University of the State of Rio de Janeiro and from the WHO Collaborating

Centre of the Radiation Emergency Medical Preparedness and Assistance Network (WHO/REMPAN) in Brazil; J. Croft, a physicist and head of the Communications Department at the National Radiological Protection Board (NRPB) in the United Kingdom; and E. Buglova, a medical doctor from the IAEA's Emergency Preparedness and Response Section.

The mission was concluded on 16 August 2002, at which time the ERC of the IAEA terminated its activation in response to the emergency.

5.2. INVESTIGATION

The IAEA team met staff from IBTEN, IBNORCA and the Caja Nacional de Salud. These meetings yielded information on the regulatory infrastructure, the chronology of the accident and the follow-up actions that were taken. In order to put this into context, the team visited the following premises:

(a) The bus terminal and its cargo handling facilities in La Paz;
(b) A bus maintenance facility, in order to carry out a reconstruction of the accident;
(c) The industrial radiography bunker facility;
(d) The IBTEN laboratory where the impounded radiography source and equipment were stored;
(e) The offices of the Caja Nacional de Salud.

In order to decide on the scope of the medical assessment programme and to provide reassurance to those persons who had been exposed (see Sections 5.3 and 5.4), the dose assessments that had been made were reviewed and a physical reconstruction of the exposures that occurred on the bus was undertaken.

Finally, a meeting of all parties was held at which the team outlined its initial findings. These findings were subsequently reviewed and refined at a consultants meeting in Vienna.

5.3. ASSESSMENT OF DOSES

5.3.1. Exposure of the IBNORCA employees

As mentioned above, none of the four radiography staff involved in the accident had been wearing individual dosimeters, even though they had all been provided with dosimeters for radiation work. This is unfortunate in that one of the purposes of individual dosimeters is to provide an input to the assessment of doses arising from any incidents and thereby to aid in the medical management, if necessary, of those exposed.

Where information from individual dosimetry is not available, the most reliable options for assessing doses fall into the following broad categories:

— Modelling the exposure;
— Physical reconstruction of the exposure with measurements;
— Biological dosimetry.

In its investigation of the accident, IBTEN chose to model the exposures and to take blood samples for chromosomal aberration analysis. The former requires a profile of the distances of people from the source concerned over time and details of any shielding of the source. This profile may be difficult to obtain with any degree of accuracy for a number of reasons. In the present case the variable factors included:

(1) The exact location of the source in the guide tube at various times during the accident (the source can easily slide around inside the guide tube);
(2) Individuals' notoriously unreliable estimates of the length of time that it took them to do various tasks;
(3) Variations in movements, which can induce large errors even when the tasks are reconstructed and timed, particularly where small source to body distances are involved;
(4) Variations in the locations and orientations of the objects that provide local shielding, which can induce large errors.

The modelled dose assessments by IBNORCA presented in Tables 2 and 3 were meant to provide rough estimates that would be representative of the upper end of the range of possible doses in this accident. The estimated total doses, namely 0.92 Gy for Worker 1 and 0.83 Gy for the Supervisor, Worker 2 and Worker 3, represented such upper bounds to the ranges of doses that they may have received. These values, together with the absence of any observable initial symptoms of acute radiation syndrome, indicated that these persons had not received doses sufficient to produce life threatening deterministic health effects.

IBTEN arranged for blood samples to be taken and sent for chromosomal aberration analysis by the Argentine authorities. The results of this analysis, shown in Table 4, indicated that Worker 1 had received the largest dose, 0.19 Gy, which was calculated with a 95% confidence interval of 0.016–0.36 Gy.

During the IAEA mission further blood samples were taken from the four radiographers and these were analysed at the laboratory of the NRPB in the United Kingdom. Blood samples were taken on 14 August 2002 and delivered to the NRPB on 17 August 2002. This second cytogenetic analysis also was performed according to IAEA protocols [15]. The NRPB laboratory dose response curve was:

$$Y = 0.001 + 0.02D + 0.06D^2$$

where Y is the number of dicentrics per cell and D is the dose in Gy. The results of the analysis by the NRPB are shown in Table 8.

Overall, fewer dicentrics were observed in the second analysis, some two months later, although none of the four persons showed results that were individually statistically different from those reported by the Argentine Nuclear Regulatory Authority. With this technique, the lower limit of dose detection is an averaged whole body dose of about 0.1 Gy of γ radiation [15], and this has large uncertainties associated with it, expressed as confidence limits. Taken together, the results from the Argentine Nuclear Regulatory Authority and the NRPB suggest that the doses did not exceed 0.2 Gy and that the lower confidence limits are indistinguishable from zero.

In both sets of cytogenetic analyses, the 95% confidence intervals were large because the doses were close to the limit of detection of the technique. However, the results are in broad agreement and should be used in preference to the assessed doses obtained from modelling. To err on the side of caution, and because the blood samples were taken closer to the time of the accident,

TABLE 8. RESULTS OF THE CYTOGENETIC DOSIMETRY CONDUCTED BY THE NRPB ON BLOOD SAMPLES OF THE IBNORCA EMPLOYEES

Person tested	Cells scored	Dicentrics/cell	Estimated dose (Gy) and 95% CI[a]
Worker 1	500	0.002	<0.10 (0–0.28)
Worker 2	500	0	0 (0–0.20)
Worker 3	500	0	0 (0–0.20)
Supervisor	500	0	0 (0–0.20)

[a] CI: confidence interval.

the results obtained by the Argentine Nuclear Regulatory Authority should be taken as the best estimates of whole body exposures.

During the IAEA mission, the Supervisor provided demonstrations of how the radiography equipment would have been manipulated in the various stages of the accident. The purpose of this was not to try to model the exposures (for reasons of the uncertainties mentioned above) but to assess the possibility for localized deterministic health effects arising from close contact with the source.

It was clear from these demonstrations that principally Worker 1 but also the others could possibly have handled the guide tube or carried it in such a way that one hand or other parts of the body were within 1 cm or so of the source. The dose rate from the source at 1 cm would have been about 0.3 Gy/s.

Sections 2.3 and 3.1 described the ways in which the source pigtail could have been disconnected in the guide tube and explained that the source was likely to have remained exposed at the snout end of the guide tube for some or all of the radiographic exposures that were performed. In order to reposition the guide tube for each radiograph, Worker 1's hands must have been in close proximity to the source. This was also likely to have been the case during the packing and unpacking of the equipment. Moreover, if the source was in the guide tube and the guide tube was then rolled into a coil, the source may have been in the lowest part of the loop and may have been close to the carrier's legs. Thus there was a significant possibility that any of those persons who handled the guide tube during the accident would have received a dose sufficient to give rise to localized deterministic health effects.

5.3.2. Exposure of the bus passengers

The time frame of the exposures of the bus passengers is reasonably well defined. For most of the passengers on the bus that day, this is an eight hour period from 16:00 to 24:00. There are some variations in this; for example, the duration would have been 30 minutes shorter for those passengers picked up at Quillacollo and it would have been longer for those passengers from Cochabamba who spent some time on the bus before it departed. Also, some time would have been spent off the bus during a meal stop. However, as shown below, these differences are small compared with other factors that can influence the estimates of doses.

The key element in assessing the doses to the passengers is the location of the source relative to them. It is known in which of the storage compartments beneath the passenger deck the source was stowed (see the view of the bus in Fig. 11). Cargo is always stored in the rearmost storage compartment and the middle compartment is reserved for passengers' luggage. The forward storage compartment is sometimes used as sleeping quarters for a relief driver; however, it is understood that on the day of the accident there was only one driver. Unfortunately it has not been possible to find the cargo handlers who were working at Cochabamba or La Paz at the time, and therefore the position of the radiography equipment in the cargo storage compartment during the journey is not known.

In its initial assessment, IBTEN calculated the doses for three possible positions for the equipment: the floor of the cargo storage compartment, the top of the compartment and halfway in between. Discussions during the IAEA mission suggested that cargo is rarely if ever stored higher than at the middle level. However, perhaps the most persuasive argument is the weight of the linked packages: 25 kg for the source container and 11.5 kg for the box with the wind-out gear and the guide tube. It is difficult to imagine that the handler loading the cargo would, or even physically could, have placed the linked packages anywhere other than on the floor of the cargo compartment. The source could have moved within the guide tube during the journey and it is likely that it would have been shaken down to the lowest level of the tube, possibly close to the floor of the cargo storage compartment. However, it is also possible that, owing to frictional forces, the source remained near the top of the package. Therefore the assumption that the source was at the middle level within the cargo storage compartment provides a worst case exposure scenario that is tenable. The other two dimensions, namely lateral and longitudinal, should also be considered. It is most likely that the source was located directly underneath seats 29 and 30 (on the loading side of the bus), but it could have been under seats 27 and 28 or in some intermediate position under the central aisle or closer to one of the rows in front of or behind these seats.

These uncertainties in the position of the source in the bus are significant for the possible doses. For example, the difference in height between the lowest possible position of the source and the highest credible position introduces a multiplication factor of about 1.7 for the possible doses to passengers in seats directly above the source, and when local shielding is taken into account, this factor is likely to be at least 2. Lateral positioning of passengers across the row above the source could introduce a further factor of 2. For more distant rows the height of the source becomes less important but the shielding factor is likely to have been greater owing to the presence of other passengers and their luggage (it was not possible to simulate this at the time of the reconstruction of the events). Therefore, in the light of these uncertainties, it would be reasonable to assign doses in broad bands.

In the initial dose assessment carried out by IBTEN, doses were calculated at the height of the seat, i.e. to the underside of the thigh. However, the whole body dose may be better represented at a height of about one third of the way up the torso, which would have reduced the estimated doses. Similarly, local shielding, for example by the decking, seat structure, other passengers and cargo, would have had a significant effect. To try to address some of these factors, a physical reconstruction of the passengers' exposures was undertaken.

Owing to practical constraints, it was not possible to carry out the dose reconstruction exercise with an identical bus. The bus available at the time of the IAEA mission was similar in most respects to the vehicle involved in the accident, but had a different seating configuration, three wider seats in a two and one configuration forming a row as opposed to the two and two configuration of narrower seats on the bus involved in the accident.

For the reconstruction, the actual equipment and the source involved in the accident were used. Decay charts indicated that the source activity was 215 GBq (5.8 Ci), less by a factor of 3.1 than at the time of the accident. The snout end of the guide tube was positioned directly under one of the seats at the middle level of the cargo storage compartment, 1.15 m below the seat (Fig. 18).

Before the main reconstructive exposure, a 5 minute exposure was made with electronic dosimeters placed on the seats in which the highest doses were likely to have been received. This had two purposes: firstly to estimate the length

FIG. 18. Reconstruction by the IAEA of the circumstances of the accident. In the foreground is the radiography equipment with its guide tube unwound up to the cargo compartment of the bus.

of exposure necessary to give meaningful readings during the main exposure, but also, more importantly, to provide an acceptable dose estimate for the medical assessment and for the discussions with the bus passengers that were to be held on the following day. When multiplied to take account of exposure times, activity decay and height to give a whole body exposure, the highest dose to a passenger was estimated to be 0.23 Gy. The corresponding dose to the buttocks and the underside of the thighs, i.e. at seat level, was estimated to be 0.42 Gy. This strongly indicated that none of the passengers would have suffered severe deterministic health effects as a result of the exposure.

For the main reconstruction it was not possible to have full human phantoms. The most practicable option was to use full water bottles as used in drinking water coolers. The main body of these was 40 cm in height and 25 cm in diameter, and thus they approximated the human torso (Fig. 19). Ten of

FIG. 19. Water bottle as used in lieu of human phantoms for the reconstruction of the dose.

these bottles were available and they were placed so as to give a representative distribution of passenger positions (Fig. 20).

Four thermoluminescent dosimeters of the NRPB were placed on each bottle: one on the base, one on the top and two in diametrically opposite positions halfway up the main body of the bottle. Apart from the bottle directly above the source, the bottles were oriented so that one of the mid-point dosimeters was facing towards the radiation source. Once arrangements for radiation safety had been made to exclude persons from the controlled area, a 30 minute exposure was made.

To a first approximation, the whole body dose could be taken to be the mean of the four dosimeter readings for each seat position. A more detailed assessment would not have been reasonable in view of the uncertainty in the position of the source and the unknown local shielding factors due to cargo, the passengers and their luggage. The mean and highest doses to the torso, corrected to an 8 hour exposure, are given in Table 9. The seat numbers are those on the bus used for the reconstruction.

On the basis of the uncertainties in the elevation and the lateral and longitudinal position of the source, adapting these results for the doses in the seats on the bus involved in the accident gives the broad bands of doses shown in Table 10. The values quoted have been rounded.

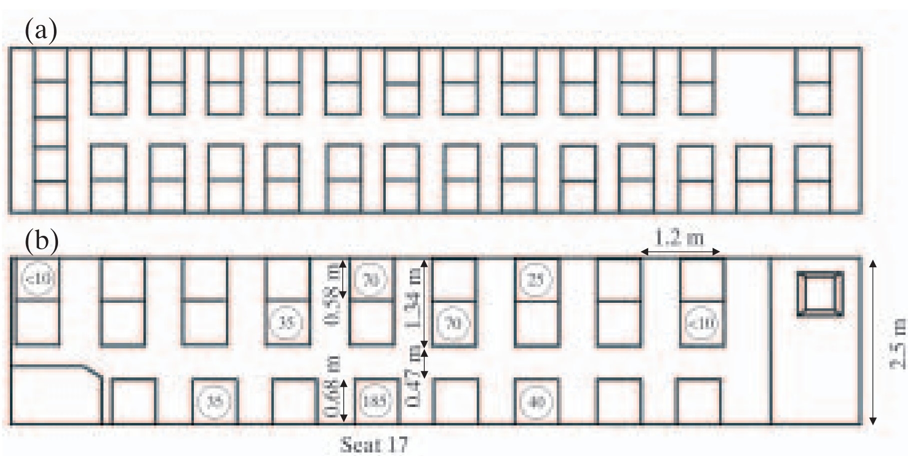

FIG. 20. Doses (mGy) registered by the dosimeters distributed on the bus seats during the dose reconstruction. Plan views of (a) the bus involved in the accident and (b) the bus used in the dose reconstruction.

TABLE 9. RESULTS OF DOSE RECONSTRUCTION PERFORMED BY THE IAEA TEAM WITH THE BUS PROVIDED FOR SIMULATION OF THE ACCIDENT

Seat number	Highest dose position (Gy)	Mean dose (Gy)
17[a]	0.500	0.185
18	0.115	0.070
16	0.155	0.070
9	0.070	0.040
25	0.070	0.035
24	0.040	0.035
10	0.040	0.025
26	0.010	0.010
34	<0.010	<0.010
4	<0.010	<0.010

[a] The dose to the feet at this distance is estimated to be 1.2 Gy.

5.3.3. Exposure of other persons

Although not specifically identified, the taxi driver and the cargo handlers at the bus terminals would also have been exposed to radiation in some degree.

For the taxi ride, if no allowance is made for the shielding effect of the Supervisor and Worker 3, who travelled in the back seat, and of the bodywork of the taxi itself, and if a source to body distance of 2 m is assumed, then the 10 minute drive could have resulted in a dose of the order of 4 mGy to the taxi driver. Although this value exceeds the annual dose limit for members of the public, it is a relatively small dose, within the range of variations in annual doses due to natural background levels of radiation.

The exposure conditions for the cargo handlers are not well defined. They can be split into two groups:

(a) Those involved in loading and unloading or carrying the source container and tubes;
(b) Those exposed in the cargo storage area of the bus terminal.

TABLE 10. RANGES OF ESTIMATED DOSES (Gy) TO THE BUS PASSENGERS BASED ON THE DOSE RECONSTRUCTION PERFORMED BY THE IAEA TEAM

Seat number (by row)	Upper	Lower
1–6	0.010	0.001
7–10	0.015	0.002
11–14	0.025	0.005
15–18	0.040	0.010
19–22	0.070	0.020
23–26	0.160	0.040
27–30	0.190	0.050
31–34	0.160	0.040
35–38	0.070	0.020
39–42	0.040	0.010
43–46	0.025	0.005
47–50	0.015	0.002
51–55	0.010	0.001

There is a small possibility that those cargo handlers in category (a) may have had parts of their body (particularly their hands) close to the source in the guide tube. However, it is unlikely that the exposure to any localized area would be sufficient to cause erythema (radiation burns). The whole body exposure in this scenario might typically be equivalent to 5 minutes at 50 cm from the source, which would give rise to a dose of the order of 20 mGy.

For those cargo handlers in category (b), the storage position of the package relative to the working positions of the cargo handlers and any intervening shielding (from other packages, structures or people) is relevant. This could be crudely represented as varying between:

(1) Exposures of less than 1 hour at a distance of 3 m from the source, giving a dose of <10 mGy;
(2) Exposures of about 5 hours at a distance of 1 m from the source, giving a dose of the order of 400 mGy.

TABLE 11. DESCRIPTIVE DATA FOR THOSE PERSONS INTERVIEWED WHO HAD BEEN INVOLVED IN THE ACCIDENT

	Sex		Age
	Male	Female	
Employees of IBNORCA	4	0	23–46
Bus passengers	4	4	14–66

5.4. MEDICAL ASSESSMENT AND ACTIONS TAKEN FOR REASSURANCE BY THE IAEA TEAM

On 14 August 2002, at the premises of the Caja Nacional de Salud in La Paz, the medical experts of the IAEA team and the specialists of the national insurance organization met some of the persons who had been involved in the accident. Altogether 12 persons were present, eight bus passengers and four workers (Table 11).

The physicians provided brief information (in Spanish) on the possible biological effects of exposure to ionizing radiation. In order to establish an order of magnitude estimate for the possible doses to the bus passengers and to estimate any consequent health effects, reference was made to doses incurred in medical procedures, doses due to natural background levels of radiation, occupational doses and epidemiological studies of radiation workers.

The physicians also briefed the attendees on the differences between deterministic and stochastic health effects, and care was taken to explain possible genetic consequences of exposure to ionizing radiation and radiation induced cancers. It is worth mentioning that there was no pregnant woman amongst the bus passengers who had been found.

A question and answer session followed the physicians' explanations, in which reference was made to the results of the dose reconstructions performed by the IAEA team (Table 12).

In the course of the briefing, the attendees were invited to a private medical interview. The eight passengers and four workers in the audience all volunteered to be interviewed. For the interview a medical form that had been modified for this particular accident on the basis of IAEA guidance was used (see the Annex).

As a result of the interviews, it was found that none of the persons examined had had early symptoms that could be associated with radiation

TABLE 12. REFERENCE DOSES USED BY THE IAEA TEAM FOR THE MEDICAL ASSESSMENT AND EXPLANATION

Individual	Age	Sex	Bus seat[a]	Estimated dose range (Gy)
Worker 1	47	M	–	0.19[b]
Worker 2	23	M	–	0.16
Worker 3	35	M	–	<0.10
Supervisor	46	M	–	0.13
Passenger 1	44	M	22P	0.02–0.07
Passenger 2	48	M	3V	0.001–0.01
Passenger 3	66	M	5V	0.001–0.01
Passenger 4	14	F	7V	0.002–0.015
Passenger 5	41	F	21V	0.02–0.07
Passenger 6	44	F	11V	0.005–0.025
Passenger 7	19	M	8P	0.002–0.015
Passenger 8	63	F	6P	0.001–0.01

[a] P: aisle; V: window.
[b] On the basis of the results of cytogenetic analysis in Argentina.

exposure, given the estimated doses. Medical examinations did not reveal any special findings among either the passengers or the four IBNORCA workers. It was concluded that the health status of all those persons who had been involved in the accident who were interviewed and examined was within the normal range at the time of examination. In general the workers and the bus passengers seemed reassured following the explanations and interviews.

Blood was taken from the four employees of IBNORCA and from one bus passenger (a 14-year-old girl) for cytogenetic dosimetry. The reason for this was the expectation that it would provide reassurance for those who had been involved in the accident. The results of the cytogenetic analysis performed for the employees of IBNORCA are discussed in Section 5.3 and presented in Table 8. The results of the analysis performed for the 14-year-old girl did not show any dicentrics. The dose was 0.0 Gy with a 95% confidence interval of between 0.00 and 0.20 Gy.

6. FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

6.1. ATTAINMENT OF MISSION OBJECTIVES

(a) To review and corroborate the assessment of doses that had been made

The circumstances of the exposure of various groups were reviewed and, to gain insights into the exposures of the passengers, a physical dose reconstruction to simulate the most credible worst case exposure scenario was undertaken. From this the following conclusions could be drawn with regard to the doses received.

Doses to the radiographers

There are significant uncertainties in the detail of the exposure profiles of the four radiographers. Taken together, the results of the chromosomal aberration analysis tests from the Argentine Nuclear Regulatory Authority and the United Kingdom NRPB suggest that the doses did not exceed 200 mGy, with the lower confidence level being indistinguishable from zero. By factoring in calculations based on possible exposure times and distances, it was concluded that it was likely that:

(i) All the radiographers received doses in excess of the dose limit for occupational exposure;
(ii) The highest dose was of the order of 200 mGy.

The radiography source was in the guide tube throughout the accident and the repeated direct handling of the guide tube by the radiographers gave rise to a significant potential for localized doses sufficient to cause deterministic health effects. Whether or not such doses were actually received would have depended on the position of the source in the tube relative to the hands or any other part of the body in contact with the tube.

Doses to members of the public

All those persons who travelled on the bus while the source was present and the staff who handled cargo are likely to have received a dose in excess of the dose limit for the public. Assessments based on the most credible worst case exposure scenario indicated a maximum dose of the order of 190 mGy to a few passengers positioned directly above the source. The maximum estimated dose for others would have decreased rapidly with distance from the source, being about 10 mGy at the front and back of the bus. Uncertainties in the position of the source and the effects of local shielding could reduce these estimates by a factor of between 3 and 10.

(b) To advise the Bolivian Government on steps to be taken to identify those people who might have been overexposed to radiation

It would have been desirable had the parties involved in this accident identified the potential scale of the accident earlier and informed the public soon afterwards. Nevertheless, once the accident had been identified, the media campaign launched was extensive and appropriate. In the light of the estimated doses, further efforts to identify those individuals who were exposed would not be warranted. Nevertheless, should passengers, workers or other parties who have not been identified as having been involved in the accident present themselves, their circumstances should be documented and a medical examination should be offered.

(c) To make recommendations on any medical assistance required

The radiographers involved were medically examined and no evidence of localized radiation injury was found. This was also the case for the eight passengers who presented for examination. In all cases there were no clinical signs or symptoms relating to radiation exposure. No special medical follow-up of the passengers seems necessary in the light of the estimated doses. In the case of the four employees of IBNORCA, medical follow-up will be needed within the health surveillance programme for occupational exposure.

(d) To assist in counselling

For those persons who responded to the public call to come forward, the IAEA mission provided an opportunity for an open forum discussion of the exposures, together with individual discussions with those who volunteered for medical examinations.

It was concluded that the mission had achieved its primary objectives. In pursuing these it was necessary to review the circumstances of the accident and to identify its causes, its consequences and the lessons to be learned. These are covered in the following sections, with the lessons to be learned targeted at different audiences.

6.2. LESSONS TO BE LEARNED

The direct cause of the accident was the failure of the radiography workers to carry out dose rate monitoring after each radiography. This is a frequent failure and a well known lesson to be learned from many other accidents. Once control of the source has been lost in this manner, the final consequences are open to chance. Fortunately in this case there were no fatalities and no observed deterministic health effects. However, the accident did result in the significant exposure of the radiographers and of passengers on the bus.

Although the direct cause is clear, it is necessary to look further to identify the circumstances that made the accident possible. The specific findings and general lessons to be learned are given (in italics) in the following sections.

6.2.1. Operating organizations

Although the radiography organization involved in this accident had some local rules and procedures, these were not comprehensive or up to date. Most importantly, they were not effectively implemented or supervised. The failure to monitor dose rates both during the radiography session and during the collection of the source container, together with the fact that none of those involved was wearing an individual dosimeter, are examples of poor safety culture.

> *The prime responsibility for radiation safety lies with the employer. Simply having policies and procedures in place is not sufficient in itself to ensure the required level of radiation safety. A safety culture needs to be fostered and maintained by management to encourage a positive attitude to safety and to discourage complacency ([11], para. 2.28). Further details regarding the development of radiation protection programmes are given in the Ref. [16].*

None of the radiographers had received appropriate training in radiation safety. The regulatory body had noted this deficiency prior to the accident.

> *Radiation protection and safety in industrial radiography, especially site radiography, rely heavily on human intervention and the correct implementation of procedures. Persons carrying out such work have high demands placed on them and they must therefore be fully trained and*

qualified. Employers need to provide suitable and adequate human resources and appropriate training in radiation protection and safety. Periodic retraining can help to ensure that the required degree of competence is maintained (Ref. [11], para. 2.30).

There was no evidence that the organization had in place any preventive maintenance programme for the radiography equipment.

An important aspect of radiological safety in industrial radiography is minimizing the potential for any decoupling of the source to challenge the operational safety procedures. To address this, manufacturers have incorporated into the container a mechanical safety interlock and have specified a preventive maintenance schedule and tolerances for the various components that might suffer wear and tear during their service life. Operating organizations must have in place and must implement an appropriate preventive maintenance programme.

The organization had not given sufficient attention to the provision and proper use of individual alarm monitors. Had Worker 1 been wearing one, it could have alerted him that the source had become decoupled and could have helped to prevent further exposure.

Individual alarm monitors are widely used in industrial radiography. If properly used in conjunction with a dose rate meter, they can provide a defence in depth aspect to safety in the operational procedures. However, for the monitors to fulfil this function, the management and the radiographers must clearly recognize that individual alarm monitors are adjuncts to the proper use of a dose rate meter and are not a substitute for this proper use. In this regard, training, effective management and safety culture are again important.

The Bolivian regulations require that radioactive sources be transported in accordance with the the Transport Regulations [13]. The arrangements for transport of the source were clearly in contravention of these regulations in many aspects. The regulatory body had identified the need for dedicated transport of appropriately placarded radioactive sources before the accident occurred.

The Transport Regulations provide an internationally recognized standard. In addition to setting standards for packaging, they place onuses on consignors, carriers, consignees and competent authorities. This accident illustrates why these provisions must be adhered to. One of the underlying concepts of the Transport Regulations is the segregation of transported *radioactive material from places occupied by persons. In particular, para. 573 states: "In the case of road vehicles, no person other than the driver and assistants shall be permitted in vehicles carrying packages, overpacks or freight containers bearing Category II-Yellow or III-Yellow labels" [13]. Thus, under the Transport Regulations, a bus would not be appropriate for the carriage of packages containing radioactive material (see Section 6.2.4 below).*

6.2.2. Regulatory body

A set of regulations was in place in Bolivia that included a requirement for radiation users to be licensed. Although the operating organization had been inspected and recommendations to address deficiencies had been made, the organization was unlicensed but was allowed to continue to operate. This position is not unknown when a regulatory body and regulations are first being established.

When regulations are developed it is important that there be a clear plan for their introduction and enforcement. This requires the availability of sufficient appropriately trained staff. It is recognized that it may not be practicable, either for the users or for the regulators, to implement all the regulations at the same time. To address this issue it may be appropriate to include transitional legal provisions that place a time limit for some requirements (e.g. licensing requirements) to be met. Thus powers and responsibilities could be introduced immediately, while licensing would have to be completed by a set date. This ensures that both existing users and the regulatory body have a clear knowledge of what has to be achieved and of the timetable for this. It avoids compromising the regulatory body and it helps to underline the intent to enforce the regulations effectively.

A critical minimum of technical expertise is one requirement for a regulatory body. This technical expertise needs to be complemented by legal expertise, especially with regard to enforcement. The availability of such expertise would have been beneficial in the accident in Cochabamba.

National authorities should ensure that legal expertise is made available within the regulatory body.

The notification of the accident to the regulators was not immediate, and the circumstances and extent of the accident were not made clear in the early communications from the operator. Nevertheless, there was some evidence to indicate the possible scale of the doses to the radiography staff (including the potential for deterministic health effects) and vigorous early regulatory intervention was indicated. Also, taking action closer to the time of the accident might have yielded significantly improved knowledge of the identity of the passengers on the bus and of those handling the radiography equipment in the cargo handling depots.

Priority should be given to the immediate follow-up of situations in which there is the possibility that dose limits have been exceeded and in which deterministic health effects may be caused.

A key element in implementing a regulatory programme is raising the level of awareness of radiation safety issues on the part of the actual users. Some of this can be achieved through formal training programmes, but there is also value in using other means of communication for information on good practices, learning the lessons from accidents, updates on regulatory guidance and other purposes.

It is desirable that the regulatory body use means of communication such as newsletters or a web site to raise awareness of radiation issues on the part of users. For example, some organizations routinely enclose a newsletter with the delivery of individual monitoring dosimeters. The inclusion of accident case studies in the newsletter is beneficial and will attract readers.

6.2.3. Medical issues

Besides the recommendation concerning the medical follow-up of the radiography workers and the bus passengers, the following points might usefully be considered by the Bolivian authorities:

(a) The need for regular medical examinations within a health surveillance programme for all workers;
(b) The need for workers to be regularly informed of the doses they have received, in accordance with individual monitoring and exposure assessment;
(c) The need for physicians and health personnel to be trained in the recognition and handling of radiation injuries and radioactive contamination of persons as a result of radiation accidents;
(d) The need to address medical response issues in the radiation emergency plan;

(e) The need for the designation and preparation in the State of hospitals for the treatment of persons accidentally exposed to radiation and/or with radiation contamination.

6.2.4. International bodies

Under the Bolivian regulations (which for the transport of radioactive material are based on the IAEA Transport Regulations [13]) the transport of radioactive material in a bus is prohibited. The size and terrain of Bolivia, as is the case in other States, can pose difficulties in the transport of radioactive material. One consideration in this issue is the availability of appropriate transport infrastructures. In Bolivia there have been issues over airlines refusing to accept radioactive material for transport. The lack of alternative carriers offering comprehensive provisions for the transport of radioactive material causes users of radioactive sources to look for cost effective options.

Conceptually there is no difference between the segregation of passengers and cargo on aircraft and in buses, but in practice there are significant differences in the controls over the cargo. If these differences in controls could be satisfactorily addressed, there would be grounds for reconsidering the absolute ban in the Transport Regulations on the transport of radioactive material by bus.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in San Salvador, IAEA, Vienna (1990).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Soreq, IAEA, Vienna (1993).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident at the Irradiation Facility in Nesvizh, IAEA, Vienna (1996).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, An Electron Accelerator Accident in Hanoi, Viet Nam, IAEA, Vienna (1996).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Gilan, IAEA, Vienna (2002).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Yanango, IAEA, Vienna (2000).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Investigation of an Accidental Exposure of Radiotherapy Patients in Panama, IAEA, Vienna (2001).

[8] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), Vol. 1. Sources, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000) Annex E.
[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from Accidents in Industrial Radiography, Safety Reports Series No. 7, IAEA, Vienna (1998).
[10] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Publication 26, Pergamon Press, Oxford and New York (1977).
[11] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANISATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).
[12] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Pergamon Press, Oxford and New York (1991).
[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulations for the Safe Transport of Radioactive Material, 1996 Edition (Revised), Safety Standards Series No. TS-R-1 (ST-1, Revised), IAEA, Vienna (2000).
[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Manual on Gamma Radiography, Practical Radiation Safety Manual No. 1, IAEA, Vienna (1996).
[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Cytogenetic Analysis for Radiation Dose Assessment, Technical Reports Series No. 405, IAEA, Vienna (2001).
[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Occupational Radiation Protection, Safety Standards Series No. RS-G-1.1, IAEA, Vienna (1999).

Annex

MEDICAL FORM FOR PERSONS INVOLVED IN THE ACCIDENT

I. Patient identification

Full name____

Address____

Date of birth _____/_____/_____ (day / month / year) Sex ☐ male ☐ female

Occupation ____

II. General information

Person completing the form ______________________________

Date and time of completion _____/_____/_____ (day / month / year) at _____

III. Previous medical history

Known diseases ____

____

Previous medical exposure________________________________

Smoking ☐ yes ☐ no

Alcohol consumption ☐ yes ☐ no

For women: Date of last period _____/_____/_____ (day / month / year)

Pregnancy at the time of the event ☐ yes ☐ no

If yes, specify term ______________________________

IV. Exposure conditions

When/where the person took the bus:

☐ Cochabamba at ________o'clock ☐ Quillacollo at ________o'clock

Duration of stay in the bus __________

Seat number in the bus _____

V. First symptoms

Nausea:

Time ____________________

Intensity ____________________

Number of times ____________________

Duration ____________________

Vomiting:

Time ____________________

Intensity ____________________

Number of times ____________________

Duration ____________________

Erythema ☐ yes ☐ no

Epilation ☐ yes ☐ no

VI. Medical findings (time of examination)

Weakness ☐ yes ☐ no

Headache ☐ yes ☐ no

Nausea ☐ yes ☐ no

Vomiting ☐ yes ☐ no

Diarrhoea ☐ yes ☐ no

Dizziness ☐ yes ☐ no

Temperature ____________________

Pulse ____________________

Blood pressure ____________________

Skin condition ____

Hair condition ____

Consciousness ____

Other ____

____

____

CONCLUSION

Signature(s) and name(s) of the doctor(s) ____________________

____

CONTRIBUTORS TO DRAFTING AND REVIEW

Buglova, E.	International Atomic Energy Agency
Crick, M.	International Atomic Energy Agency
Croft, J.	National Radiological Protection Board, United Kingdom
Ferruz-Cruz, P.	International Atomic Energy Agency
Lloyd, D.	National Radiological Protection Board, United Kingdom
Miranda, A.	Bolivian Institute for Nuclear Science and Technology, Bolivia
Nogueira de Oliveira, C.	International Atomic Energy Agency
Valverde, N.	University of the State of Rio de Janeiro, Brazil
Wrixon, A.D.	International Atomic Energy Agency

Consultants Meeting

Vienna, Austria: 14–18 October 2002