The Radiological Accident in Goiânia

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1988

The cover photograph shows a scene during the decontamination following the radiological accident in Goiânia. A hole has been made with the excavator in the wall of a house to remove a radiation hot spot before demolition All photographs by courtesy of the National Nuclear Energy Commission (CNEN), Rio de Janeiro, Brazil.

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Printed by the IAEA in Austria
September 1988

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1988

THIS REPORT IS ALSO PUBLISHED IN
FRENCH, RUSSIAN AND SPANISH

THE RADIOLOGICAL ACCIDENT IN GOIÂNIA
IAEA, VIENNA, 1988
STI/PUB/815
ISBN 92-0-129088-8

FOREWORD
by the Director General

The Government and authorities in Brazil were faced with a tragic accident in Goiânia resulting from the misuse of a strongly radioactive medical teletherapy source not under radiation protection surveillance. They have taken a number of measures to strengthen control over such sources in the future, and a review meeting was organized jointly by the Brazilian National Nuclear Energy Commission (CNEN) and the IAEA. The purpose of the meeting was to enable an international panel of specialists to examine the causes and consequences of the accident and to enable interested persons and authorities in other States to learn from Brazil's experience, with a view to reducing the risk of such accidents and being adequately equipped to deal with any that might occur.

This report stems from that examination. It describes how the accident occurred, and goes on to examine how it was managed and how its consequences were contained. Finally, it sets out observations and recommendations arising from the review.

The review meeting and the present report are not unique undertakings on the part of the IAEA. Under its safety programme, it is the IAEA's intention to follow up any serious radiological accident with review and analysis and to produce a detailed account from which all States may learn.

The applications of nuclear energy and nuclear materials in industry, medicine, agriculture and scientific research can be of great help in raising productivity, diagnosing and treating disease and improving agriculture. Such activities cannot be entirely free of the risk of accidents. Any human endeavour entails a certain degree of risk, while refraining from endeavour carries risks of its own.

The public must feel confident, however, that the responsible authorities and individuals do all in their power to minimize these risks; a process which includes learning from any accident that may occur despite all the precautions taken.

Radiological accidents are infrequent occurrences. Indeed, given the number of radioactive sources in use around the world in medical, agricultural and industrial applications, the rarity of such accidents bears witness to the effectiveness of the safety regulations and measures in force.

The fact that accidents are uncommon should not, however, give grounds for complacency. No radiological accident is acceptable, and one that threatens widespread contamination is bound to alarm a public that has not yet come to terms with radioactivity.

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

The report on the accident suggests that its consequences could have been much more serious had those engaged in the response to it not discharged their responsibilities with skill, courage and determination. A major contribution was made by those individuals who recognized the seriousness of the situation and alerted the authorities to the need for urgent action. Once alerted, the authorities responded promptly and effectively; in Goiânia and Goiás State, in the Federal agencies of the Brazilian Government and elsewhere in Brazil, and, indeed, in other countries. Special mention must be made of CNEN, which co-ordinated the response to the accident within Goiás State and at the national and international levels.

The accident was the first test of the IAEA's role, under the new international Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, in helping to co-ordinate the actions of States Party willing to offer assistance in the event of a radiological accident.

The IAEA wishes to express its gratitude to CNEN for its positive and helpful attitude from the outset, for informing other Member States about the accident in Goiânia, and for enabling others to benefit from the lessons that can be drawn from it.

The IAEA is particularly grateful to the Directorate of the Institute of Radiation Protection and Dosimetry (IRD) for the support provided in the organization of the review meeting.

EDITORIAL NOTE

CONTENTS

PART II. THE HUMAN CONSEQUENCES: DEALING WITH THE PEOPLE AFFECTED

PART III. THE ENVIRONMENTAL CONTAMINATION: ASSESSMENT AND REMEDIAL ACTIONS

EXECUTIVE SUMMARY

PART I. THE ACCIDENT

It is now known that at about the end of 1985 a private radiotherapy institute, the Instituto Goiano de Radioterapia in Goiânia, Brazil, moved to new premises, taking with it a cobalt-60 teletherapy unit and leaving in place a caesium-137 teletherapy unit without notifying the licensing authority as required under the terms of the institute's licence. The former premises were subsequently partly demolished. As a result, the caesium-137 teletherapy unit became totally insecure. Two people entered the premises and, not knowing what the unit was but thinking it might have some scrap value, removed the source assembly from the radiation head of the machine. This they took home and tried to dismantle.

In the attempt the source capsule was ruptured. The radioactive source was in the form of caesium chloride salt, which is highly soluble and readily dispersible. Contamination of the environment ensued, with one result being the external irradiation and internal contamination of several persons. Thus began one of the most serious radiological accidents ever to have occurred.

After the source capsule was ruptured, the remnants of the source assembly were sold for scrap to a junkyard owner. He noticed that the source material glowed blue in the dark. Several persons were fascinated by this and over a period of days friends and relatives came and saw the phenomenon. Fragments of the source the size of rice grains were distributed to several families. This proceeded for five days, by which time a number of people were showing gastrointestinal symptoms arising from their exposure to radiation from the source.

The symptoms were not initially recognized as being due to irradiation. However, one of the persons irradiated connected the illnesses with the source capsule and took the remnants to the public health department in the city. This action began a chain of events which led to the discovery of the accident.

A local physicist was the first to assess, by monitoring, the scale of the accident and took actions on his own initiative to evacuate two areas. At the same time the authorities were informed, upon which the speed and the scale of the response were impressive. Several other sites of significant contamination were quickly identified and residents evacuated.

PART II. THE HUMAN CONSEQUENCES: DEALING WITH THE PEOPLE AFFECTED

Shortly after it had been recognized that a serious radiological accident had occurred, specialists — including physicists and physicians — were dispatched from

Rio de Janeiro and São Paulo to Goiânia. On arrival they found that a stadium had been designated as a temporary holding area where contaminated and/or injured persons could be identified. Medical triage was carried out, from which 20 persons were identified as needing hospital treatment.

Fourteen of these people were subsequently admitted to the Marcilio Dias Naval Hospital in Rio de Janeiro. The remaining six patients were cared for in the Goiânia General Hospital. Here a whole body counter was set up to assist in the bioassay programme and to monitor the efficacy of the drug Prussian Blue, which was given to patients in both hospitals to promote the decorporation of caesium. Cytogenetic analysis was very helpful in distinguishing the severely irradiated persons from those less exposed who did not require intensive medical care.

Decontamination of the patients' skin and dealing with desquamation from radiation injuries and contaminated excreta posed major problems of care. Daily haematological and medical examinations, good nursing care and bioassay of blood cultures contributed to the early detection and therapy of local systemic infections.

Four of the casualties died within four weeks of their admission to hospital. The post-mortem examinations showed haemorrhagic and septic complications associated with the acute radiation syndrome. The best independent estimates of the total body radiation doses of these four people, by cytogenetic analysis, ranged from 4.5 Gy to over 6 Gy. Two patients with similar estimated doses survived. A new hormone-like drug, granulocyte macrophage colony stimulating factor (GMCSF), was used in the treatment of overexposed persons, with questionable results. Within two months all surviving patients in Rio de Janeiro were returned to the Goiânia General Hospital, where decorporation of caesium continued until it was safe to discharge them from hospital.

Many individuals incurred external and internal exposure. In total, some 112 000 persons were monitored, of whom 249 were contaminated either internally or externally. Some suffered very high internal and external contamination owing to the way they had handled the caesium chloride powder, such as daubing their skin and eating with contaminated hands, and via contamination of buildings, furnishings, fittings and utensils.

More than 110 blood samples from persons affected by the accident were analysed by cytogenetic methods. The frequency of chromosomal aberrations in cultured lymphocytes was determined and the absorbed dose was estimated using in vitro calibration curves. The dose estimates varied from zero up to 7 Gy. Poisson distribution statistical analysis of cells with chromosomal aberrations indicated that some individuals had incurred non-uniform exposures. Highly exposed individuals are still being monitored for lymphocytes carrying cytogenetic aberrations.

Urine samples were collected from all individuals potentially having internal contamination and their analysis was used as a screening method. Urine and faecal samples were collected daily from patients with internal contamination. Intakes and committed doses were estimated with age specific mathematical models. The efficacy of Prussian Blue in promoting decorporation of caesium was evaluated by means of the ratio of the amounts of caesium excreted in faeces and in urine. A whole body counter was set up in Goiânia, and the effect on the biological half-life of caesium in the organism of the dosage of Prussian Blue administered to patients was estimated.

PART III. THE ENVIRONMENTAL CONTAMINATION: ASSESSMENT AND REMEDIAL ACTIONS

The environment was severely contaminated in the accident. The actions taken to clean up the contamination can be divided into two phases. The first phase corresponds to the urgent actions needed to bring all potential sources of contamination under control, and was in the main completed by 3 October, but elements of this phase persisted until Christmas 1987, when all the main contamination sites had been dealt with. The second phase, which can be regarded as the remedial phase aiming to restore normal living conditions, lasted until March 1988.

The primary objectives of the urgent response were to prevent high individual radiation doses that might bring about non-stochastic effects; to identify the main sites of contamination; and to establish control over these sites. In the initial response, all actions were aimed at bringing sources of actual exposure under control, and this took three days.

Initial radiation surveys were conducted on foot over the contaminated areas. Seven main foci of contamination were identified, including the junkyards concerned, some of them with dose levels of up to 2 $Sv \cdot h^{-1}$ at one metre.

An aerial survey by suitably equipped helicopter confirmed that no major areas of contamination had been overlooked. Over a period of two days all of the more than 67 square kilometres of urban areas of Goiânia were monitored. The extents of the seven known principal foci were confirmed and only one previously unknown, minor area, giving rise to a dose rate of 21 $mSv \cdot h^{-1}$ at one metre, was discovered.

It was possible for lesser areas of contamination to have been missed, especially in the vicinity of the heavily contaminated areas around the main foci. A complementary system of monitoring covering large areas, although limited to roads, was put into practice. This system used detectors mounted on and in cars, and 80% of the Goiânia road network, over 2000 km, was thus covered. The main foci of contamination were the junkyards and residences where the integrity of the source capsule was breached; these covered an area of about 1 km^2.

Action levels in this initial response were set for the control of access (10 $\mu Sv \cdot h^{-1}$); for evacuation and prohibited access (2.5 $\mu Sv \cdot h^{-1}$ and later 10 $\mu Sv \cdot h^{-1}$ for houses, and 150 $\mu Sv \cdot h^{-1}$ for unoccupied areas); and for workers participating in accident management (dose limits and corresponding dose rates per day, week and month). In total, 85 houses were found to have significant contamination, and 200 individuals were evacuated from 41 of them. After two weeks, 30 houses were free for reoccupation. It should be emphasized that these levels, which correspond roughly to one tenth of the lowest values of the intervention levels recommended by the International Commission on Radiological Protection and the IAEA (non-action levels), were extremely restrictive, owing to political and social pressures.

Subsequently, the dissemination of contamination throughout the area and the hydrographic basin was assessed. A laboratory was set up in Goiânia for measuring the caesium content of soils, groundwater, sediment and river water, drinking water, air and foodstuffs. Countermeasures were only necessary, however, for soil and fruit within a 50 metre radius of the main foci.

The subsequent response, consisting mainly of actions undertaken for recovery, faced various difficulties in surveying the urban area and the river basin. These were compounded by the heavy rain that had fallen between 21 and 28 September, which had further dispersed caesium into the environment. Instead of being washed out as expected, radioactive materials were deposited on roofs, and this was the major contributor to dose rates in houses.

Levels of contamination in drinking water were very low. The groundwater was also found to be free of contamination, except for a few wells near the main foci of contamination with concentrations of caesium just above the detection level.

The main countermeasures undertaken during this remedial phase were the decontamination of the main sites of contamination (including areas outside the main foci), of houses, of public places, of vehicles and so on. For decontamination at the main foci, heavy machinery was necessary to remove large amounts of soil and for demolishing houses. Large numbers of various types of receptacles for the waste also had to be constructed. In addition, a temporary waste storage site had to be planned and built. This was done by the middle of November, and decontamination of the main foci and remaining areas was carried out from mid-November up until the end of December 1987.

The investigation levels selected for considering the various actions corresponded to a dose of 5 mSv in the first year and a long term projected dose of 1 mSv per year in subsequent years. The work included the demolition (and removal) of seven houses and the removal of soil. Areas from which soil was removed were covered with concrete or a soil pad. In less contaminated places, the main source of exposure was contaminated dust deposited on the soil; after removal of the soil layers where necessary, surfaces were covered with clean soil. Of 159 houses monitored, 42 required decontamination. This decontamination was achieved by vacuum cleaning inside and by washing with high pressure water jets outside. Various procedures for chemical decontamination proved to be effective, each adapted to the circumstances, the material concerned and the level of radioactivity.

The action levels for these remedial actions were selected under strong political and public pressures. The levels were set substantially lower than would have resulted from an optimization process. In most cases, they could be regarded as more applicable to normal situations than to an accident recovery phase.

After the Christmas holidays in December 1987 the areas of lower dose rate surrounding the main foci were decontaminated. There was no need for heavy machinery, and optimization procedures were developed and adopted. This stage lasted until March 1988.

From its inception, the response generated large quantities of radioactive wastes. A temporary waste storage site was chosen 20 km from Goiânia. Wastes were classified into non-radioactive (below 74 $kBq \cdot kg^{-1}$), low level (below 2 $mSv \cdot h^{-1}$) and medium level (between 2 $mSv \cdot h^{-1}$ and 20 $mSv \cdot h^{-1}$). Various types of packaging were used, according to the levels of contamination. The packaging of wastes required 3800 metal drums (200 L), 1400 metal boxes (5 tonnes), 10 shipping containers (32 m^3) and 6 sets of concrete packaging. The temporary storage site was designed for a volume of waste of 4000–5000 m^3, encapsulated in about 12 500 drums and 1470 boxes.

The final total volume of waste stored was 3500 m^3, or more than 275 lorry loads. This large volume is directly attributable to the restrictive action levels chosen, both in the emergency period and in the recovery phase. The economic burden of such levels, especially in the latter phase, is far from insignificant.

A sampling system was built to monitor the runoff (including rainwater) from the platform on which the waste was placed. The best estimate of the radioactivity accounted for in contamination is around 44 TBq (1200 Ci), compared with the known radioactivity of the caesium chloride source before the accident of 50.9 TBq (1375 Ci). No decision has yet been made on the final disposal site for the waste.

PART IV. OBSERVATIONS AND RECOMMENDATIONS

Very often reviews of radiological accidents serve only to call attention to what is already well known. Many observations and recommendations emerged from the review of the accident in Goiânia. However, observations made here do not necessarily refer to the specific circumstances of the accident.

On the subject of the potential occurrence of such accidents, one major observation is that nothing can diminish the responsibility of the person designated as liable for the security of a radioactive source. Radioactive sources that are removed from the location defined in the process of notification, registration and licensing can present a major hazard. Means to preclude such breaches of care should therefore be ensured by the person liable for a radioactive source, and these should include verification procedures and appropriate security arrangements. Although the regulatory system is a check on the effectiveness of the professional and management system, it should be emphasized that regulatory and legal control cannot and must not detract from managerial responsibility.

In order to facilitate the discharging of responsibility by the person liable for a radioactive source, suitable ways of complying with regulatory requirements should be specific, simple and enforceable. In particular, good communication is required between all concerned in implementing and enforcing radiological protection requirements.

Recognition by the general public of the potential danger of radiation sources is an important factor in lessening the likelihood of radiological accidents. Due consideration should be given to a system of markings for radiation hazards that would be recognizable to the wider public.

The physical and chemical properties of radioactive sources are very important in relation to radiological accidents. They should be taken into account in the licensing for manufacture of such sources, in view of the potential influence of these properties on the consequences of accidents with and misuse of sources.

If, all precautions notwithstanding, an accident does occur and a radiological hazard is foreseen, there should be a well understood chain of information and command. In this regard, it is worth mentioning that preparations to respond to radiological emergencies should cover not only nuclear accidents but the entire range of possible accidents entailing radiation exposure.

Medically, experience in Goiânia confirmed in general the adequacy of presently available diagnostic techniques, antibiotics, and methods for platelet separation and transfusion. In addition, it demonstrated the usefulness of cytogenetic dose estimates and the remarkable efficacy of Prussian Blue in eliminating internal contamination by caesium-137.

The treatment of casualties of radiological accidents is extremely varied and complex. They must be cared for in hospitals by staff who are engaged on a daily basis in the haematological, chemotherapeutic, radiotherapeutic and surgical treatment of patients at risk from cancer, immunosuppression and blood dyscrasias. Generally, medical personnel and facilities are not prepared for dealing with radiation injuries and radiological emergencies. Provision should be made in radiological emergency plans for immediate assistance from medical specialists trained to handle such patients. Recognition of the nature of radiation injury, however, depends on the education of non-nuclear workers as well as on trained health professionals, all of whom are dependent upon widely disseminated educational programmes.

On the subject of dealing with the environmental contamination due to an accident, it is worth noting the issue of decisions on intervention levels. There is usually a temptation to impose extremely restrictive criteria for remedial actions, generally prompted by political and social considerations. Such criteria, however, impose a substantial economic and social burden in addition to that caused by the accident itself, and this is not always warranted.

Finally, it is worth mentioning that an accident should be documented as soon as possible, since the facts tend to become blurred with the passage of time. Dissemination of information to the communications media, the public and, indeed, the response force is especially important. In particular, the response teams should receive support in administration and public information appropriate to the scale of the emergency. Major emergencies require prompt on-site administrative and public informational support. All individuals who are likely responders to radiological emergencies should undergo training, both formal and in drills, appropriate to their likely functions.

Part I

THE ACCIDENT

1. INTRODUCTION

On 13 September 1987, a shielded, strongly radioactive caesium-137 source (50.9 TBq, or 1375 Ci, at the time) was removed from its protective housing in a teletherapy machine in an abandoned clinic in Goiânia, Brazil, and subsequently ruptured. Consequently, many people incurred large doses of radiation, due to both external and internal exposure. Four of the casualties ultimately died and 28 people suffered radiation burns. Residences and public places were contaminated. The decontamination necessitated the demolition of seven residences and various other buildings, and the removal of the topsoil from large areas. In total about 3500 m^3 of radioactive waste were generated.

The accident in Goiânia was one of the most serious radiological accidents to have occurred. However, it has similarities with a number of other accidents, such as those in Mexico City (1962), Algeria (1978), Morocco (1983) and Ciudad Juárez in Mexico (1983). Indeed, the last of these was strikingly similar to the accident in Goiânia.

The extent to which these accidents were reported in readily accessible literature has varied considerably, with a consequent loss of useful information about them. With this in mind, and with the perception that greater attention needs to be paid to radiological protection outside the nuclear sector, the IAEA has collaborated with the Brazilian authorities in undertaking this review of the accident in Goiânia.

1.1. THE OBJECTIVE OF THE REPORT

The objectives of the review of the accident were:

(a) to bring together in a coherent report the facts about the accident;
(b) to identify lessons that can be learned about reducing the likelihood of occurrence of such accidents, and how to deal with them if they do occur;
(c) to obtain as much information as possible about the medical effects of radiation exposure and the care of highly exposed and contaminated persons;
(d) to identify lessons to be learned in the management of accidents with widespread contamination;
(e) to assess the effectiveness of international co-operation in the emergency response and to identify possible improvements.

1.2 THE FORMAT OF THE REPORT

Such a review as this must necessarily seek to give a detached, objective account of what happened in the accident and how it was dealt with. To this end, the report is separated into five main parts, namely:

— A description and analysis of the accident: the chronology of the removal and rupture of the source, the discovery of the accident and the initial response.
— The human consequences: dealing with the people affected. Management, treatment and care of the casualties and the dosimetry for internal and external exposure.
— Assessment of the environmental contamination and remedial actions.
— Observations and recommendations: lessons to be learned.
— Appendices and annexes giving further details and managerial, scientific and technical information relating to the accident.

It is hoped that this report will help responsible authorities in formulating approaches that will limit the potential for, and the consequences of, radiological accidents, and in planning to deal with emergencies. With regard to the latter, it should not be forgotten that in an office, with the benefit of hindsight, it is easy to formulate emergency plans that would have been adequate to deal with the 'last' accident. When accidents happen, they inevitably have their own characteristics that necessitate the adaptation and modification of the basic plan. Moreover, accidents give rise to trauma and stresses that perhaps only those who have been directly concerned in them can readily appreciate.

2. BACKGROUND INFORMATION

2.1. THE SETTING IN GOIÂNIA

Goiânia is the capital of Goiás State on the central Brazilian plateau, which is known for its cereal farms and cattle ranches. The mean annual temperature is 21.9°C (often reaching 40°C) and the climate is humid with an annual rainfall of 1700 mm.

Goiânia is a large city with a population of about one million. The section of the city where the accident occurred is one of the poorer areas, and the standard of literacy of the population is limited. Figure 1 gives an impression of the relative size of the area of the city that was contaminated, and the location of Goiânia in relation to the cities of Rio de Janeiro (1348 km away) and São Paulo (919 km away), where the major radiological protection resources are situated.

A number of State and city authorities and organizations featured in the events and these are briefly described here. The Federal Ministry of Health is responsible for health matters nationally; some responsibilities for health are devolved from the Federal Ministry to the State Health Secretaries. Environmental matters are dealt with by a State agency, SEMAGO. Goiânia itself has a public health department, the Vigilância Sanitária, whose responsibilities include, for example, matters related to food and drugs.

2.2. THE RELEVANT ORGANIZATIONS AND THE RADIOLOGICAL PROTECTION INFRASTRUCTURE IN BRAZIL

The competent national authority for nuclear energy in Brazil is the National Nuclear Energy Commission (CNEN), whose President reports directly to the President of the Republic. CNEN has three research institutes: the Institute for Nuclear and Energy Research (IPEN) in São Paulo, and the Institute of Radiation Protection and Dosimetry (IRD) and the Nuclear Engineering Institute (IEN) together with CNEN headquarters in Rio de Janeiro (see Fig. 2).

IPEN has a research reactor that is used to supply most of Brazil's medical radioisotopes and sources for industrial uses. There are also thorium and uranium treatment plants. IPEN has a radiation protection department to service its own needs and to perform some external regulatory inspection functions in the south of Brazil.

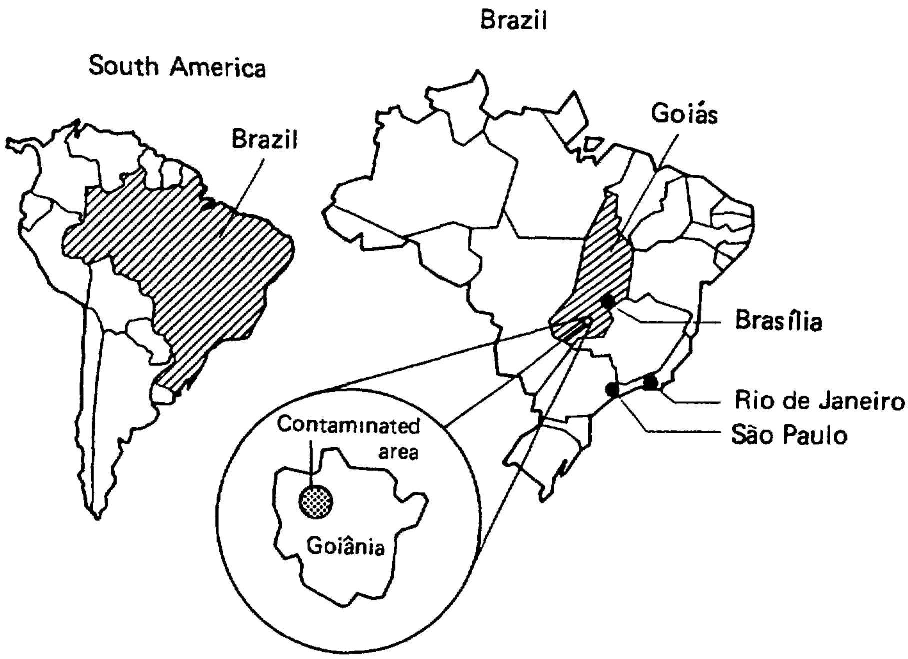

FIG 1 Plan showing the location of Goiânia in relation to Rio de Janeiro (1348 km) and São Paulo (919 km), where the major radiological protection resources are situated, and giving an impression of the relative size of the contaminated area of the city.

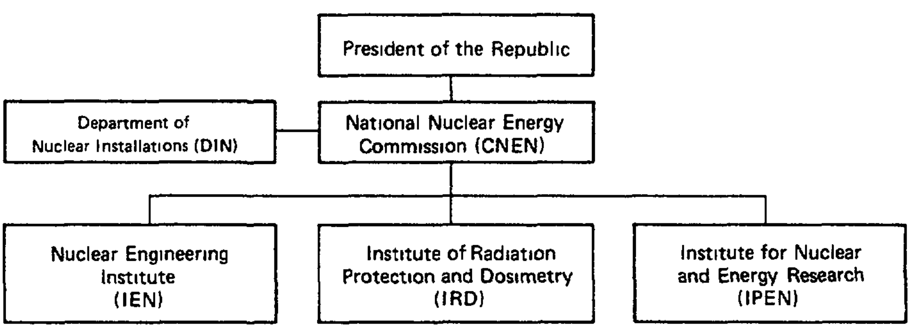

FIG 2. The three research institutes and the regulatory department of Brazil's National Nuclear Energy Commission, CNEN.

IEN also has a research reactor and associated capabilities in radiation protection, but its work is mainly oriented towards instrumentation and nuclear engineering.

As its title implies, IRD is a principal centre in Brazil for radiation protection matters, and as such provided most of the staff and facilities for dealing with the accident. It has a number of departments, including the following:

(a) The Environmental Radiation Protection Department covers environmental impact assessments, effluent control, radiochemistry and research;
(b) The Personal Monitoring Department provides both external and internal personal monitoring services. For the latter there are groups working on dose assessment, modelling, bioassay, whole body monitoring and cytogenetic dosimetry;
(c) The Occupational Radiation Protection Department carries out a programme of inspections, monitoring and training for medical and industrial uses and for the nuclear fuel cycle;
(d) The Metrology Department has a Secondary Standard Dosimetry Laboratory and provides a nationwide instrument calibration service;
(e) The Training and Education Department arranges training courses in radiation protection for different levels of users.

In addition to CNEN, it is relevant to note several other Federal Government agencies. Empresas Nucleares Brasileiras SA (NUCLEBRAS) is responsible for activities related to the nuclear fuel cycle, reactor components, research and commercialization of nuclear materials. NUCLEBRAS has an office in Goiânia to oversee the company's uranium exploration in central Brazil. This office provided some of the instrumentation used in the initial local response to the accident. The generation of electricity from nuclear sources is the responsibility of FURNAS, which operates a nuclear power plant at Angra. Under the Emergency Plan for the nuclear power plant at Angra, any radiation casualties would be taken to the Marcilio Dias Naval Hospital in Rio de Janeiro, which has a dedicated ward for this purpose.

2.3. THE REGULATORY FRAMEWORK AND RESPONSIBILITIES

CNEN is the regulatory authority for licensing the purchase and transport of radioactive sources (Law 6189 of 16 December 1974). It also has the responsibility and power to regulate the production, use, security and disposal of radioactive materials in their various areas of use. In the area of medical uses, both CNEN and the Federal and State Health Secretaries have regulatory responsibilities, which are divided as follows.

CNEN operates a licensing system that relates both to individuals and to facilities. Health physicists or radiation protection officers have to undergo prescribed training and to pass appropriate examinations in radiation protection, depending on the type of facility. Having successfully completed this training, they receive a certificate of proficiency. In order for an organization to obtain a licence to use radioactive sources, it must have personnel in its service with the appropriate certificates of proficiency.

CNEN also requires plans for new facilities to be submitted before building can begin, together with all radiation safety documentation, such as on procedures, local rules, instrumentation and personal monitoring, and in particular contingency plans for an emergency. These are examined and when the facility has been built a commissioning inspection is carried out to verify that the arrangements are satisfactory. Only then is a licence granted for the operation of a facility. These licences are subject to a number of conditions, principally that CNEN be informed of any material changes, for example if it is desired to move or dispose of sources. CNEN Regulations 6/73 specify the legal requirements with which users must comply once a licence has been granted.

The subsequent inspection of medical facilities under these Regulations is the responsibility of the Federal Ministry of Health under Law 6229 of 17 July 1975. This responsibility was in turn devolved under Decree 77052 of 19 January 1976 to the State Health Secretaries. The extent to which this responsibility was discharged varied between States.

2.4 EMERGENCY ARRANGEMENTS

The emergency arrangements that pertained within CNEN at the time of the accident were designed to cope with two main categories of accident. Firstly, there was the Emergency Plan for the Angra nuclear power plant, which was intended for managing a nuclear power plant accident; and secondly, there were arrangements for dealing with radiological emergencies in the non-nuclear power sector. These are usually on a small scale; for example, transport accidents or accidents with radiography sources. The Goiânia accident did not fall into either category, and elements from both sets of emergency arrangements were adopted. The salient features of both sets are given in the following.

Figure 3 shows a schematic diagram of the major emergency response groups in the Emergency Plan for the Angra nuclear power plant. The initials shown are those of the groups as they are named in Brazil, and the names given in English are descriptive rather than a direct translation. Major decisions would be taken at the political level in the General Co-ordination Committee, on which would be represented the major Government agencies such as CNEN, FURNAS and Federal and State Ministries. The input from CNEN would be formulated by its Executive Group for Emergency Control (GECE) on the advice of the Technical Evaluation Group (GERE). Two of the Groups reporting to GERE, the Headquarters Plant Safety Evaluation Group (GASU) and the Site Plant Safety Evaluation Group (GIOU), are concerned with the safety of the Angra plant and were not directly relevant to the Goiânia accident.

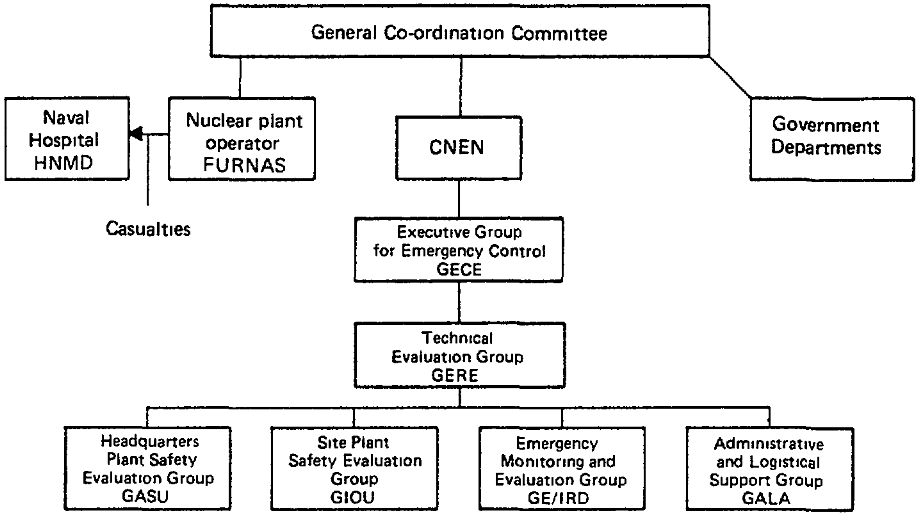

FIG. 3. Schematic diagram of the key emergency response groups for the Angra nuclear power plant

During an emergency the Emergency Monitoring and Evaluation Group (GE/IRD) would be responsible for all off-site monitoring of the environment and the population and for evaluating the results. There is also an Administrative and Logistical Support Group (GALA). Both these groups were concerned to some degree with the Goiânia accident. Within IRD there was an emergency group consisting of the designated co-ordinators of various monitoring and support teams. Although these arrangements were not designed for an emergency such as the one at Goiânia, the underlying preparation and planning for emergency actions undoubtedly helped. For example, the availability of an emergency control room fully equipped with a communications network was very useful.

The arrangements for radiological emergencies in the non-nuclear power sector were designed to ensure that there was always a central person who could be contacted in an emergency, and who could arrange for appropriate assistance. The central contact person, or nuclear emergency co-ordinator, under the Emergency Plan, was the Director of CNEN's Department of Nuclear Installations (DIN) in Rio de Janeiro. He would contact the Director of either IPEN in São Paulo or IRD in Rio de Janeiro, depending on where the emergency occurred. Each of these groups has designated emergency co-ordinators (different from those for the Emergency Plan for the Angra nuclear power plant). The co-ordinators would quickly dispatch someone with appropriate experience to the scene of the accident with monitoring equipment, either to deal with it directly or, if necessary, to evaluate what further resources might be required.

3. DESCRIPTION OF THE ACCIDENT

3.1. THE FACILITIES CONCERNED IN THE ACCIDENT

The Instituto Goiano de Radioterapia (IGR) was a private radiotherapy institute owned by a medical partnership. The treatment facilities of the institute's clinic included rooms for teletherapy with caesium-137 and cobalt-60. The IGR had followed the normal licensing procedure described in Section 2.3 and on 17 June 1971 CNEN approved the importation of the caesium-137 source. Shortly afterwards the equipment was installed and inspected and became operational. Under the terms of the operating licence issued by CNEN, a physicist and a physician (one of the partners) were jointly responsible for ensuring that the conditions of the licence were complied with. In particular, there was a requirement that any significant change in the status of the equipment or the facilities had to be reported to CNEN.

It is now known that at about the end of 1985 the IGR ceased operating from these premises and a new partnership took over other premises. The cobalt-60 teletherapy unit was moved to these other premises. Ownership of the contents of the IGR clinic was disputed and the caesium-137 teletherapy unit was left in place. CNEN did not receive appropriate notifications of these changes in status, as required under the terms of the institute's licence. Most of the clinic, together with some surrounding properties, was demolished. The treatment rooms were not demolished but were left in a derelict state and were apparently used by vagrants. (See Photographs 1–3.)

The circumstances that led to the abandonment of the teletherapy machine complete with its caesium-137 source in the old clinic, its becoming insecure and subsequently being broken up have not been completely clarified. Moreover, at the time of writing they are the subject of legal proceedings. However, nothing can deflect from the fact that the professional and moral responsibility for the security of a radioactive source must lie with the person or persons licensed as responsible for it.

3.2. THE TELETHERAPY MACHINE AND ITS RADIOACTIVE SOURCE

The teletherapy unit in question was a model Cesapan F-3000 designed by Barazetti and Company of Milan, Italy, in the 1950s and marketed by Generay SpA

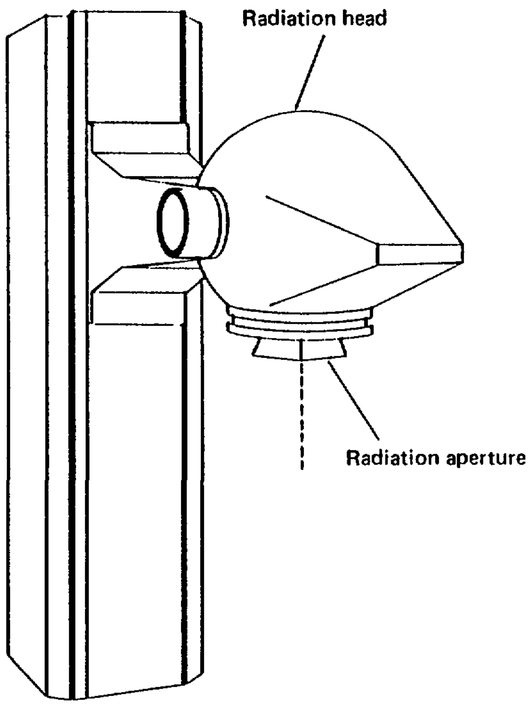

FIG. 4. Schematic view of a teletherapy machine similar to the one from which the source assembly was removed in Goiânia. The radiation head is adjustable vertically and can be rotated about two horizontal axes.

of Italy. Figure 4 shows an artist's impression of a similar teletherapy unit. In order to understand what happened subsequently, it is necessary to distinguish the major components of the teletherapy unit.

The *sealed radioactive source capsule* was set in a *source wheel,* made of lead and stainless steel, to form the *rotating shutter* mechanism (see Fig. 5). To produce a radiation beam, the shutter was rotated electrically to align the source capsule with the *radiation aperture.* After an exposure or in the event of a power failure, a spring loaded device returned the shutter with the radioactive source to the 'off' or 'safe' position. Between the rotating shutter and its electric drive mechanism there was a cylindrical *shielding plug.* These elements can be collectively referred to as the *rotating assembly.* The unit was designed so that the rotating assembly could be removed with special tools from the shielding of the *radiation head.*

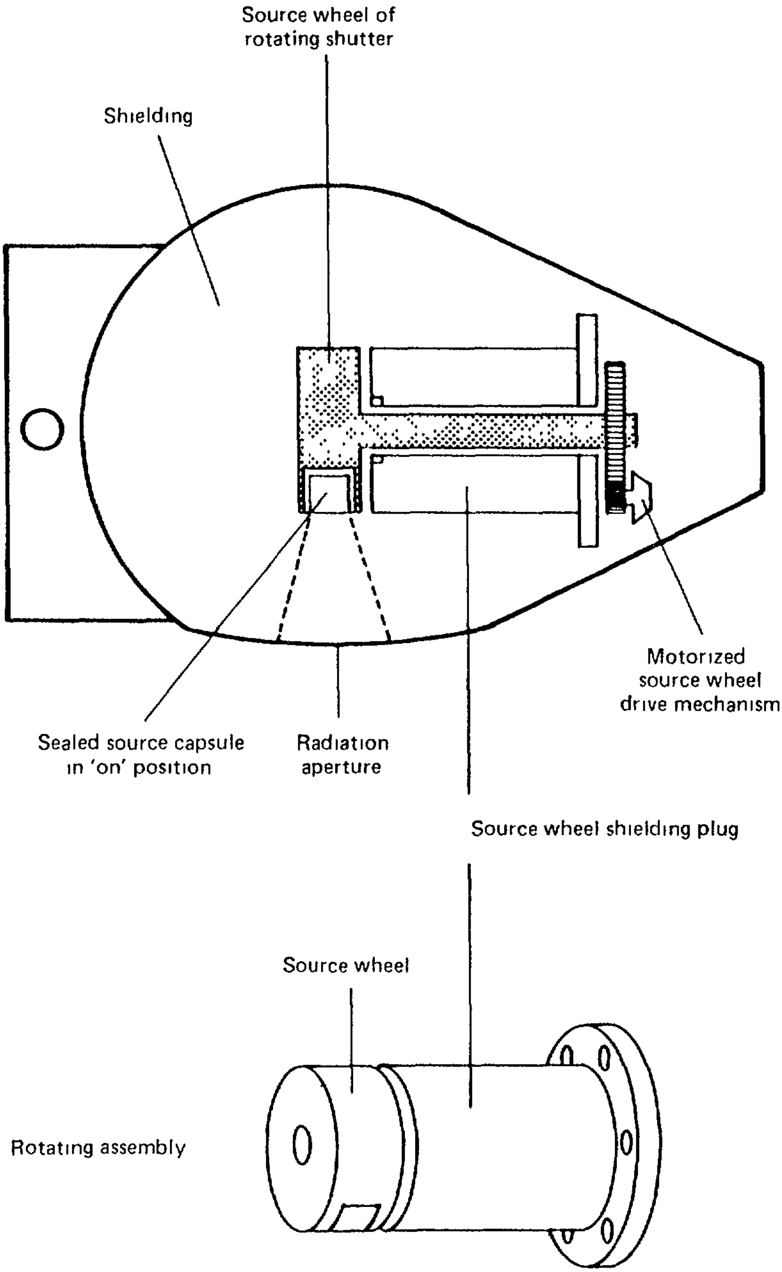

FIG 5 Cross-sectional diagram of the radiation head of a teletherapy machine similar to the one from which the source assembly was removed in Goiânia, showing the rotating assembly for the source capsule

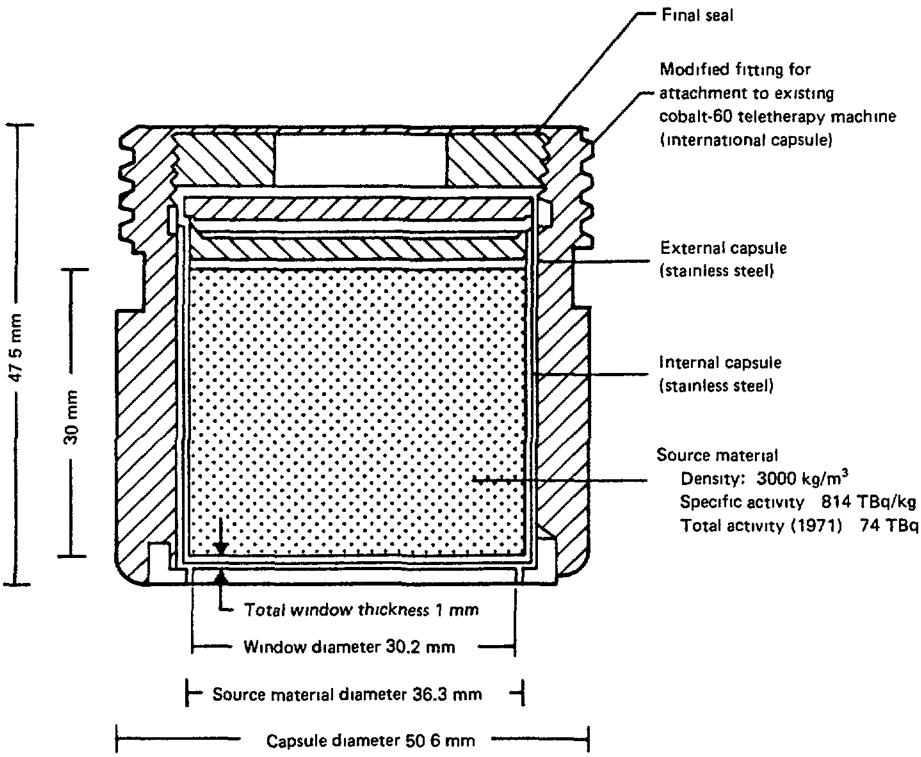

FIG. 6. Cross-sectional diagram of an international standard capsule. Such a capsule of radioactive caesium chloride was broken open in the accident in Goiânia. The source was compacted to a coherent mass and sealed within two stainless steel capsules

The serial number of the sealed radioactive source is not known, but from other information the source is thought to have been produced at the Oak Ridge National Laboratory (ORNL) facility in the United States of America in about 1970. The radioactive source was caesium-137 in the form of highly soluble caesium chloride salt. This had been compacted to form a coherent mass which was doubly sealed within two stainless steel capsules, as shown in Fig. 6. These in turn were sealed within what is known as an *international standard capsule* having standardized dimensions common to most radiotherapy units. Figure 6 shows a cross-sectional view of a source sealed in an international standard capsule.

Table I gives basic data on caesium-137 and the source in question, and data relevant for radiological protection purposes.

TABLE I. BASIC DATA ON CAESIUM-137

Basic data on caesium-137		
Gamma emissions		0.66 MeV (84%)
Beta emissions	Maximum energies	0.51 MeV (95%)
		1 17 MeV (5%)
	Mean energy	0.187 MeV
Half-life		30 years
Specific gamma ray constant	8.9×10^{-2} $mGy \cdot h^{-1}$ at 1 m per GBq	
	(0.33 $rad \cdot h^{-1}$ at 1 m per Ci)	
Data on the caesium source of the IGR clinic (September 1987)		
Radioactivity	50.9 TBq (1375 Ci)	
Dose rate at 1 m	4.56 $Gy \cdot h^{-1}$ (456 $rad \cdot h^{-1}$)	
Radioactive material		
Volume	3.1×10^{-5} m^3	
Mass	0.093 kg	
Specific activity	0 55 $TBq \cdot g^{-1}$ (15.1 $Ci \cdot g^{-1}$)	
Radiological protection data		
Dose rate at 1 m from uniform ground contamination	1.6×10^{-12} $Sv \cdot h^{-1} \cdot (Bq \cdot m^{-2})^{-1}$	
Dose per unit intake (ingestion)	1.2×10^{-8} $Sv \cdot Bq^{-1}$	
Dose per unit intake (inhalation)	8.7×10^{-9} $Sv \cdot Bq^{-1}$	
Annual limit of intake (oral)	$4 0 \times 10^6$ Bq	
Annual limit of intake (inhalation)	6.0×10^6 Bq	
Derived air concentration	2.0×10^3 $Bq \cdot m^{-3}$	

3.3. CHRONOLOGY OF THE ACCIDENT

There are a number of different accounts of what occurred to precipitate the accident in Goiânia. These accounts derive from several interviews with various individuals. Whilst these versions of events are generally consistent, there are some minor inconsistencies, mainly in descriptions of the parts of the teletherapy unit. The sequence of events in Table II, in which only the initials of the people affected

Text cont. on p 29.

TABLE II. CHRONOLOGY OF THE ACCIDENT IN GOIÂNIA

10–13 Sept. 1987	R.A. had heard rumours that valuable equipment had been left in the disused clinic of the IGR (Location A). R.A. and a friend, W.P., went to the site of the disused clinic and tried to dismantle the teletherapy unit with simple tools. R.A. and W.P. finally succeeded in removing the rotating assembly. The shiny stainless steel casing appeared valuable to them and they took it in a wheelbarrow to R.A.'s house (Location B), half a kilometre from the clinic.
	Since no contamination was found at the clinic, the source assembly was presumably still intact at this stage. However, from the moment they removed the rotating assembly, they would potentially have been exposed to the direct beam, as they would have been if they had rotated the source wheel into the 'on' position while it was still in the radiation head. This would have given a dose rate of 4.6 $Gy \cdot h^{-1}$ *at 1 m.*
13 Sept.	W.P. and R.A. were vomiting, but assumed that this was due to something they had eaten.
14 Sept.	W.P. had diarrhoea and felt dizzy, and one hand was swollen (oedema).
	W.P. subsequently had a hand/wrist burn consistent with having held the rotating assembly with one hand/wrist over the beam aperture.
15 Sept.	W.P. sought medical assistance. His symptoms were diagnosed as being due to some kind of allergic reaction caused by eating bad food. On medical advice he stayed at home for a week, feeling poorly and doing only light work.
18 Sept.	The rotating assembly had been placed on the ground under a mango tree in R.A.'s garden. Here R.A. worked intermittently to remove the source wheel of the rotating shutter. In the course of the attempt he punctured the 1 mm thick window of the source capsule with a screwdriver and scooped out some of the source. Thinking it might be gunpowder, he attempted to light it. On 18 September he succeeded in removing the source wheel.
	When measured on 2 October, the residual contamination under the mango tree gave a dose rate of 1.1 $Gy \cdot h^{-1}$ *at 1 m. The whole of R.A.'s house and its grounds were extensively contaminated. The house had to be demolished and the topsoil removed.*

18 Sept.	The pieces of the rotating assembly were sold to D.F., who lived next to the junkyard he managed (Junkyard I, Location C). The pieces were transported in a wheelbarrow (by an employee of D.F.). That night D.F. went into the garage where the pieces had been placed and noticed a blue glow emanating from the source capsule. He thought it looked pretty and that the powder might be valuable (like a gemstone) or even supernatural, and took the capsule into the house. Over the next three days various neighbours, relatives and acquaintances were invited to see the capsule as a curiosity. During this time he and his wife M.F.1 examined the powder closely. *M.F.1 (dose 5.7 Gy) subsequently died. D.F. (dose 7.0 Gy) survived, possibly because he spent more time out of the house and his exposure was fractionated.*
21 Sept.	E.F.1, a friend of D.F.'s, visited him and with the aid of a screwdriver removed some fragments of the source from the capsule. These were about the size of rice grains, but readily crumbled into powder. E.F.1 gave some of the colourful fragments to his brother E.F 2 and took the rest home. D F. also distributed fragments to his family. Subsequently there were several instances of people daubing the radioactive powder on their skin, as with the glitter used at carnival time
21–23 Sept.	M.F.1 was vomiting and had diarrhoea. She was examined at São Lucas Hospital. The diagnosis was the same as for W.P. (an allergic reaction to something she had eaten) and she was sent home to rest. Her mother M.A.1 came over for two days to nurse her and then returned to her home, some distance from Goiânia, taking a significant amount of contamination with her. *M.A.1 had an estimated initial intake of 10 MBq (270 μCi) and a dose of 4.3 Gy estimated on the basis of cytogenetic analysis. Although critically ill at one stage, she survived.*

22–24 Sept.	The pieces of the rotating assembly were handled and worked on by D.F.'s employees, principally I.S. and A.S., to extract the lead. At one stage Z.S. visited and offered to return to cut up the pieces with an oxyacetylene torch. However, he forgot to do so. *I.S. and A.S. incurred doses of 4.5 Gy and 5.3 Gy respectively. Both subsequently died. Their exposures were probably acute while working on the effectively unshielded remnants of the source assembly.*
23 Sept.	W.P. was admitted to Santa Maria Hospital where he stayed until 27 Sept., when the skin effects of radiation exposure were diagnosed as a symptom of some disease, and he was transferred to the Tropical Diseases Hospital.
24 Sept.	I.F., the brother of D.F., went to Junkyard I and was given some fragments of the source. He took them back to his house, next to a junkyard (Junkyard II, Location D). They were placed on the table during a meal. His six-year-old daughter L.F.2 handled them while eating (by hand), as did the rest of the family to a lesser extent. *L.F.2 subsequently died, having had an estimated intake of 1.0 GBq (27 mCi) and received an estimated dose of 6.0 Gy.*
25 Sept.	D.F. sold the lead and the remnants of the source assembly to the owner of Junkyard III (Location E).
26 Sept.	K.S., an employee at Junkyard II, and another person went back to the old IGR clinic and removed the remainder of the equipment, principally the shielding container (weighing about 300 kg), and took it to Junkyard II.
28 Sept.	By this time a significant number of people were physically ill. M.F.1 was convinced that the glowing powder from the source assembly was causing the sickness. She went with G.S., an employee of D.F.'s, to Junkyard III and had him put the remnants of the rotating assembly and the source assembly in a bag. They took the bag by bus to premises of the Vigilância Sanitária (Location F). G.S. carried

	the bag there from the bus on his shoulder. At these premises the bag was placed on the desk of Dr. P.M., and M.F.1 told him that it was "killing her family".
	G.S. incurred a significant radiation burn on his shoulder and an estimated whole body dose of 3.0 Gy, and had an estimated intake of 100 MBq (2.7 mCi).
28 Sept.	Dr. P.M. left the source remnants in the bag on his desk for some time but was then worried enough to remove it to a courtyard and put it on a chair by the external wall of the premises. (It remained there for one day.)
	Dr. P.M. received an estimated dose of 1.3 Gy. His intake was negligible (since the source remnants remained in the bag).
	M.F.1 and G.S. were sent to a Health Centre. There the initial diagnosis was that they had contracted a tropical disease. They were then sent to the Tropical Diseases Hospital. Several other people who had been contaminated in the incident and showed similar symptoms had already been to the Tropical Diseases Hospital, and similar diagnoses had been made. However, one of the doctors, Dr. R.P., had begun to suspect that the patients' skin lesions had been caused by radiation damage. Consequently, he contacted Dr. A.M., who worked both at the Tropical Diseases Hospital and as superintendent of the Toxicological Information Centre. Dr. A.M. had been contacted independently by Dr. P.M. from the Vigilância Sanitária about the suspicious package (the bag of source remnants), which he had originally thought contained pieces from X-ray equipment. After the patients had been further examined, Drs R.P. and A.M. considered that the matter required further investigation. They contacted Dr. J.P. at the Department of the Environment of Goiás State. Dr. J.P. proposed that they have a medical physicist look at the suspicious package. Dr. J.P. knew a physicist, W.F., who happened to be visiting Goiânia at the time; however, he was unable to contact him until early the next day.
	The pace of the events then quickened as the seriousness of the accident began to be appreciated; consequently, approximate times are given.

29 Sept. 08:00	W.F., the licensed medical physicist who was known to Dr. J.P. and who happened to be visiting Goiânia at the time, was reached by telephone and asked whether he would be able to take some measurements around a suspicious package at the Vigilância Sanitária. He thought he knew where he could borrow a dose rate monitor, and agreed to do this. One of the Government agencies concerned in the nuclear fuel cycle, NUCLEBRAS, has offices in Goiânia that deal with prospecting for uranium. W.F. went to these offices and asked to borrow a dose rate monitor. After some delay he was lent a scintillometer (a dose rate meter with a scintillation detector highly sensitive to radiation). It had a fast response time and a dynamic range of 0.02 to 30 $\mu Gy \cdot h^{-1}$, being normally used for geological measurements. He set off for the Vigilância Sanitária, and while still some distance away he switched on the monitor. It immediately deflected full scale irrespective of the direction in which he pointed it. He assumed the meter was defective and returned to the NUCLEBRAS offices to fetch a replacement.
10:20	W.F. arrived at the Vigilância Sanitária. Having switched on the replacement monitor upon leaving the NUCLEBRAS offices, he was by then convinced that there was a major source of radiation in the vicinity. In the interim Dr. P.M. had become worried enough to call the fire brigade. W.F. arrived just in time to dissuade the fire brigade from their initial intention of picking up the source and throwing it into a river.
11:00	W.F. then persuaded the occupants of the Vigilância Sanitária to vacate the premises. The police and fire brigade supervised to prevent anyone from re-entering the building.
12:00	Dr. P.M. explained where the source had come from and he and W.F. went together to Junkyard I. There they found that over a wide area the radiation monitor deflected off the scale, and there was evidence of contamination. This convinced them that the contamination was extensive. They talked to D.F. from Junkyard I and with some difficulty persuaded him, his family and many neighbours to vacate the area.

13:00	W.F. and others went to the offices of the Secretary for Health of Goiás State to inform the authorities of the incident and its significance and to obtain further assistance. As can perhaps be appreciated, the officials were incredulous of the account of the incident and the assessment of the potential scale of the evacuation necessary. The officials took some persuading that the matter was important enough to warrant the attention of the Secretary for Health. W.F. and others persevered, and were eventually permitted to see him and apprised him of the seriousness of the situation.
15:00	The Director of the Department of Nuclear Installations in CNEN was reached by telephone as the nominated co-ordinator for nuclear emergencies (referred to as NEC). He suggested that they contact the hospital physicist at the IGR for help, and that they would be able better to determine the nature of the incident and the extent of the area affected with the wider range of instruments at his disposal NEC also contacted the licensed physicist and the physician from the IGR, and the source was tentatively identified as possibly originating from the IGR.
16:00–20:00	Several actions were taken more or less at the same time in Goiânia. In particular: (a) The Tropical Diseases Hospital was contacted and informed that a number of people had been contaminated and were suffering from the effects of radiation exposure. (b) The various elements of the civil defence forces (the police, the fire brigade, ambulances, hospitals) were alerted. (c) The known sites of contamination, the Vigilância Sanitária and Junkyard I, were resurveyed with the equipment from the IGR. (d) The Goiás State Secretary for Health held a meeting and made plans for receiving contaminated persons in the city's Olympic stadium (Location H). By this time the press was taking an interest in events.

22:00	Z.S. (who had earlier offered to cut up the pieces of the rotating assembly with an oxyacetylene torch) found W.F. and explained how the source assembly had been broken up and where the pieces had been taken. This enabled the monitoring team to identify more of the sites of major contamination and to evacuate more contaminated persons. In the night of 29–30 September, 22 people were identified at the stadium as potentially having been highly exposed. They were put into tents separately from the others. This segregation was based partly on contamination measurements and medical symptoms, but also on the family groupings at the sites of major contamination. Some initial screening was done by Dr. A.M. and a colleague, and those with lesions were sent to the Tropical Diseases Hospital to join other patients already there. By this time the hospital had been informed that the patients were contaminated and should be kept isolated.

appear, seems to be the most plausible description of what happened. It includes a large number of people and extends to several sites in or near the Aeroporto section of Goiânia. In order to help the reader follow what happened, three figures (Figs 7–9: *see inside back cover*) have been included at the end of the report to supplement the description in Table II.

Figure 7 is a plan of Goiânia showing the principal sites of contamination. Figure 8 is a schematic diagram of the chronology of the accident, adapted from a drawing made shortly after the accident by the investigators in attempting to establish what had happened. Figure 9 shows a chart of the persons most seriously contaminated in the accident at Goiânia, listed by site of exposure and family membership. Estimates (from cytogenetic data) of doses incurred and information on those admitted to hospital and on the four deaths as a result of exposure are also given.

It is relevant to note that the interest aroused by the blue glow that emanated from the radioactive caesium chloride significantly affected the course of the accident. Also, caesium chloride's high solubility contributed to the extensive contamination of persons, property and the environment. But for these factors, the accident might have developed similarly to the accident with cobalt-60 that occurred in Ciudad Juárez, Mexico, in 1983, which resulted in little contamination and no deaths.

Subsequently, the phenomenon of the blue glow was observed by individuals from ORNL and the United States Department of Energy's Radiation Emergency Assistance Center/Training Site (REAC/TS) at Oak Ridge, USA, during the disencapsulation of a caesium-137 chloride source in early 1988. This glow is thought to be associated with fluorescence or Cerenkov radiation due to the absorption of moisture by the source. Further study is in progress in Oak Ridge to determine the nature of this blue glow.

4. INITIAL ACTIONS UPON DISCOVERY OF THE ACCIDENT

The accident was discovered on the afternoon of 28 September, and its seriousness first began to be appreciated on the morning of 29 September. Before considering the initial response phase in which the local authorities took control, it is worth commenting here on some specific aspects of the sequence of events. (More general comments are made in the Observations and Recommendations.)

4.1. INITIAL ACTIONS BY THE AUTHORITIES IN GOIÂNIA

In the following are described the initial response of the authorities in Goiânia, the notification and mobilization of CNEN, and initial actions by CNEN's lead, medical and physics teams upon their arrival in Goiânia. It is then described how initial resources were augmented and organized to implement the strategy to restore the situation to normal. This phase took from Tuesday 29 September to Saturday 3 October.

The authorities in Goiânia mobilized police, fire and civil defence forces and by 20:00 on 29 September had designated the nearby Olympic stadium as a staging area for isolating patients and screening others for contamination. The two known main areas of contamination, the Vigilância Sanitária and Junkyard I, were resurveyed with the monitoring equipment from the new clinic of the IGR, residents in the vicinity were evacuated and further access was controlled. Those who had possibly been contaminated were identified and directed to the stadium.

Over the night of 29–30 September, rumours spread about what had happened. The effect was exacerbated the following morning when people woke up to find areas of the district cordoned off with no coherent explanation. Many people tried to go to the Olympic stadium for reassurance, straining the limited monitoring resources then available. (See Photographs 4 and 5.)

Although no local plans for responding to radiological emergencies on this scale had existed, the authorities' improvised strategy worked effectively in bringing the situation under control and preventing further serious exposure. Once personnel from CNEN started to arrive, the local authorities began a transition to supporting them, providing facilities, equipment and administrative support, as well as the field resources necessary for the initial follow-up. The local authorities performed effectively in leaving the authorities of CNEN with a more manageable situation for them to begin to restore to normal.

4.2. INITIAL RESOURCE MOBILIZATION

The emergency arrangements were put into effect through CNEN's Executive Group for Emergency Control, GECE. Authorized by the acting President, the Executive Director responsible for safety actuated the Emergency Group of the Department of Nuclear Installations (GEDIN) as prescribed. The Director of GEDIN was appointed co-ordinator for Goiânia, and then took all necessary steps to actuate the Emergency Plan.

The Director of the Institute of Radiation Protection and Dosimetry, IRD, was assigned the continuing task of identifying and mobilizing appropriate technical and physical resources from IRD to meet requests as needs arose The first step was to get in touch with key medical and physics personnel. Later, additional personnel were required, as well as a great deal of materials and equipment. The sophisticated administrative and logistical support provided for in the Angra Emergency Plan was useful in this regard

4.3. CNEN LEAD TEAM

At 18:00 on 29 September the co-ordinator for nuclear emergencies, NEC, left Rio de Janeiro for Goiânia, arriving just after midnight (00:30) on Wednesday 30 September. He had been joined en route by two technicians from IPEN in São Paulo, who had brought suitable monitoring equipment on the basis of preliminary information obtained from the physicist W.F.

The lead team went first to the derelict clinic of the IGR. Finding no sign of a radioactive source and no trace of contamination, they proceeded to the Vigilância Sanitária and subsequently to the other key places. They confirmed the location of the source remnants in a bag on a chair in the front courtyard Figure 10, a dose rate survey for the premises of the Vigilância Sanitária, shows the ambient dose rates there. In particular, the dose rate 1 m from the source remnants was 0.4 $Sv \cdot h^{-1}$, indicating radioactivity of about 4.5 TBq (120 Ci), or less than 10% of the source.

Over the next several hours in the night, the physicist W.F. who had discovered what had happened showed the CNEN team the places he had identified as the principal sites of contamination. W.F. and the authorities in Goiânia decided to evacuate residents from areas where the dose rate exceeded 2.5 $\mu Sv \cdot h^{-1}$. In view of the pressing circumstances, an elaborate philosophical basis for an intervention criterion was not to have been expected. This first approximation was simply based on the internationally recommended occupational dose limit of 50 mSv per year. W F. was aware that compliance with an occupational dose limit of 50 mSv per year for a full time worker would be ensured if the dose rate on the external surface of a barrier were limited to 25 $\mu Sv \cdot h^{-1}$. He also knew that individual dose limits for the public used to be ten times lower than the occupational dose limits, giving the criterion of a dose rate limit of 2.5 $\mu Sv \cdot h^{-1}$.

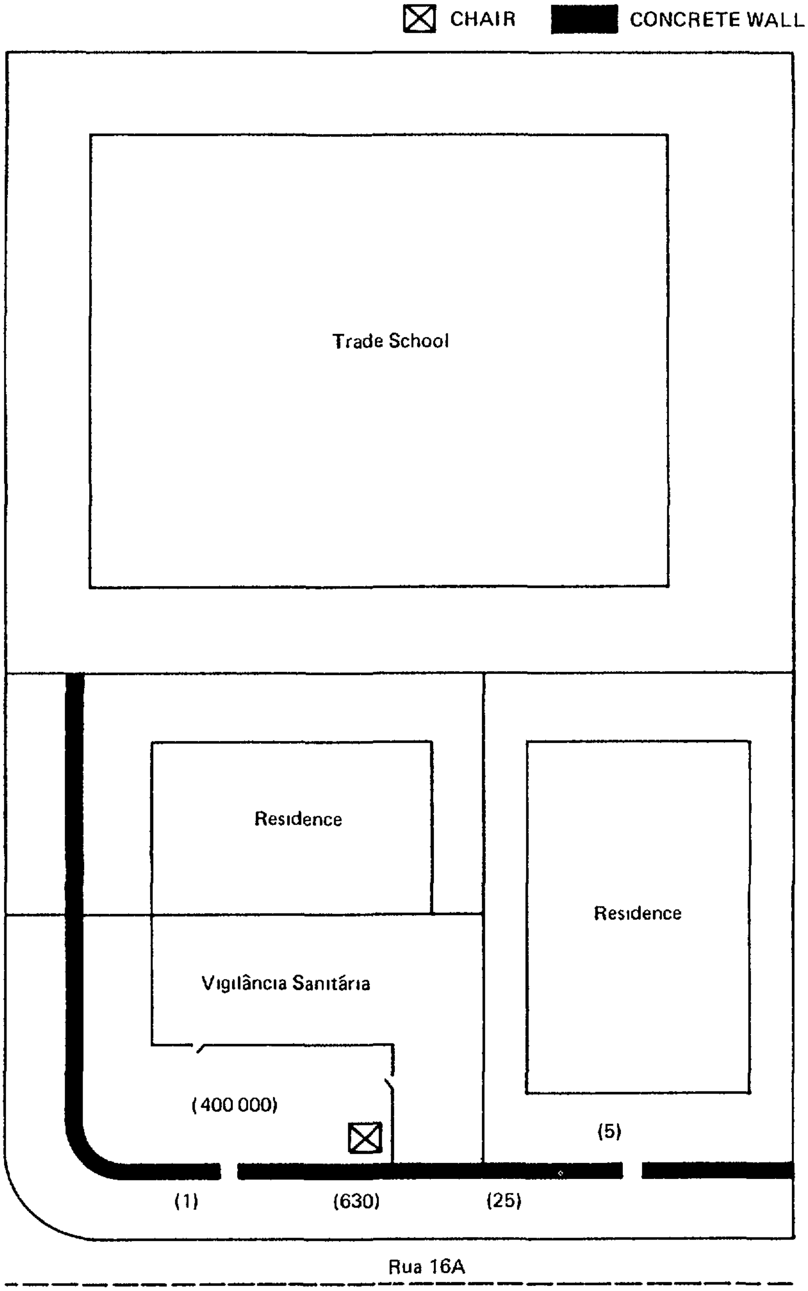

FIG 10. The dose rate (in $\mu Sv\ h^{-1}$) around the Vigilância Sanitária on Rua 16A (16A Street) (the public health department in Goiânia)

The CNEN lead team decided not to change this simple criterion in the initial phase, having arrived at a similar conclusion from different considerations. Firstly, it was felt that it would not be desirable, or politically acceptable, to allow local residents to incur a dose exceeding 5 mSv in the year. Secondly, the team recognized that the house occupancy factor (governing daily duration of exposure) was greater than the corresponding factor for occupational exposure. They also initially estimated that the cleanup would take about three months (i.e. that the exposure would be incurred for only one quarter of a year). It was thought that these two considerations approximately cancelled each other out, bearing out the criterion of a dose rate limit of 2.5 $\mu Sv \cdot h^{-1}$. After the initial phase, however, this simple criterion of the intervention level of dose rate was refined and adjusted. (See Section 7.3.)

W.F. and the CNEN team then went to the Olympic stadium, where those affected had been put in tents at one end of the stadium field. CNEN personnel directed that all contaminated persons take showers, having found that no attempt had been made to decontaminate them for fear of contaminating the water. Clothes were placed in bags. Additionally, the physicists set up contamination monitoring equipment to screen the hundreds of people who had heard about the accident and were waiting at the stadium to be checked.

At 03:00 on Wednesday 30 September the NEC reported back to CNEN headquarters. He assessed the situation as critical and indicated that a large amount of resources would be needed.

On the morning of 30 September the NEC turned his attention to dealing with the source remnants in the courtyard of the Vigilância Sanitária. A small crane was used to lift a section of sewer pipe over the two metre high wall of the courtyard and to lower it over the chair. Concrete was then pumped over the wall and into the pipe, filling it and covering the chair and the source remnants As a result, the dose rates in the surrounding area were significantly reduced, and since contamination was not a major problem at this site, much of the area cordoned off could be reopened. This operation was completed by early afternoon.

4.4. ADVANCE CNEN MEDICAL TEAM

A physician from CNEN-IRD arrived by air at 06:30 on Wednesday 30 September with two more IRD physicists. Directed to the stadium, the physician found that the physician from the Tropical Diseases Hospital who had first recognized the possibility that overexposure to radiation had caused the symptoms of the patients he had already seen had been at the stadium overnight and had already screened those who had been sent there. In all, 22 further persons were identified with symptoms of overexposure. Eleven had already been sent to the Tropical Diseases Hospital.

As those people transferred to the Tropical Diseases Hospital were under the care of other physicians, the CNEN physician remained with the physician from the Tropical Diseases Hospital at the stadium recording medical histories and making examinations. By the end of the day the two physicians had examined another 50 to 70 contaminated people. Many more medical actions were taken between then and 3 October. These are described in Section 5.

4.5. AUGMENTATION OF THE RESPONSE

The former IRD Director had been called by the IRD Director at 17:00 on Tuesday 29 September and asked to prepare to go to Goiânia to deal with the teletherapy contamination accident, where he was asked by the NEC to act as deputy NEC. At this stage there was still confusion about the origin of the contamination, and the information that was available about the IGR clinic's radioactive source did not include its chemical form. He was particularly concerned about the dispersal of the radioactive source. He concluded that it could not have been spread so easily had it been cobalt (a metal), and that it was therefore probably caesium in the form of a salt such as caesium chloride. Tracing confirmatory information on the form of the source was found to be difficult. At 09:00 on 30 September he was further informed that the contamination was due to caesium and that six or seven people had been admitted to hospital.

The deputy NEC, two physicians and health physics support staff from Rio de Janeiro flew to Goiânia, arriving at 16:00. At the Olympic stadium they found a crowd of people: those affected by the accident, people seeking reassurance and people interested in what was happening, including the press. The contaminated sites had been cordoned off over the night of 29–30 September and this had alarmed people, since there had as yet been no public announcement made concerning the accident. The group went immediately to a briefing by the NEC and the local authorities on the areas that were contaminated, the evacuation and the handling of contaminated people at the stadium.

4.6. INITIAL ORGANIZATION

The deputy NEC, on the basis of his reading of a report on the Mexican incident in 1983, recommended that a crucial first step before cleanup began was to make a thorough, well documented survey of contamination levels. This was accepted and was an important step in formulating plans to deal with the accident. CNEN's initial headquarters were set up under the stadium and remained there for more than four days until OSEGO, the State Health Ministry for Goiás State, provided facilities at its headquarters.

During this period the tents in which people had been housed blew down in a violent storm. This hindered operations for some time and was a foretaste of the adverse weather in which some decontamination work had to be done.

Initially, there were only five people to deal with the health physics aspects, including W.F. and the physicist from the IGR. On 30 September the NEC requested additional help, naming persons to be assigned to each task, on the basis of the plan of action drawn up. Personnel were selected on the basis of their professional qualities, including their ability to perform under stress. On Thursday 1 October 15 more workers arrived. The 20 then available were divided into three groups for management, area verification and decontamination. The last group was further divided into four subgroups, one for each of the main areas of contamination.

The press and the public at large were naturally interested in what was going on and the time spent answering their queries was a constant drain on the resources that were available to bring the situation under control. In retrospect the assignment from the beginning of a press officer with subsequent support for public information purposes would have been very helpful.

Record keeping became possible only on the third day, since workers were overburdened with surveying and training others in screening for contamination. At this point the need for administrative support for the technical staff was recognized. All personnel were housed in a hotel about two kilometres from the contaminated area, which contributed to the efficiency of the operation. From Saturday 3 October, when the headquarters were moved to the OSEGO facility, the process became progressively more organized as administrative support, including secretarial, telex and photocopying services, was made available. An information co-ordinator was assigned. Daily oral and written reports were required from everyone doing decontamination work and formed the basis for specific revisions of the general strategy. In retrospect, it seems that it would have been useful to have designated an official recorder.

By Saturday 3 October more resources were available and a more detailed survey of the sites had been made. The monitoring team at the stadium had found 249 people with detectable contamination. Those with external contamination only were readily decontaminated, but 129 people were found also to have internal contamination and were referred for medical care. The main contaminated sites had been identified and, although workers were still checking for other possible sites, this effectively marked the end of the initial phase of taking control and ensuring that no one else was at risk of serious exposure.

Maps were requested on Wednesday 30 September and were received on Friday 2 October, and all hot spots were marked. Residents in areas where dose rates were in excess of 2.5 $\mu Sv \cdot h^{-1}$ were evacuated by Saturday 3 October. (Action criteria are discussed in Part III.)

4.7. INITIAL MEDICAL TREATMENT OF THOSE INJURED

The initial medical priority was to treat the 11 most seriously affected patients who had already been admitted to the Tropical Diseases Hospital or the Santa Maria Hospital. These patients were transferred to occupy the entire third floor of one wing of the Goiânia General Hospital, which had been cleared in order to have all the patients in one radiologically and biologically controllable location.

As might be expected, no medical personnel at this local hospital were trained and prepared to deal with radiologically contaminated patients. The patients were therefore left unattended until the two medical specialists arrived. Matters were further compounded by a labour strike in effect at the time. The physicians and the radiation protection support staff were equipped with monitoring equipment and standard protective clothing (caps, gloves, overalls). They established a contamination control area, arranged in accordance with USNCRP Report No. 65[1]. The physicians began making physical and laboratory examinations, taking blood samples and treating symptoms.

At 18:30 on Wednesday 30 September the medical team was joined by a physician from FURNAS in Rio de Janeiro. The medical triage took 12 hours. The physicians decided to transfer six of the 11 patients to specialized facilities at the Marcilio Dias Naval Hospital in Rio de Janeiro. Their selection was based on the relative severity of the symptoms and the need for better equipment for treating the patients. The physician from FURNAS and the six patients were picked up in Goiânia on Thursday 1 October at 09:00 and were flown to Rio de Janeiro and admitted to the Marcilio Dias Naval Hospital at 12:30. Four more patients were transferred to the hospital on 3 October.

4.8. TRANSITION TO A LONGER TERM CONTROL PHASE

By Saturday 3 October the situation had been brought under control. The main concerns of the response teams then became the further treatment of the injured and improvement of the conditions at the sites of contamination. After the initial urgency, they proceeded at a more deliberate pace. Plans were made for a longer period. Further necessary surveys were made and resource needs were assessed. Procedures were written for access control; for equipment quality control; and for selection for cytogenetic and other blood tests; and specifications were set for waste containers.

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[1] UNITED STATES NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, Management of Persons Accidentally Contaminated with Radionuclides, Rep No. 65, USNCRP, Bethesda, MD (1980)

These and other subsequent actions can be considered in terms of those concerning the people affected and those to clean up the environment. These are described in Parts II and III respectively.

Descriptions of each of the main lines of activity — medical, survey and decontamination, dosimetry, waste management, the response of the public — are presented in separate sections of the report. These sections go into considerable detail so that specialists have the information necessary to draw lessons from the accident in Goiânia.

Part II

THE HUMAN CONSEQUENCES: DEALING WITH THE PEOPLE AFFECTED

5. MEDICAL RESPONSE

5.1. INTRODUCTION

The radiological accident in Goiânia had serious medical consequences and resulted in four fatalities. However, it was not unlike several previous accidents in which there were injuries among the public. It presents striking parallels to accidents in Mexico City in 1962, in Algeria in 1978, in Morocco in 1983 and in Ciudad Juárez, Mexico, in 1983: most notably, the incidence of significant whole body irradiation and the ensuing acute radiation syndrome, together with severe local radiation burns in some individuals. The accident in Ciudad Juárez resulted in external contamination of several individuals with cobalt-60; however, the levels were low, and no significant internal contamination was incurred.

One notable feature of the accident in Goiânia was the severe external and internal contamination with caesium-137 that complicated patient care and prompted the extensive use of hexacyanoferrate, $[Fe(CN)_6]^{4-}$ (as Prussian Blue, or Radiogardase^R), for the first time in the history of radiological accidents. The accident is unique in that the casualties incurred initial acute whole body external exposures followed by chronic whole body exposure at low dose rates from internally deposited caesium-137. These exposures varied depending on the amount of time spent near the source and on the amount of caesium-137 deposited internally.

The radiological aspects of the accident were further complicated by the incomplete exposure histories and the lack of information on exactly when the respective exposures began. Some external exposures were undoubtedly fractionated as a result of working and personal habits. In addition, the more seriously overexposed persons suffered acute local radiation injury to the skin from beta irradiation and to deeper lying tissue from penetrating gamma radiation. This variation in the nature of exposures (and the consequent uncertainties) complicated the interpretation of cytogenetic dose estimates that were based on dose–response curves derived from high dose rates.

Following the discovery of the accident on 28 September and its confirmation by radiological survey on 29 September (by the medical physicist W.F. and Goiás State health personnel), the CNEN emergency arrangements were put into effect. A physician, a dosimetrist and a radiation protection technologist were dispatched from Rio de Janeiro to Goiânia on the morning of 30 September. By the time this group arrived, the four main sites of contamination in the city had been brought under control, residents had been evacuated from the immediate vicinities of the contaminated sites, and a staging area for radiological monitoring and medical triage of individuals had been set up at the Olympic stadium in Goiânia. Twenty-two affected people were gathered in the stadium when the medical team arrived. These 22 persons were either occupants of the houses near to the yard where the source had been broken open or relatives or employees of the owners of the two junkyards to which pieces of the caesium-137 teletherapy unit had been taken.

Upon arriving at the Olympic stadium, the medical team learned that 11 contaminated people had already been admitted to the Hospital for Tropical Diseases and to Santa Maria Hospital in Goiânia, on the instructions of the local health authorities. These 11 people had been admitted to hospital on 28 September and were thought to be suffering from food poisoning, contact dermatitis or pemphigus, a disease of some prevalence in central Brazil. It was later learned that most of them had experienced nausea, vomiting, diarrhoea, dizziness and fatigue. All but one of the 11 had radiation induced skin injuries to different extents to hands, feet, legs or other circumscribed areas of the body (See Photographs 25, 26, 28–31.)

5.2. INITIAL RESPONSE

Upon arrival at the Olympic stadium staging area, the medical response team was briefed by local authorities. The 22 persons assembled at the stadium were radiologically monitored and all of them were found to be externally contaminated with caesium-137 Contaminated clothing was removed and all were decontaminated by taking several baths with soap and water. This proved to be 50–80% effective as determined by hand held monitors. After decontamination, interviews were conducted to determine whether the medical histories were compatible with the signs and symptoms of the acute radiation syndrome. Medical histories had been recorded and cursory medical examinations made of all 22 people by 18:00 on 30 September. By this time, two more physicians and health physics support personnel had been dispatched from Rio de Janeiro. Both physicians had undergone training in dealing with radiation casualties. One of them had completed three months of intensive study (as an IAEA fellow) in the management of radiological accidents several months before the accident in Goiânia.

The medical team considered that the most urgent task was to treat the 11 patients already at the Tropical Diseases Hospital and Santa Maria Hospital. This decision was based upon information from the hospitals' medical staff on the patients' medical status reports. On the evening of 30 September, the 11 patients were transferred from the Tropical Diseases Hospital and Santa Maria Hospital to a suitable ward at the Goiânia General Hospital.

When the medical team (three physicians and technical support personnel) arrived at the Goiânia General Hospital, they set up contamination and exposure control on the basis of a radiological survey. They formed a plan of action following guidelines in USNCRP Report No. 65[1] and applying their knowledge gained in training of how to manage radiation accidents. Patients were examined and medical histories recorded. All these patients were considered to be suffering from the acute radiation syndrome, or from minor to extensive radiation induced skin lesions, and from external and internal caesium-137 contamination. Radiological surveys over skin lesions gave dose rates as high as 15 $mSv \cdot h^{-1}$, and a survey of a six-year-old girl showed an average dose rate of 3 $mSv \cdot h^{-1}$ in skin contact.

Samples of blood, urine and faeces were obtained from each of the patients. Internal contamination with caesium-137 was confirmed by gross counting of urine and faecal samples. Skin decontamination was performed on all patients using mild soap and water, acetic acid and titanium dioxide. Decontamination was only partially successful since sweating resulted in recontamination of the skin from internally deposited caesium-137.

Early on 1 October, a decision was made to transfer (in a military aircraft) six of the 11 patients to the tertiary care centre at the Marcilio Dias Naval Hospital in Rio de Janeiro. Clinical criteria used in this decision were medical history; prodromal signs and symptoms; the time to the onset of vomiting and the number of episodes; the severity of skin lesions; the occurrence of epilation; and gross estimations of body content of radioactive caesium based on radiological survey. Blood counts were unreliable at that time. The six patients were flown to Rio de Janeiro accompanied by one of the team physicians. On 3 October, four more patients were transferred to Rio de Janeiro because of their deteriorating medical condition.

By 3 October, the full magnitude of the accident had been appreciated and the number of support personnel was significantly increased. Until the expected need for a whole body counter arose, the equipment and supplies for basic medical management were adequate. It was anticipated that stocks of Prussian Blue (Radiogardase[R]) in Brazil would be quickly depleted. Additional supplies were therefore requested from the Gesellschaft für Strahlen- und Umweltforschung (Society for Research on Radiation and the Environment) in Neuherberg, Federal Republic of Germany.

At the Goiânia General Hospital, staffing (basic medical) of the dedicated ward was complete by 7 October. The provision of medical care was not compromised during the interim period. Among the clinical laboratory staff there was some fear or concern for personal health, but this was allayed by the personal assurances and informal instruction given by the two attending physicians. The general medical community in Goiânia, however, was reluctant to help. Nevertheless, one additional physician from the hospital staff joined the medical team in Goiânia. The medical emergency response capabilities of the Goiânia General Hospital were completed in

[1] UNITED STATES NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, Management of Persons Accidentally Contaminated with Radionuclides, Rep. No. 65, USNCRP, Bethesda, MD (1980).

the first week of November when a whole body counter specially designed for measuring the high dose rates of the patients there was installed. (See Photograph 32)

In Rio de Janeiro the Marcilio Dias Naval Hospital quickly organized its radiological emergency response staff and made operational a previously designated receiving/treatment area for radiation accident casualties There was some fear of radiation exposure among the clinical laboratory staff, but they were reassured by education and by the setting up of a special dedicated laboratory near the patient treatment area

5 3 THE TREATMENT

The therapeutic procedures followed during the critical phase of the emergency response included

- managing the critical period of the acute radiation syndrome, manifested by bone marrow depression;
- treating local radiation injury;
- decorporation of caesium-137 from the body;
- general support and psychotherapy.

5.3.1. Treatment of the acute radiation syndrome

For the most severely irradiated patients, treatment was directed to the assessment and management of the haematological crisis associated with the acute radiation syndrome. Through patient interviews, the generation of haemographs and reconstruction of the accident, efforts were directed to determining the initial day of exposure, the duration of exposure, dose estimates by cytogenetic techniques, and the severity of internal contamination with caesium-137. These data were useful in predicting the degree of haematological depression and the consequent degree of susceptibility to infection. Cytogenetic techniques indicated that the radiation doses of the patients in Rio de Janeiro ranged from 1 Gy to 7 Gy These cytogenetic dose estimates, although complicated by continuous radiation from internally deposited caesium-137, were useful in prognosis and in anticipating medical management problems associated with bone marrow depression. Medical management was thus based on each patient's clinical course and not predominantly upon cytogenetic dosimetry

Cultures were obtained by standard methods from blood, skin, wounds and body orifices to identify bacterial, fungal and viral infections On the basis of the results of the cultures and the clinical courses, patients were treated with systemic or topical antibacterial, antifungal or antiviral agents.

The basic medical handling of the patients consisted of the following:

(a) Accommodation in rooms with reverse isolation.
(b) Diets without raw vegetables or uncooked food.
(c) Nail trimming and scrubbing.
(d) Local neomycin in the nasal cavities.
(e) Gut sterilization if the concentration of neutrophils was less than $1.5 \times 10^9\ L^{-1}$, with oral trimethoprim/sulphamethoxazole and nystatin.
(f) Systemic administration of antibiotics if fever exceeded 38.5°C or there were other signs of infection in a granulocytic patient (neutrophil concentration below $0.75 \times 10^9\ L^{-1}$); empirical antibiotic regimen consisted of *iv* gentamicin, cephalothin and carbenicillin, changed to cefoperazone, imipenem and/or piperacillin[2] as a result of the evolution and/or cultures; persons with persistent fever for more than 48–72 hours received amphotericin B.
(g) Administration of irradiated (25 Gy) red packed cells and platelet infusions to maintain levels of haemoglobin above $1.55\ mmol \cdot L^{-1}$ ($0.1\ kg \cdot L^{-1}$) and of platelets above $20 \times 10^9\ L^{-1}$, or whenever bleeding occurred in a patient with a platelet count below $60 \times 10^9\ L^{-1}$.
(h) Acyclovir, commencing about three weeks after radiation exposure, to prevent the activation of herpes virus.
(i) Antihelminthics, such as mebendazole and thiabendazole, according to the results of stool examinations or empirically (eosinophilia).

The clinical course and laboratory findings indicated that bone marrow transplantation was not required by any patient.

A departure from clinical practice in previous radiation accidents was the use of granulocyte macrophage colony stimulating factor (GMCSF), which was administered to eight patients in hospital in Rio de Janeiro. Four patients who received GMCSF subsequently died as a result of their radiation doses (4–6 Gy) with complications of haemorrhage and infection. The four surviving patients treated with GMCSF had the lower estimated doses (2.5–4.4 Gy) among the overexposed group. Two patients who incurred high doses (6.2 and 7.1 Gy) and exhibited severe bone marrow depression but who did not receive GMCSF survived.

5.3.2. Treatment of local radiation injuries

Radiation induced skin injury was observed in 19 of 20 hospital patients. Patients exhibited swelling, erythema, bronzing, dry desquamation and blistering while in hospital in Goiânia. Lesions were induced in hands, feet, legs, armpits and numerous small areas on the chest, abdomen, face, arms and the anteriomedial aspects of the legs. (See Photographs 25, 26, 28–31.) In the first week of October

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[2] Two patients received vancomycin and one amikacin and cefoxitin.

1987 the majority of skin lesions ruptured and secreted fluid. Infection of the lesions was not a major problem.

By 12 October the skin lesions exhibited drying, sloughing of necrotic skin and re-epithelization, confirming the occurrence of superficial injury by beta irradiation. (See Photograph 31.) This course was followed about three weeks later by deep lesions in ten of the 20 patients, indicative of gamma insult to deeper lying tissues. (See Photograph 26.)

All skin lesions were contaminated with caesium-137; dose rates of up to 15 $mSv \cdot h^{-1}$ were measured close to some lesions. Contamination levels were significantly reduced through sloughing of necrotic skin and by further attempts to decontaminate In both Rio de Janeiro and Goiânia, localized burns were treated by topical applications of antiseptic and analgesic solutions, antibiotic creams, neomycin, juice of the aloe vera (thromboxane inhibitor) and alantoin (an anti-inflammatory agent) For patients in Goiânia, two additional therapeutic approaches were adopted: injections of antiplatelet activating factor to lessen capillary injury and injections of vasodilators such as Trental^R and Iridux^R. The clinical course was approximately the same in both hospitals.

Blood pool imaging was employed at the Marcilio Dias Naval Hospital. This was useful in determining the demarcation between injured and normal arterioles. It also helped in the case in which amputation was necessitated on 15 October. Within 48 hours the patient's clinical course was improving and the patient survived the acute radiation syndrome Later a further five patients required surgical intervention, namely four debridements and one skin graft.

5.3.3. Acceleration of decorporation

The Goiânia accident resulted in the highest levels of caesium-137 contamination clinically recorded. External contamination was observed in 249 persons out of some 112 000 people monitored in Goiânia. Decontamination to remove externally deposited caesium-137 was successful in those individuals exhibiting little or no internal contamination. Internal contamination in other patients resulted in repeated recontamination of the skin due to sweating. The internally deposited caesium-137 presented a very different management problem, from both the medical and the health physics points of view. (Levels of internal contamination are discussed later.) The highest individual dose from internally deposited caesium-137 was being accumulated at an initial rate of 0.25 $Gy \cdot d^{-1}$

In the Goiânia accident, Prussian Blue (Radiogardase^R) was administered to 46 persons. The doses of Prussian Blue varied from 1 $g \cdot d^{-1}$ to 10 $g \cdot d^{-1}$. The initial dose for adults was 3 $g \cdot d^{-1}$ in three equal doses. For those patients who had intakes of more than five times the annual limit of intake for caesium-137, the initial dose varied from 4 $g \cdot d^{-1}$ to 6 $g \cdot d^{-1}$, taken in four to six equal doses. The dose administered to 13 children was initially 1.0–1.5 $g \cdot d^{-1}$

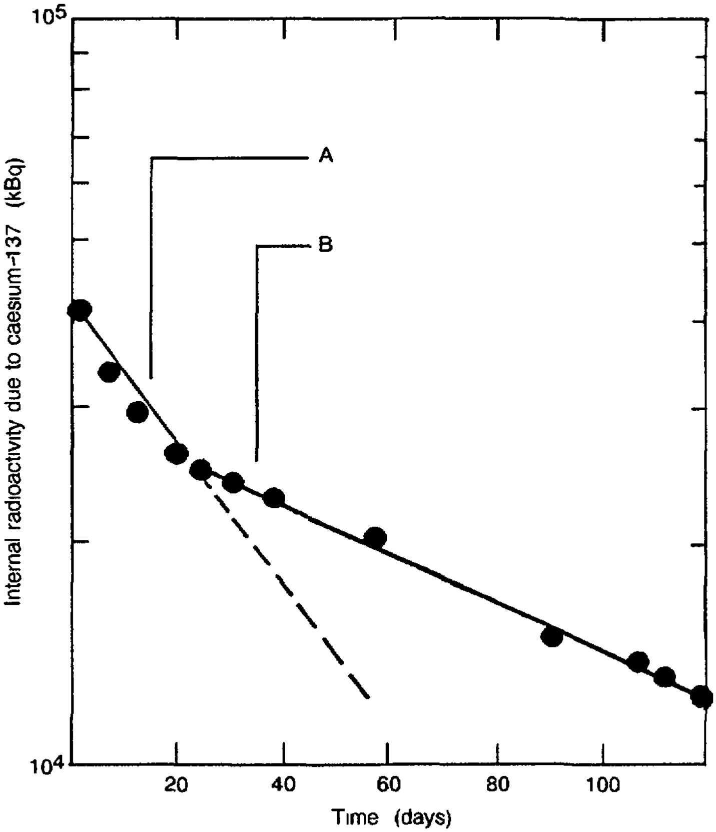

FIG. 11. The effect of the administration of Prussian Blue: plot of content of radioactive material in the body versus time. A: administration of 10 g of Prussian Blue per day. B: after cessation of administration of Prussian Blue.

From the results of the radiochemical analyses it was observed that increasing the dose of Prussian Blue resulted in higher radioactivities of faecal samples. From whole body measurements it was observed that an increase in the dose of Prussian Blue expedited the decorporation of caesium-137. No dose–response curve is yet available, but Fig. 11 illustrates this effect for one patient. Following these studies, the most seriously contaminated adults and adolescents were administered 10 $g \cdot d^{-1}$ in eight to ten equal doses and children were given 3 $g \cdot d^{-1}$ in three equal doses.

More detailed studies of the effect of the administration of Prussian Blue on the biological half-life of caesium are being conducted. Radiochemical and in vivo analyses are being conducted periodically on patients with internal contamination.

Since there were no data in the literature relating to the administration of such high doses of Prussian Blue, the medical teams took special care at all times to ensure the early detection of any side-effects. The serum levels of potassium were evaluated routinely twice a week and whenever there was a clinical indication to do so No significant variations in the serum levels of potassium were found One apparent side-effect was constipation in a very small number of patients; however, these patients responded well to diet control and laxatives

Diuretics were used in patients having elevated rates of internal contamination and no clinical contra-indication to such treatment. A total of 17 patients received diuretics, six of these patients also needed diuretics because of hypertension. The diuretics administered were furosemide in doses of 40 $mg \cdot d^{-1}$ or hydrochlorothiazide in doses of 50–100 $mg \cdot d^{-1}$, both administered orally However, data from urinary analysis demonstrated the ineffectiveness of diuretics as a means of decorporating caesium-137, and their administration was discontinued

Water overloads consisting of 3 L of potassium rich liquid a day were given to some patients who had high levels of internal contamination and who were receiving Prussian Blue and diuretics

The high levels of internally deposited caesium-137 presented some special medical problems in that all body fluids and excreta had to be collected and saved for analysis Strict control measures for contamination and exposure had to be taken at all times over the three months for which the patients were in hospital in order that the patients did not present a significant health risk to medical personnel Accumulated doses to medical staff were below 5 mSv over the duration of the patients' hospital care.

5.3.4. General support and psychological care

The provisions described were intended to combat diseases identified during the hospital treatment, such as arterial hypertension, heart failure and arrhythmia or urinary infections Special emphasis was given to supportive psychological therapy, not only to minimize the psychological after-effects of the prolonged confinement and the stress sustained as a result of the accident itself, but also to ensure effective psychiatric treatment for some patients previously treated for psychiatric disorders.

5 4 POST-MORTEM STUDIES. AUTOPSIES

Autopsies were carried out on the four patients who died by the forensic pathologists with support from the medical team and health physics support group of the Marcilio Dias Naval Hospital Specimens were obtained for bacteriological and histopathological studies

5.4.1. Case 1: M.F.1: 38-year-old woman; died 23 October 1987

The external examination showed: Orbital haematomas; severe alopecia; mucosal pallor; and haemorrhages in the neck, thorax, conjunctivae, arms, legs and skin.

The internal examination showed: Diffuse haemorrhages in all organs, most severe in the lungs and heart. The blood was fluid and dark. Haemorrhagic plaques were found throughout the skeletal muscles. There was cerebral oedema. The leptomeninges showed multiple foci of haemorrhage. The cerebrospinal fluid was xanthochromic. Multiple areas of haemorrhage were present in the serosae of intestines and stomach. The lumina of these organs contained large amounts of haemorrhagic faecal material. There were diffuse oedema and petechiae throughout the intestinal and gastric mucosae. The liver was enlarged and soft.

Gross impression: Widely disseminated haemorrhagic diathesis (the acute radiation syndrome). Cerebral oedema and petechial haemorrhages (possibly secondary to septic toxaemia).

5.4.2. Case 2: L.F.2: 6-year-old girl; died 23 October 1987

The external examination showed: Severe oedema in the face, neck and superior third of the thorax; mucosal pallor. Multiple spots of alopecia. Multiple areas of petechiae throughout the skin, mucosae and conjunctivae. Multiple areas of epidermal dry desquamation with areas of hyperpigmentation. Areas of dermal ulceration, especially in the abdomen, periumbilical area and legs. Large area of necrosis in the palm of the left hand, also affecting the fingers. There were dark spots on the soles of the feet.

The internal examination showed: Multiple areas of haemorrhage in plaques and spots through the entire skeletal musculature. The internal organs were heavily congested with haemorrhagic areas. The lungs and heart were the organs most affected by the diffuse haemorrhage. The lumina of the stomach and intestines contained haemorrhagic material with involvement of the mucosae. The renal pelves were haemorrhagic. Ecchymoses and petechial haemorrhages were also found in the serosae and in the cerebral and medullary leptomeninges. The spinal fluid was clear.

Gross impression: Disseminated haemorrhagic diathesis (secondary to the acute radiation syndrome). Haemorrhagic pneumonia and haemorrhagic nephritis, myocardial myomalacia.

5.4.3. Case 3: I.S.: 22-year-old man; died 27 October 1987

The external examination showed: Mucosal pallor Haemorrhages in the conjunctivae and mucosae, as well as petechiae in the skin. Multiple depigmented dermal areas of desquamation Foci of necrosis and localized inflammation. These lesions were more severe on the internal surfaces of the thighs, scrotum and penis, and in the gluteal and inguinal regions. There were areas of epidermal desquamation and necrosis on the palms of the hands

The internal examination showed. Haemorrhagic ecchymoses and petechiae of the serosae, most severe in the pericardium The lungs were firm, haemorrhagic and poorly aerated Their cut surface showed slightly elevated yellowish areas. There were fibrinous adhesions in the interlobular spaces. The right ventricle of the heart was enlarged Haemorrhagic petechiae and ecchymoses were found in the interventricular and subendocardial myocardium. The gastric and intestinal mucosae showed petechial haemorrhages. There was generalized hyperplasia of the lymph nodes There was hyperaemia of the leptomeninges.

Gross impression· Bilateral haemorrhagic bronchopneumonia (secondary to total body irradiation) Fibrous pleuritis, right ventricular hypertrophy. Lymph node hyperplasia

5.4.4. Case 4: A.S.: 18-year-old man; died 28 October 1987

The external examination showed: Diffuse mucosal pallor Generalized and severe alopecia. Multiple areas of hyperchromasia in the epidermis with desquamating lesions, but with no inflammatory foci. There was an area of desquamation with necrosis in the palm of the left hand.

The internal examination showed Diffuse congestion of all organs. The lungs were enlarged, showing haemorrhagic areas, particularly in the inferior lobes, where the cut surfaces had small elevated areas The heart was enlarged, mainly owing to the enlargement of the right ventricle. Haemorrhagic subendocardial and subpericardial petechiae were found The stomach and intestines showed mucosal petechial haemorrhages The skeletal muscles contained several haemorrhagic ecchymoses but less severe than those in the first two cases. The liver, spleen, kidneys, pancreas and adrenal glands showed petechial haemorrhages.

Gross impression. Bilateral haemorrhagic bronchopneumonia. Generalized systemic and cardiac haemorrhagic diathesis (secondary to the acute radiation syndrome) Right ventricular hypertrophy.

6. DOSIMETRY

From the initial discovery of the accident in Goiânia it was evident that many individuals had been irradiated and that this had been by various mixes of external beam irradiation, skin contamination and internal contamination. Various dosimetry techniques were used to provide inputs to the initial screening of potentially exposed persons, the subsequent medical management of patients, and a general scientific assessment of the accident. The principal techniques used were as follows:

— Internal dosimetry: bioassay and whole body monitoring;
— Cytogenetics: estimation of doses by chromosomal aberration analysis;
— External dosimetry: dose estimates from reconstructions and on the basis of radiation effects.

These techniques, the facilities necessary, the difficulties encountered and the results obtained are described in the following sections.

6.1. INTERNAL DOSIMETRY

6.1.1. Methods

The potential pathways for internal contamination were by inhalation, by ingestion and through wounds. Inhalation was not considered to be a major route, and air monitoring data and other data subsequently bore this out. The first step was to identify the people who had internal contamination, and the immediate action concentrated on estimating their intakes by monitoring urine and faecal samples. At the levels of radioactivity prevailing, samples had to be collected very carefully so as to prevent cross-contamination. The samples were collected in Goiânia and were sent by air to Rio de Janeiro to be analysed. Many of the initial samples were so radioactive that a portable dose rate meter gave high readings. This simple means of monitoring was therefore used both to screen patients in hospital and to distinguish samples that required special handling. For the bioassay work, caesium-137 standards for urine and faeces were prepared. Later a phantom for disposable nappies (diapers) was found to be necessary because a number of babies were found to be internally contaminated with caesium-137.

TABLE III VARIATION IN THE 70 YEAR COMMITTED DOSE FROM A SINGLE UPTAKE OF CAESIUM-137 WITH A UNIT AMOUNT OF RADIOACTIVITY, WITHOUT ADMINISTRATION OF PRUSSIAN BLUE

Biotype	Percentage remaining after 15 days	Committed dose ($Gy\ Bq^{-1}$)
Newborn	66.7	3.85×10^{-8}
One year old	44.5	7.82×10^{-9}
Five years old	54.7	7.13×10^{-9}
Ten years old	61.1	7.22×10^{-9}
15 years old	74.5	9.76×10^{-9}
Adult man	82.1	9.94×10^{-9}
Adult woman	82.1	8.22×10^{-9}

Since people of a broad range of ages had been contaminated, it was considered necessary to use age specific modelling to provide the physicians with relevant data, such as caesium intakes, excretion rates and the committed dose profiles (the doses received over different time periods). An age specific model based on reports from Oak Ridge National Laboratory[3] was used for this purpose. These models were also useful subsequently in assessing the effectiveness of treating internal contamination with Prussian Blue. Models were produced for newborn, one-year-old, five-year-old, ten-year-old, 15-year-old and adult biotypes. The age specific models proved useful. Table III gives an indication of variations with age in the committed dose per unit uptake.

When individuals were screened, it was necessary to advise physicians on the effectiveness of measures to remove caesium-137 from the body, particularly on the effect of the administration of Prussian Blue. Caesium nuclides would normally be expected to be eliminated from the body mainly by the excretion of urine (80% in urine and 20% in faeces). The effect of Prussian Blue is to increase the rate of faecal excretion. Faecal and urine samples were collected daily from the internally contaminated patients and the in-faeces to in-urine ratios for the excretion of caesium-137 were determined every day. It was immediately apparent that in most cases the effect

[3] OAK RIDGE NATIONAL LABORATORY, Estimating Dose Rates to Organs as a Function of Age following Internal Exposure to Radionuclides, ORNL-TM-8265, Oak Ridge, TN (1984), also ORNL-TM-8385, Oak Ridge, TN

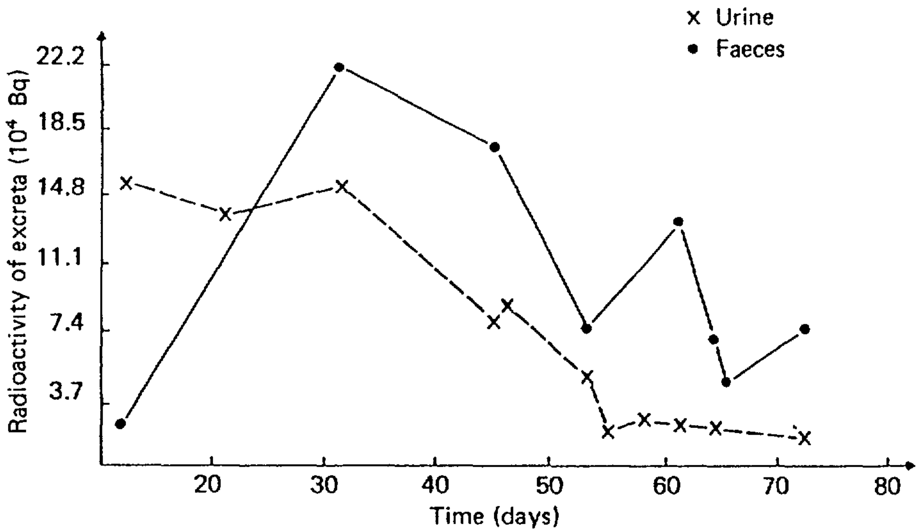

FIG 12 A typical example of the effect of the administration of Prussian Blue on the radioactivity of a patient's excreta

of Prussian Blue was to increase significantly the rate of excretion in faeces, to the extent that this became the dominant mode. In some cases the ratio was even reversed; that is, the in-faeces to in-urine ratio rose to 4:1. In general, the effect was a function of the dose of Prussian Blue administered and of the patient's metabolism. The relation between the amount of Prussian Blue administered to patients and the rate of elimination of caesium from the body in faeces, as influenced by the amount of caesium internally deposited and by metabolic factors, is still under study. Figure 12 shows a typical graph of the rate of elimination of caesium in faeces and in urine.

The next step was to evaluate quantitatively the efficacy of Prussian Blue in reducing the biological half-life of caesium in the body. For this purpose, a field whole body counter was set up in early November in Goiânia. Those people who had been internally contaminated were periodically monitored, at a frequency dependent on each person's caesium intake and treatment for decontamination. Three patients from the Marcilio Dias Naval Hospital in Rio de Janeiro were measured at IRD's whole body monitoring facility before returning to Goiânia, and the results were in accordance with those obtained at the improvised facility at Goiânia. The results of the various measurements are described in Section 6.1.2.

After the accident occurred in Goiânia the laboratory in Rio de Janeiro was fully devoted to it. The facilities had originally been designed for the routine analysis of low level excreta samples, and the high radioactivity of the samples taken from patients after the accident caused some difficulties. This was particularly the case in the early stages after the accident, when samples were also arriving in non-standard packages which might have been contaminated.

The laboratory had two entrances, one from the interior of the building and one directly from the exterior. This proved very helpful, since it was possible to set up standard radiological protection procedures for personnel at the entrance inside the building, and flow controls and contamination controls on samples at the exterior door.

An adjacent room which was also accessible directly from the exterior was converted to a storage area for the boxes of radioactive samples that were arriving, and awaiting analysis or disposal. The laboratory floor was covered with plastic sheeting to facilitate decontamination. During the first four weeks after the accident, nine people were engaged in performing laboratory measurements and two people in the dose assessment group

By four weeks after the accident the needs had changed, and a field whole body counter was set up at the General Hospital in Goiânia. The whole body counter was installed in the centre of a room measuring 4.0 m × 3.5 m, with seven layers of 2 mm thick lead sheet on the floor. After some trials, it proved best to use an NaI(Tl) detector 200 mm in diameter and 100 mm thick, collimated by a lead shield 50 mm thick installed about 2.2 m from the ground. A fibre glass leisure chair was placed with its centre about 2 m below the centre of the detector.

Short counting times (e.g. 2 min) were indicated by the levels of radioactivity, by the need for a steady throughput of patients and by the need for decontamination measures. The detection level for a counting time of 2 min was 9.1 kBq (247 nCi) at a 95% confidence level. Normal procedures for in vivo counting were followed, such as changing of patients' clothing and recording of heights and weights.

This system was operated until 14 January 1988, when the monitoring facility was transferred to Rua 57 (57th Street) near the initial foci of the accident. These sites had by then been decontaminated and CNEN had installed a laboratory there. The room in which the whole body counter was set up was shielded with lead sheets 2 mm thick on the walls and a lead pad 130 mm thick on the floor. The midpoint of the detector was placed 2.2 m above the floor and 2 m above the same leisure chair used for counting. (See Photograph 32.) The radioactivity detection threshold for a 2 min counting time was 7.3 kBq (197 nCi).

By April 1988 about 600 individuals had been measured at the Goiânia whole body monitoring facility. The in vivo monitoring required two to three people to operate the system and to compute results in situ. In January a laboratory for measuring levels of radioactivity in excreta, with three further staff, was added to the field whole body monitoring facility at Rua 57.

6.1.2. General results

During the first four weeks after the accident, all information on internal contamination derived from measurements on excreta made in Rio de Janeiro. These

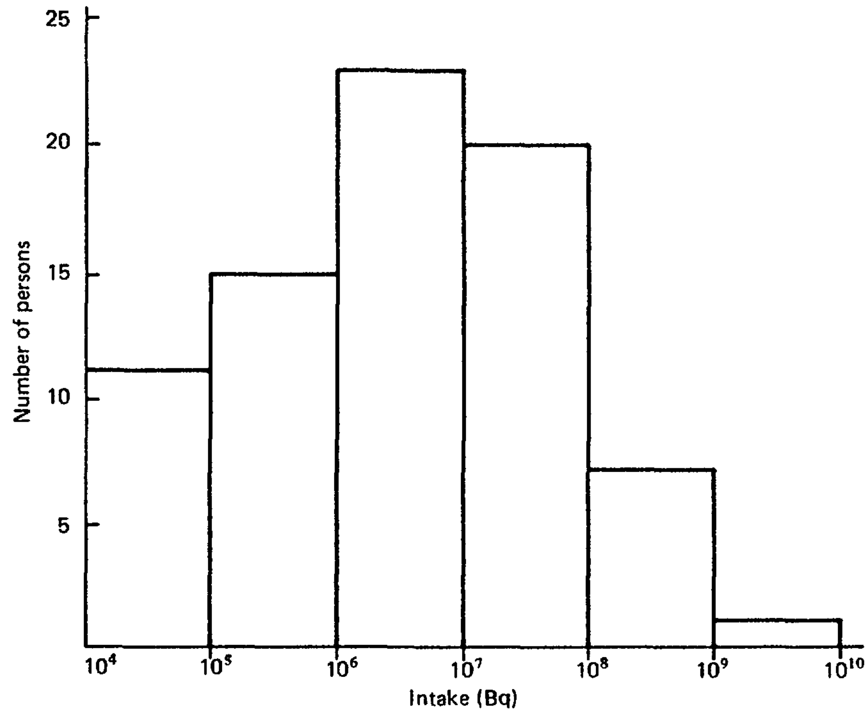

FIG 13. Histogram of the frequency distribution of estimated radioactivity of intakes of persons contaminated. number of individuals versus radioactivity in becquerels

were considered to be the most meaningful measurements that could be made at that time. From these measurements it was possible to identify those people with significant contamination and those without, and it was possible to estimate dose commitments. More than 4000 urine and faecal samples from a total of 80 persons were analysed in the period from October 1987 to January 1988. Figure 13 is a histogram showing the frequency distribution of the intakes of caesium-137. The internal 70 year dose commitments which would have been incurred if no decontamination measures had been taken are presented in Fig. 14. The six-year-old girl who died on 23 October, L.F.2, had an intake of caesium-137 of 1.0 GBq (27 mCi), the greatest recorded, and had an estimated internal dose of about 4 Gy at the time of death.

In order to assess the efficacy of Prussian Blue in promoting the decontamination process, theoretical contents of radioactive material in the body were back-calculated from the urinary excretion data and compared with data obtained from the whole body monitoring. A statistical test showed no significant differences between

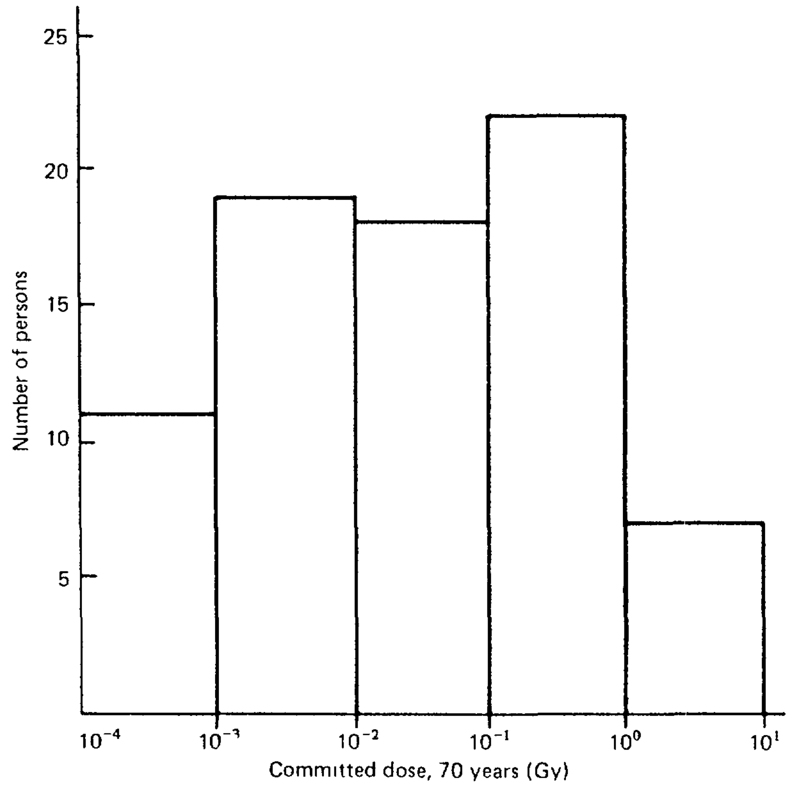

FIG 14 Histogram of the frequency distribution of projected committed doses without decontamination therapies of persons contaminated number of individuals versus 70 year committed dose in grays

the in-body radioactivities determined from the in vivo monitoring results and those estimated from the urinary excretion data This indicates the following

(a) that the declining radioactivity levels in urine shown by the excretion data reflected a real decrease in in-body radioactivity;

(b) that the modelling was appropriate and validated for this case, and

(c) that Prussian Blue was efficacious in promoting the elimination of caesium-137 from the body provided that the dosage was large enough (more than $3\ g \cdot d^{-1}$).

A detailed analysis of the effects of the different dosages of Prussian Blue administered on the biological half-life of caesium-137 is still being conducted However, the initial results, although not refined, do show that the rate of elimination of caesium-137 is increased by the drug. This can be seen, for example, in

Fig. 11 which shows the content of radioactive material in the body as a function of time for an adult who voluntarily stopped taking the drug. After administration of the medication had been stopped, the biological half-life determined from measurements made over a period of 120 days was about 100 days, which is the expected biological half-life of caesium-137 in adults. This biological half-life was longer than that determined while Prussian Blue was being administered. The next stage in the analysis of the results will be to make a full assessment of the reduction effected in the dose commitments of the 62 patients to whom Prussian Blue was administered.

It was concluded that a number of things were necessary to deal with the accident, namely:

(a) Sufficient staff with the necessary training and expertise to be able to adapt standard procedures. In this respect the IAEA funded training programme was particularly helpful;
(b) A laboratory for in vitro measurements with two separate entrances proved very helpful for protecting the health of personnel and for minimizing the potential for cross-contamination of samples;
(c) An in vivo monitoring facility with spare detectors and electronic attachments that could be moved to Goiânia to set up the improvised monitoring facility there;
(d) Models that relate bioassay data to intakes, in-body radioactivity and dose commitments, and that are applicable for different radionuclides and age groups.

Follow-up studies on the persons who were contaminated are being performed. These are initially aimed at determining the patients' real committed doses, taking into account the effects of the doses of Prussian Blue administered. Also, as previously mentioned, a continuing programme on bioassay and whole body monitoring is in progress and will contribute to the further study of the effects of Prussian Blue. However, one confusing factor will be the variation in dosage during each patient's treatment. Periodic in vivo measurements on blood samples, wounds and organs are being performed for 20 people to look at possibly inhomogeneous distributions of caesium and its retention in the body tissues. A special case of a woman with a newborn baby is under study in order to evaluate mechanisms of retention and transfer by nursing.

Guidelines were needed for the discharge of patients from hospitals so that they could safely return to their communities. The radiological protection guidelines followed for the discharge of patients from hospital are listed in Annex II. Because it was apparent from the patients' time in hospital that they did not always comply with requests, such as to retain all their excreta in bottles, these guidelines were pessimistically drafted.

6.2 DOSE ASSESSMENT BY CYTOGENETIC ANALYSIS

Blood samples were collected from all people identified by the medical team as potentially having incurred doses higher than 0.1 Gy (110 people in all), and were sent to the cytogenetic facility in Rio de Janeiro for doses to be estimated. The laboratory was set up in 1983. Standard procedures and methods are used as specified in IAEA Technical Report No. 260[4]. During the emergency period of the accident, additional supplies of essential chemicals (unavailable in Brazil) for culturing the blood samples were sent from the Laboratory of Radiation Genetics and Chemical Mutagenesis of the State University of Leiden in the Netherlands. Other routine laboratory supplies were available at the laboratory.

The first blood samples were received on 2 October, and more than 25 blood samples were received for analysis during the first week. The first samples analysed were those from the ten highly exposed patients who had been admitted to the Marcilio Dias Naval Hospital in Rio de Janeiro Whole blood samples were set up and after 48 hours the lymphocytes were harvested and processed for chromosomal analysis. In this initial phase, 100 cells were analysed in each case to make a preliminary dose assessment. Chromosomal type aberrations, namely dicentric and centric ring chromosomes and acentric fragments, were scored. Since no calibration curve for caesium-137 was available, a calibration curve generated for cobalt-60 gamma rays at a dose rate of 0.12 $Gy \cdot min^{-1}$ was used for the dose estimate.

The first results were made available three days after receiving the blood samples. For highly exposed individuals, an analysis of 100 cells was sufficient. However, for lower exposures (as evidenced by the lower frequency of aberrations) 200 to 300 cells were scored. The speedy communication of results to the physicians was useful to them in treating the patients. The distribution of doses estimated by cytogenetic analysis is presented in Fig. 15. This shows that estimated doses exceeded 1.0 Gy for 21 people and exceeded 4.0 Gy for 8 people No estimated dose exceeded 7.0 Gy.

Where the whole body exposure had been uniform the incidence of aberrations among lymphocytes followed a Poisson distribution. Deviation from a Poisson distribution (over-dispersion) could indicate a non-uniform (partial body) exposure. A preliminary analysis of the individuals with estimated doses of 0.5 Gy or more indicated that six of them had undergone non-uniform exposure. Their whole body dose estimates were 0.5 Gy, 0.6 Gy, 0.7 Gy, 1.3 Gy, 2.7 Gy and 4.5 Gy. Although several of the other individuals whose estimated doses were high may have undergone non-uniform exposure (with different parts of the body receiving different doses), the resolution of the Poisson analysis is not sensitive enough to discern this.

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[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Biological Dosimetry· Chromosomal Aberration Analysis for Dose Assessment, Technical Reports Series No. 260, IAEA, Vienna (1986)

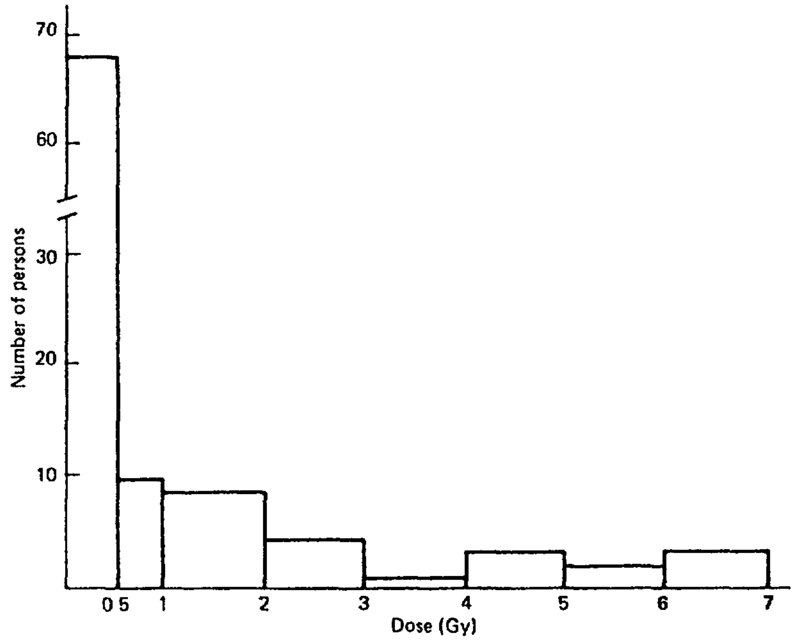

FIG. 15. Histogram of the frequency distribution of cytogenetic dose estimates of persons contaminated: number of individuals versus dose in grays.

Blood samples were also sent to several countries for cytogenetic analysis. The dose estimates derived were lower than those previously estimated. This discrepancy was not surprising, as factors such as delayed initiation of lymphocyte cultures (i.e. interphase death of highly exposed cells), differences in scoring criteria and the use of different calibration curves (acute or chronic) can influence the estimation of doses. It is concluded that cytogenetic techniques were most useful for estimating the radiation doses incurred.

Six exposed individuals have been followed up, with regard to the frequencies of incidence of aberrations in lymphocytes at different times after the accident. Three main patterns were found, namely:

(a) in two cases the frequencies of incidence of aberrations remained constant up to one month after the accident and declined to about 30% of the initial frequency three months later;

(b) in two cases a gradual decrease of about 20% every three months was found; and

(c) *in two of the cases of highest internal contamination there were increases in the frequencies of incidence of aberrations (by 50% and 100%) over a three month period.*

The follow-up studies will be continued for another five years to assess the frequencies of incidence of both stable (translocations) and unstable (dicentric and centric rings) aberrations in 15 selected individuals.

6.3 EXTERNAL DOSIMETRY

In the immediate aftermath of a radiological accident, dose estimates based on ambient dose rates and reconstruction of the sequence of events can often provide a useful input to the initial screening of patients. As soon as the accident in Goiânia was discovered, it was clear that making dose estimates for the casualties would be very difficult because of the complex mix of contamination and external irradiation, the latter having complicated exposure geometries with mostly unknown time factors. However, some gross assessments were made for screening purposes, together with more detailed dose assessments for four more straightforward cases. These were dose estimates for the two persons (G.S. and M.F.1) who took the remnants of the source assembly by bus to the Vigilância Sanitária; the dose to Dr. P.M at the Vigilância Sanitária; and the external dose to one patient, E.F , who carried a fragment of the source in his trouser pocket. Even these dose estimates were qualified by significant uncertainties.

Subsequently, further attempts were made to utilize the documented dose rate surveys and occupancy factors on the basis of more detailed information from the patients. Because of the difficulties in reconstructing the various scenarios, these assessments are not yet complete. In parallel to this, several projects are being carried out concerning some of the persons exposed, for whom it may be possible to use more sophisticated techniques to quantify doses. For instance, an electron spin resonance technique is being used for dosimetry on bones and teeth, and thermoluminescent dosimetry is being used for relevant items that would be indicative of the doses incurred

Part III

THE ENVIRONMENTAL CONTAMINATION: ASSESSMENT AND REMEDIAL ACTIONS

7. INTRODUCTION AND ACCOUNT OF ACTIONS TAKEN

8. ENVIRONMENTAL ASSESSMENTS

9. DECONTAMINATION

10. WASTE DISPOSAL

7. INTRODUCTION AND ACCOUNT OF ACTIONS TAKEN

7.1. INTRODUCTION

In preparing plans for radiological emergency preparedness, and indeed in describing radiological accidents that have occurred, it is useful to consider an accident in phases. For potential nuclear power accidents, significant effort has been put into this preparation.[5]

Radiological accidents not related to nuclear power are usually many orders of magnitude smaller in scale than potential nuclear power accidents, and the planning and potential phasing tend to be somewhat less sophisticated. Indeed, for most such accidents the action to be taken can be roughly divided into two time periods or phases:

(a) The *initial phase,* when urgent action is required
  (i) to identify potential sources of acute exposure and
  (ii) to bring exposure under control.

(b) The *recovery phase,* when urgent action is no longer required and the objective is to restore the situation to normal.

However, as the scale and complexity of the accident increase there will tend to be a blurring of the distinction between phases and the emergence of subphases that might have different durations for the different facets of the accident.

Section 7 gives an overview of the physical response to the accident in Goiânia that covers a time period from its discovery on 28 September 1987 through to March 1988. Specific aspects of the physical response work, such as environmental assessments, decontamination and waste disposal, are considered in more detail in Sections 8–10. Later in Section 7 the subject of the phase descriptions that might be appropriate for the accident in Goiânia are considered.

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[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Public in the Event of Major Radiation Accidents: Principles for Planning, Publication 40, Pergamon Press, Oxford and New York (1984);
INTERNATIONAL ATOMIC ENERGY AGENCY, Principles for Establishing Intervention Levels for the Protection of the Public in the Event of a Nuclear Accident or Radiological Emergency, Safety Series No. 72, IAEA, Vienna (1985).

7.2. OVERVIEW

The main foci of contamination in the accident were the yards where the source assembly was broken out of its shielding and where the source capsule was ruptured, and the residences of the people most affected. These were mainly within an area of about 1 km^2 in the Aeroporto, Central and Ferroviarios districts of Goiânia although there were some areas of slight contamination elsewhere. It took about 11 weeks of intensive work to survey and decontaminate the highly contaminated sites in this area and a further three months to deal with the residual low levels of contamination.

In the initial phase of the response the primary objectives had been

(a) to identify the main sites of contamination,
(b) to evacuate residences where levels of radioactivity exceeded the intervention levels adopted;
(c) to establish health physics controls around these areas, preventing access where necessary;
(d) to identify persons who had incurred significant doses or were contaminated.

In the main these objectives had been achieved by Saturday 3 October, with seven main foci of contamination (see Fig. 16) having been identified. In retrospect, this could be considered as the end of the urgent initial phase of the response in that the major sources of hazard were under control. However, as will be seen later, it was still possible to discover other less severely contaminated areas, and to have to set up controls

The week from 3 to 10 October might be described as a period of retrenchment and development of a general programme for the recovery phase. This included assessing the resources needed, in terms of personnel, hardware and disposable items required. The difficulties in assembling all the necessary items some 1000 km away from the major centres of radiological expertise were considerable. Here the Administrative and Logistical Support Group, GALA, in the Angra Emergency Plan proved useful, particularly for its contacts with the Brazilian Air Force for transport purposes. While GALA formed the basis for the logistical support, experience from the accident demonstrated the need for improvisation and for there to be a managerial authority available to obviate bureaucracy.

Although some remedial actions had been taken during the initial phase, such as concreting over the source remnants in the courtyard of the Vigilância Sanitária, it had been decided very early on that no major effort at decontamination would be made until comprehensive surveys had been carried out and a waste repository site was being prepared. Before this, written procedures, action criteria and quality control procedures were prepared The general survey programme had a number of elements. Firstly, there was the need to ensure that no significant areas of contamination had been missed. Two principal monitoring techniques were used:

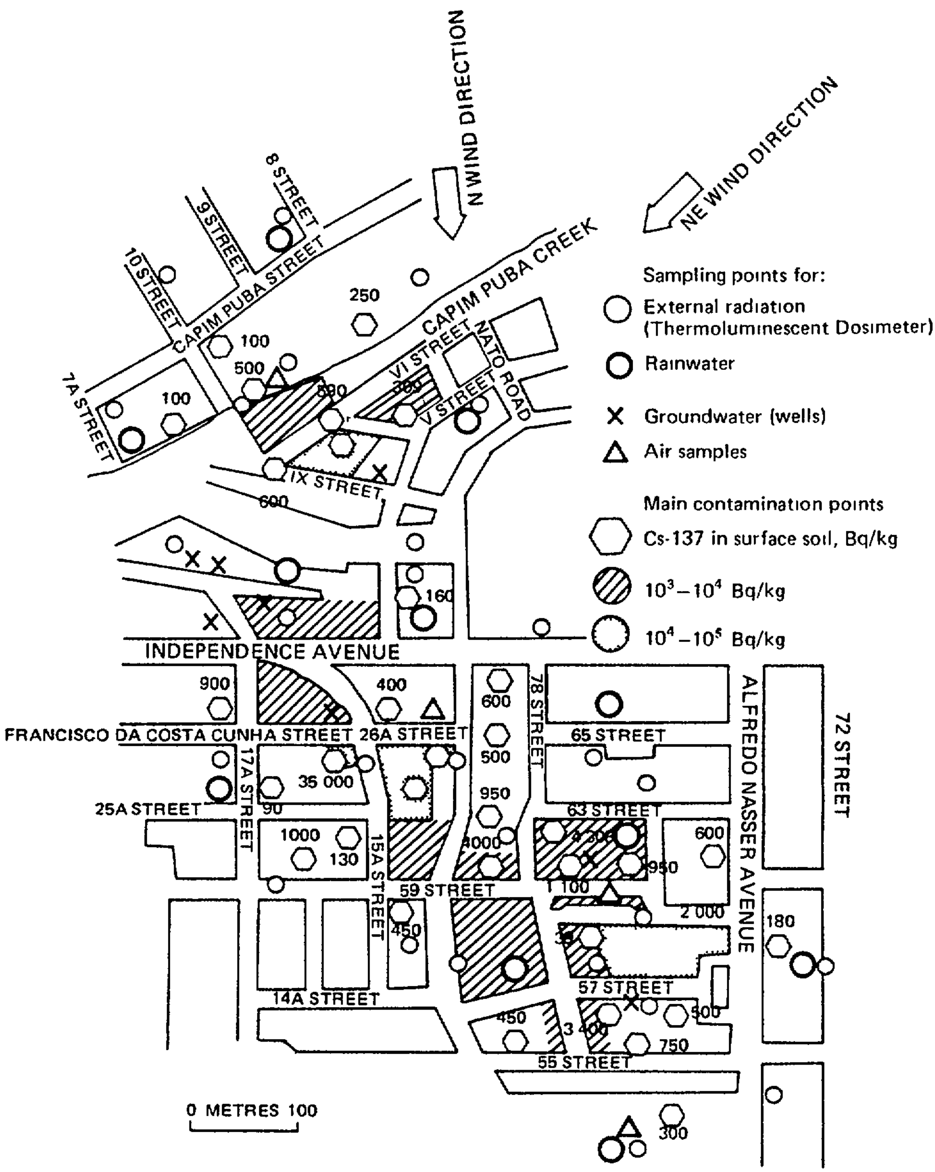

FIG 16. Plan of the Aeroporto section of Goiânia showing the locations of the principal sites of contamination and the sampling points.

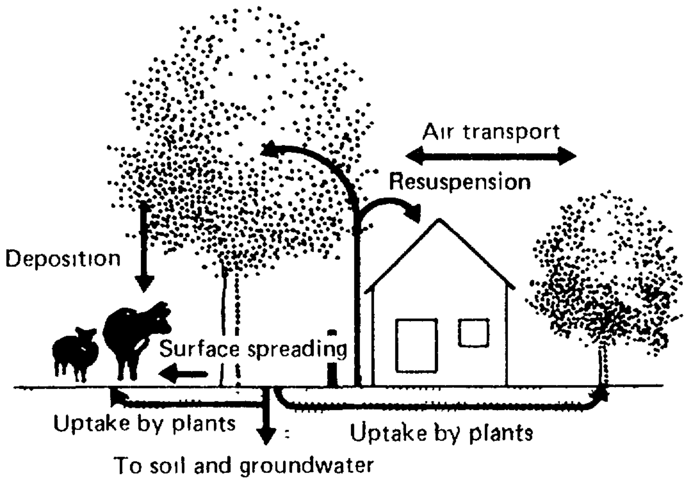

FIG 17 Contamination pathways for caesium.

(a) An aerial survey of the city was carried out on 7 and 8 October using detectors mounted in a helicopter. This was an adaptation of an established airborne geophysical survey technique.

(b) Initial surveys of the road network were carried out with the instruments used in the helicopter now installed in a car. At the same time another car with a 2 in × 2 in NaI(Tl) crystal also surveyed different areas of the city in search of possible new foci of contamination. More precise measurements were carried out later with detectors mounted in the back of an estate car (station wagon). (See Photograph 6.)

To complement these techniques, the patients in hospital and the inhabitants of contaminated residences were asked about visitors they may have had and about their own movements during the relevant period. This indicated the potential transport routes for contamination, and indeed some 42 other less contaminated sites, both in and outside the city, were found. The importance of this questioning of the people affected should not be underestimated, as it directs the monitoring resources and makes the most effective use of them. A significant amount of monitoring on foot using hand held monitors was necessary adequately to survey public places and residences, and items such as cars. Many other items were monitored, including, largely to reassure the public, banknotes.

During the initial phase action had also been taken to start a programme of monitoring to determine whether radioactive contamination was being transported via various water borne routes, but particularly to ensure that no significant amounts were entering water supplies, however unlikely such an eventuality. In October the sampling network was not systematic but responded to requests from the local authorities and allegations from the general population. A sampling network was later planned and set up with the aim of evaluating all the environmental pathways. (Caesium contamination pathways are shown in Fig. 17.)

As a result of these surveys and environmental assessments, various remedial actions such as chemical decontamination, removal of topsoil and the collection of contaminated clothes and home grown produce were necessary. At an early stage it became evident that large volumes of radioactive waste were going to be generated, and by 3 October plans for dealing with this were under consideration. The assemblage of suitable receptacles was evidently going to be difficult logistically. Their specifications depended to some extent on the disposal site, the means of transport and the regulatory requirements. As might be expected, the incident engendered much adverse public reaction to anything to do with radiation, and there was therefore a major political element to, and a delay in, the selection of a disposal site. Any site in Goiânia was ruled out. On 16 October a site 20 km out of the city was chosen but was stated to be only a temporary disposal site.

The decision on the location of the waste storage site, its planning and construction took more time than had been expected. Only by mid-November did it become possible to start major decontamination work. In the interim, activities were generally restricted to preparation and to preventing the situation from deteriorating. The preparation included:

(a) the design and construction of waste containers;
(b) the assemblage of the heavy machinery necessary for major decontamination, such as excavators and back- and front-loaders;
(c) the updating of written operational procedures;
(d) the testing of various decontamination techniques;
(e) the preparation of a work timetable.

Some actual decontamination was carried out but this was mainly away from the principal foci and was concentrated on decontaminating the insides of evacuated houses.

The lack of a repository site and an accumulation of logistical and political problems caused some loss of momentum. The programme was given impetus anew by the following actions:

(a) the President of CNEN decided to take the lead himself in Goiânia, thus reducing the number of steps in the decision making processes of local and Federal authorities;
(b) the President of the Republic visited Goiânia;
(c) a target date of 21 December was set for decontaminating the main areas, allowing the residents evacuated and the work-force to return home for Christmas.

By this time the work-force engaged in the response to the accident in Goiânia comprised about 250 professional and technical staff and 300 other staff in support, transport, demolition, and so on There were also very significant efforts at the headquarters and institutes of CNEN in Rio de Janeiro and São Paulo, providing various analytical and dosimetry services The target date of 21 December was met by working 12-hour shifts every day, often in adverse weather conditions.

This marked the end of what might be called the containment element of the work, in that the remaining contamination did not pose a significant hazard in the short term Before this, any laxity in the control systems or the very real threat of a bad storm could have renewed the spread of contamination. Further remedial action was necessary, however, to deal with the contaminated areas around the main foci, where levels of radioactivity were no longer so high and which could therefore be surveyed and dealt with. During this stage there was no need for heavy machinery and only manual operation and chemical processes were used Time was no longer so critical, and optimization procedures were developed and adopted This work resumed after Christmas and lasted up until March 1988

In retrospect there seem to have been three main elements to the work, namely

(a) gaining control,
(b) containing the problem,
(c) taking remedial action

There were overlaps in time between these three elements and with the two main phases of the accident. For example, while control was gained within the five days of the initial phase, further less contaminated areas were found later that warranted some control being taken. Follow-up and feedback are also important elements that are too easily forgotten. In this regard it is important to note that the facts of an accident need to be documented as soon as possible, since they tend to become blurred with the passage of time. If lessons are to be learned from the experience of accidents and fed back to improve emergency preparedness, then full use must be made of each opportunity.

7.3. CRITERIA FOR ACTION

Throughout the response a number of dose criteria were used, from which action levels in terms of measurable quantities were derived. These action levels are discussed more in later sections, however, their underlying philosophy and dose criteria are considered in this section

7.3.1. Evacuation

Guidance on intervention levels for the protection of the public in the event of a nuclear accident or radiological emergency has been published both by the ICRP and by the IAEA (see Section 7.1), and these reports are compatible. Evacuation is the most disruptive of protective measures in a radiological accident, and decisions on whether to evacuate must be taken in the light of the specific circumstances prevailing. However, the two reports mentioned indicate that evacuation would not normally be contemplated at dose levels below 50 mSv per year, and that it would almost certainly be implemented at dose levels above 500 mSv per year.

As explained in Section 4, the decision to evacuate houses was taken by the physicist W.F. on the basis of a derived working dose rate limit of 2.5 $\mu Sv \cdot h^{-1}$ at 1 m height inside the house. This was fundamentally linked to the former dose limit for the public of 5 mSv per year for non-accidental (anticipated) exposures. Under the circumstances of the discovery of the accident in Goiânia, and with no way of quickly accounting for any dose component due to internal contamination, an elaborate philosophical basis for the decision making was not to have been expected. During the first few days of the response the CNEN team retained the simply derived criterion. After about a week the criterion for evacuation was relaxed to a dose rate limit of 10 $\mu Sv \cdot h^{-1}$. This new figure was still based on a dose limit of 5 mSv per year, but a number of dose modifying factors were considered in arriving at it. These factors, with possible ranges (between 0 and 1) given in parentheses, were:

(a) an occupancy factor (0.30 to 0.75);
(b) a geographical distribution factor to relate the mean dose rate to the maximum dose rate (0.1 to 0.2); and
(c) a time distribution factor to reflect the decrease in radioactivity due, for example, to cleaning or weathering (0.1 to 0.4).

In each case the most conservative (highest) value was used. Although detailed procedures were developed at the time for a more elaborate scheme of actions and criteria based on higher reference dose levels, they were never implemented as the accident in Goiânia was not officially declared an emergency. The approach adopted was heavily influenced by political and social pressures and an unwillingness for the accident to be considered as an emergency in any way comparable with a possible nuclear power accident.

It must be recognized by decision makers that the adoption of a restrictive value for an intervention level of dose for evacuation (5 mSv per year) might carry with it economic and social burdens which may be exacerbated by the use of cumulative pessimistic factors in deriving action levels.

7.3.2. Remedial actions

Various remedial actions were undertaken, such as decontamination of property, collection of contaminated clothing, removal of contaminated soil, and placing of restrictions on home grown produce near the principal foci. The dose criterion adopted was that the dose to the critical group in the first year should not exceed 5 mSv. Action levels were derived from this criterion, and subsequently long term doses were assessed against a criterion of doses being less than 1 mSv per year. It was found that the 5 mSv criterion was the limiting factor.

It was recognized that there were a number of possible pathways for exposure (see Fig. 17), and upper bounds for the dose in the first year via the principal pathways were therefore set as follows:

(a) inside houses (external exposure): 1 mSv;
(b) outside houses (pathways from contaminated soil): 4 mSv, broken down into 3 mSv due to external irradiation and 1 mSv due to internal exposure, such as via contaminated fruit and produce.

The upper bound for exposure inside houses applied only to external exposure (mostly deriving from contamination on roofs), since it was considered that the action level adopted for surface contamination would render the internal exposure component negligible. This action level was set at 37 $kBq \cdot m^{-2}$, which was the level set in CNEN basic regulations for non-active areas. For external exposure, an occupancy factor of 0.5 (12 hours a day) was assumed, which gave an action level for decontamination of 0.5 $\mu Sv \cdot h^{-1}$ when allowance was made for the background dose rate

Again, both the dose criteria and the models for the derived action levels (see subsequent sections) were chosen in the context of strong social and political pressures. It should be noted that the values selected are more applicable to normal circumstances rather than to the conditions prevailing in the immediate aftermath of an accident.

On the basis of the 3 mSv upper bound for external exposure via soil and a garden occupancy factor of 0.5 (12 hours per day), and on the assumption of an infinite plane source and a natural background rate of 0.2 $\mu Sv \cdot h^{-1}$, an action level of 1 0 $\mu Sv \cdot h^{-1}$ was derived. This value corresponds to a surface radioactivity of 430 $kBq \cdot m^{-2}$, or 22.5 $kBq \cdot kg^{-1}$ in the top 15 mm of soil, which is where the highest radioactivity was found. An investigation level of 10^4 $Bq \cdot kg^{-1}$ was set.

A value of 1 mSv was estimated for the projected committed effective dose equivalent from the use of gardens in the first year after the accident, at this level of radioactivity in surface soil. This was done by using site specific data and a model such as that described in IAEA Safety Series No. 57[6]. Internal exposure pathways that were taken into consideration (neglecting the inhalation of resuspended material) included those via the ingestion of contaminated fruit, chicken, eggs, pork and leafy vegetables. However, for fruit already contaminated by the initial deposition after the accident a derived level of 650 $Bq \cdot kg^{-1}$ was set for pruning trees and picking out fruit according to the Brazilian norms for food

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Models and Parameters for Assessing the Environmental Transfer of Radionuclides from Routine Releases Exposures of Critical Groups, Safety Series No. 57, IAEA, Vienna (1982).

8. ENVIRONMENTAL ASSESSMENTS

8.1. DISPERSION OF THE CONTAMINATION

During the initial phase of the response the response team had formed a general picture of the sites and the extent of the contamination. They had identified seven main areas of contamination. These sites were mostly in urbanized suburbs where small vegetable gardens and fruit trees were common, and where there were also some chicken coops. All houses have a piped supply of fresh water and are linked to the sewerage system. In some places there are artesian wells, but they are only used during prolonged periods of water shortage. Sewage water and rainwater are both discharged to Capim Puba creek. This flows to the Meia Ponte river, which passes through Goiânia from the north-east to the south-west (see Fig. 18).

According to meteorological data of the Brazilian Ministry of Agriculture, 25.2 mm of rain fell in Goiânia on 21 September and 18.4 mm on 23 September, then there was no more rain until 27 to 28 September, when 8.7 mm fell. These rains were preceded by winds and very high temperatures. Over the 15 days before the discovery of the accident the mean temperature was 26.4°C.

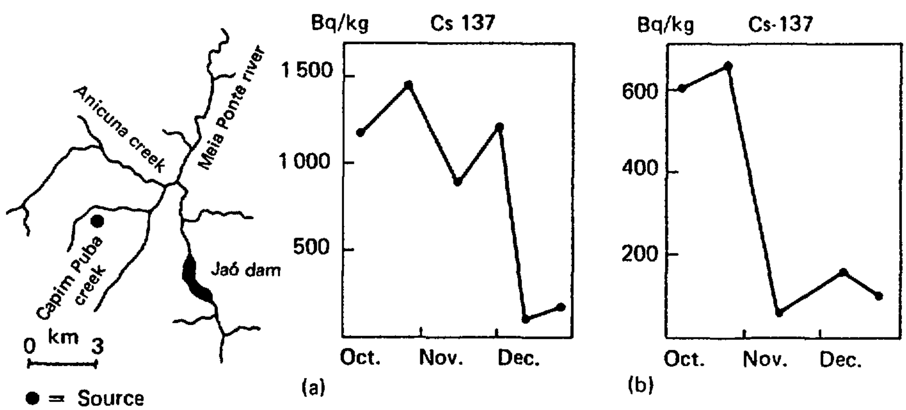

FIG. 18. Plan of rivers in Goiânia and plot of concentrations of caesium-137 in sediment samples from (a) Anicuna creek and (b) Jaó dam.

Caesium chloride is highly soluble, and its dispersion from the broken source capsule into the environment was increased by the rainfall. It had initially been thought that, because of the high rainfall, the contamination would either have been washed into the clay soil and retained or been drained off. This was not the case, however The high temperatures dried out the ground and high winds caused resuspension and dispersion. Indeed, the scale of the effect came as a surprise. For some houses, contamination deposited on roofs was the major contributor to dose rates indoors, and the roof tiles had to be removed.

In addition to these natural processes, there was also transport of radioactive materials by people passing through the contaminated sites, as well as instances of the deposition of contaminated household wastes in unused gardens.

8.2. RADIOLOGICAL SURVEYS

8.2.1. Aerial survey

During the course of the initial phase of the response, it was necessary to confirm that all the major sources of contamination had indeed been traced. To do this, an aerial survey of Goiânia was carried out by helicopter on 7 and 8 October. A portable battery powered gamma spectrometer having NaI(Tl) detectors with a total volume of 840 cm^3 was used. After testing on the ground, a test flight was made away from contaminated sites to measure local background radiation Tests were also done to check that the down-draughts due to the helicopter rotor did not significantly resuspend and further disperse the contamination. Most of the survey was flown at an altitude of 40 m, and a circle of radius 80 m was effectively monitored. The ground speed was between 50 $km \cdot h^{-1}$ and 70 $km \cdot h^{-1}$. Over two days, all the urban areas of Goiânia were monitored (about 67 km^2). This confirmed that no sites of major contamination had been missed, and one discrete spot of radioactivity was found that gave rise to a dose rate of 21 $mSv \cdot h^{-1}$ at 1 m (Fig. 19 shows a typical analogue record obtained over contaminated areas)

8.2.2. Survey by car

It was still possible that sites of lesser contamination had been missed by the aerial survey, especially in the vicinities of the heavily contaminated sites which gave rise to high background readings. A complementary system of monitoring that likewise could survey large areas, and was not as labour intensive as surveying with hand held instruments, was therefore necessary. This need was initially met by mounting the detectors used in the helicopter in a car and surveying the areas adjacent to the main foci of contamination and several other areas of the city. In addition, a NaI(Tl) detector to monitor the creeks was attached to a car to search for new foci in different

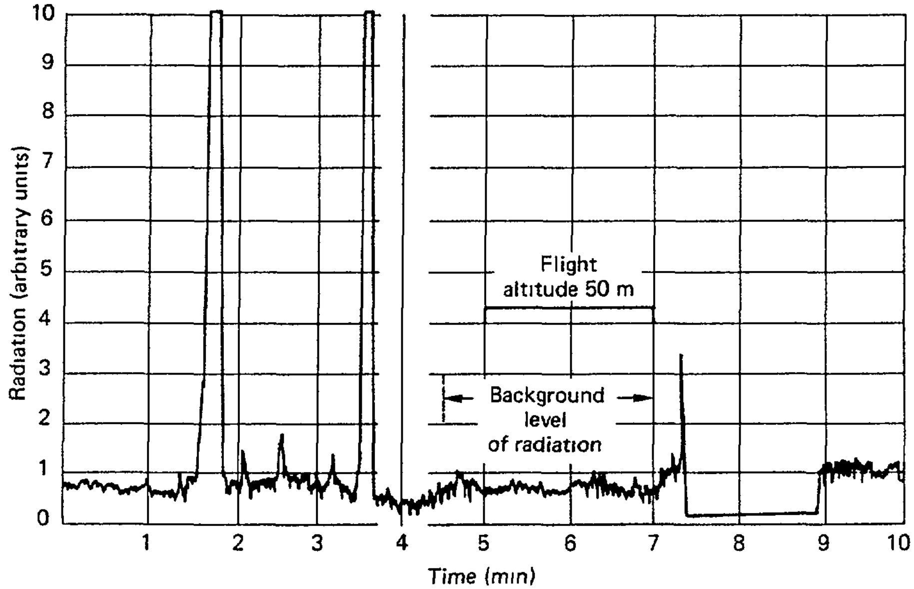

FIG. 19. A recorder trace from an aerial radiation survey The background reading was taken at 50 m altitude over open land away from the contaminated area of Goiânia The peaks represent radiometric anomalies over contaminated areas.

quarters of the city. Later on a set of detectors was mounted at the back of a car. (See Photograph 6.) Both 100 mm × 100 mm NaI(Tl) detectors and Geiger–Müller (GM) type detectors were used. One problem encountered was that the electronics were sensitive to temperature variations, and a car with air conditioning was required. The monitoring programme had two phases. The first phase lasted until December and was primarily aimed at monitoring the area outside the main foci of contamination. After Christmas a second survey was carried out once these foci had been decontaminated.

8.2.3. Use of hand held monitors

More precise dose rate measurements were made and more detailed contamination monitoring was carried out near the principal foci.

Figure 16, indicative of this extensive measurement programme, shows broad dose rates and contamination bands around the several principal foci. More detailed dose rate measurements are shown in Fig. 20 (for the house and yard where the source capsule was first ruptured) and in Figs 21 and 22. Figure 23 shows a typical less contaminated site where contamination had been brought in by residents and visitors.

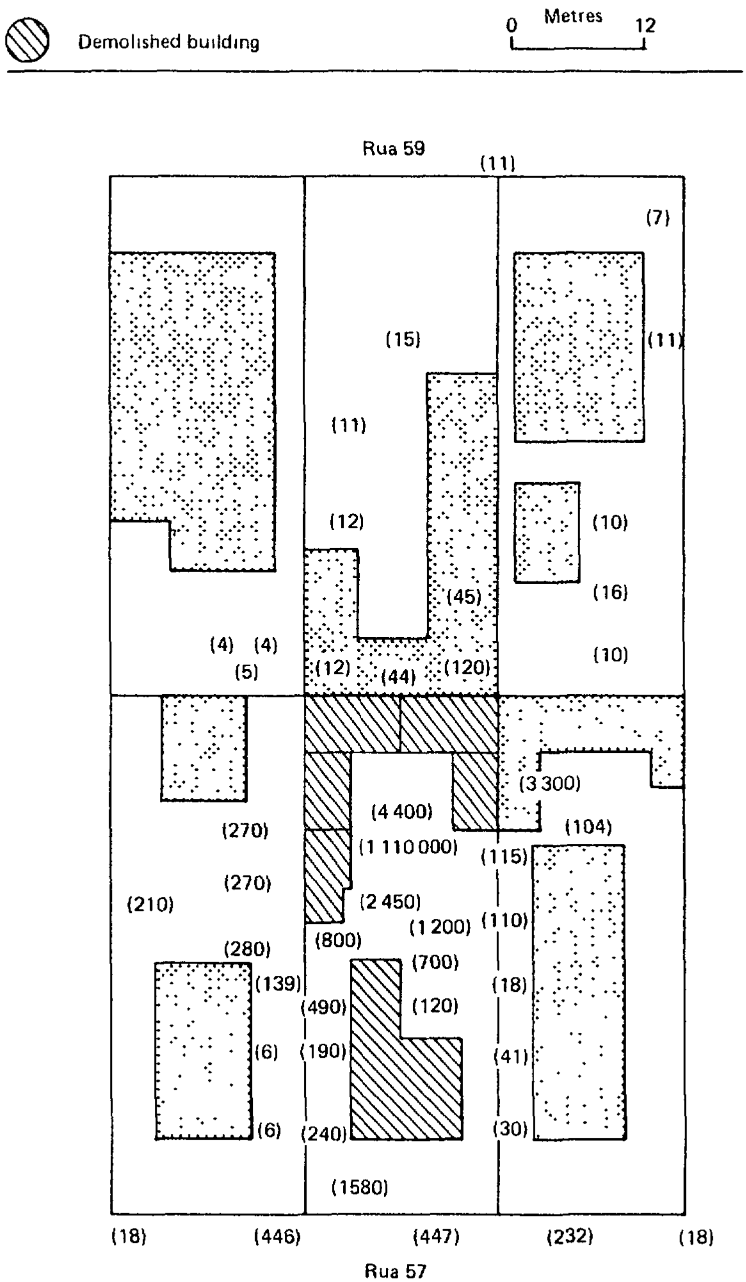

FIG 20 Dose rates (in $\mu Sv \cdot h^{-1}$) around the house of R A in Rua 57 (57th Street).

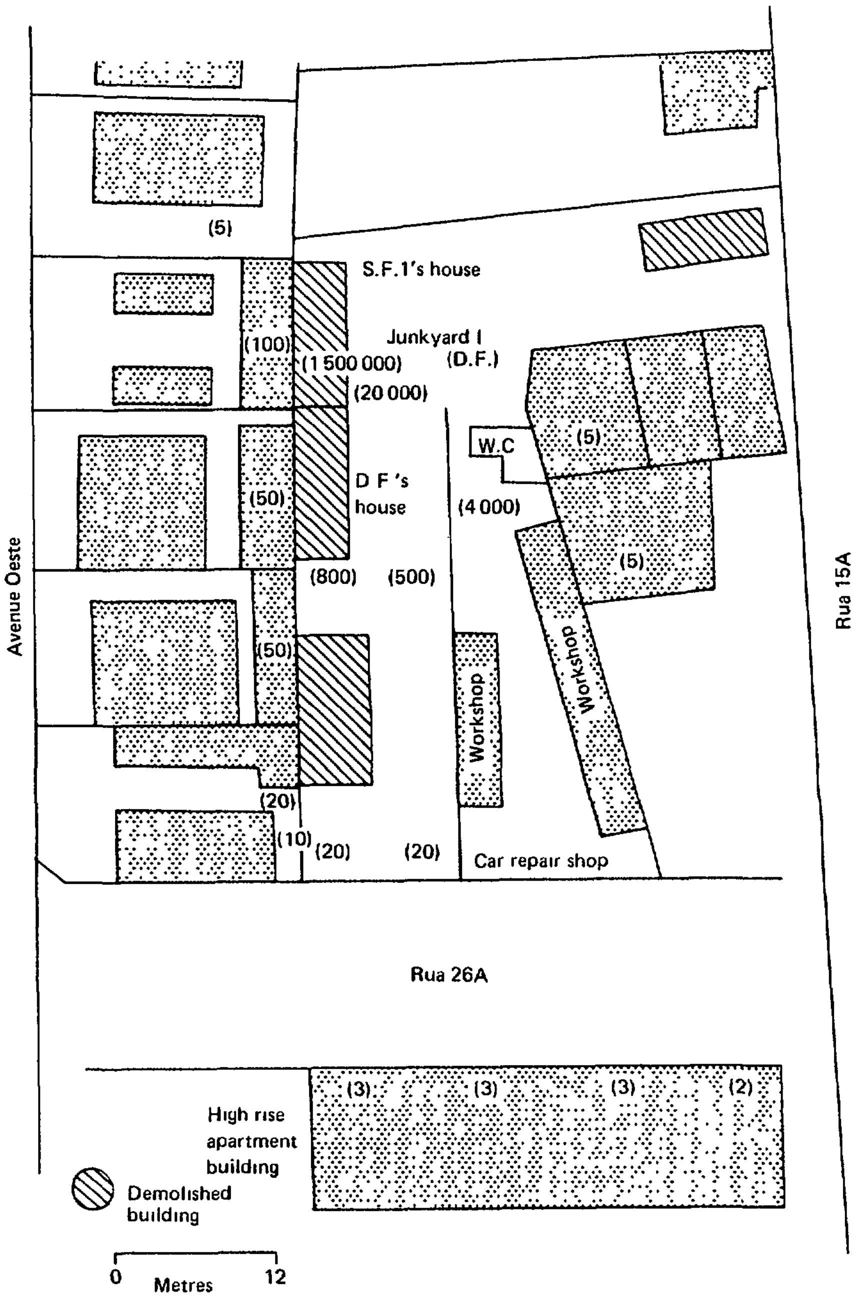

FIG. 21. *Dose rates (in $\mu Sv \cdot h^{-1}$) around the house of D.F. in Rua 15A (15A Street).*

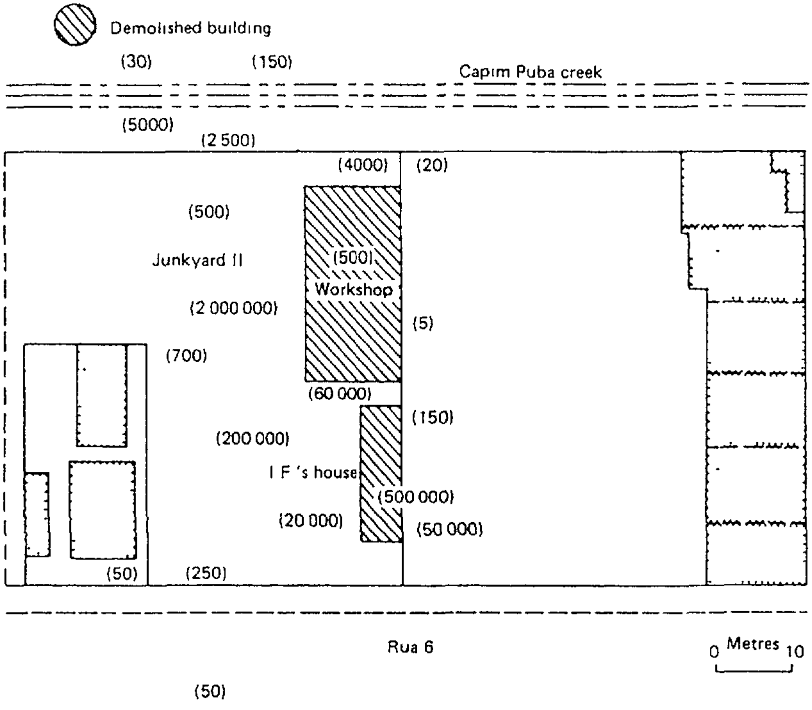

FIG 22 Dose rates (in $\mu Sv \cdot h^{-1}$) around the house of I F in Rua 6 (6th Street)

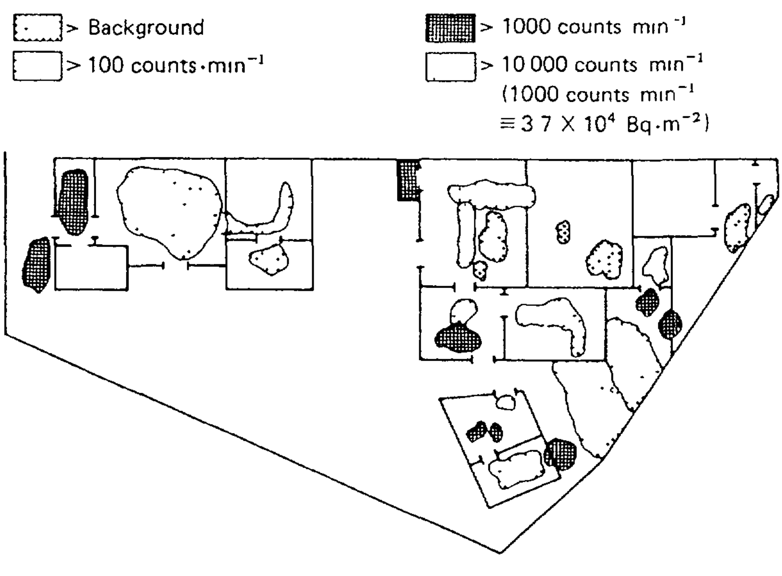

FIG 23. Dose rates (in $\mu Sv\ h^{-1}$) in a housing area contaminated by residents and visitors

8.3. ENVIRONMENTAL MONITORING

To quantify the environmental dispersion of caesium, more than 1300 measurements were made of radioactivity due to caesium-137 in soil, vegetation, water and air. Emphasis was put on investigating areas near (within about 50 m of) the main foci. Initially, a multichannel analyser with a 2 in × 2 in NaI crystal was used at a special laboratory set up in Goiânia by mid-October. However, it was found that a single channel analyser with a 3 in × 3 in NaI crystal was sensitive enough for short (10 min) counting times, since only caesium-137 was present. (This meant that the instruments could be significantly simpler than those that would be required for accidents causing contamination by many radionuclides.)

8.3.1. Soil

The distribution of radioactivity levels for about 400 soil samples is shown in Fig. 16. The levels ranged from 10^2 to 10^5 $Bq \cdot kg^{-1}$ and decreased with distance from the main foci. They reflected the wind pattern, showing the effects of resuspension and further dispersion. Soil profiles later showed that for any specific radioactivity at the surface, the top 15 mm of soil retained an average of 60% of the caesium. (See Photograph 19.)

8.3.2. Vegetation

At the same locations as for soil, 263 samples of vegetation were collected and analysed, including leaves, branches and fruit. Leaf radioactivity closely paralleled that of the soil in level and distribution owing to deposition of dust, a mechanism confirmed by the fact that washing reduced the radioactivity by 50%.

8.3.3. Meia Ponte river

Monitoring of the hydrographic basin was initially performed during the first days of October and included surface water, suspended matter, bottom sediments and fish and the screening of the river bottom. This included, in particular, the Capim Puba creek, a tributary of the Meia Ponte river that receives both flood control water and sewage from the area of the three most contaminated sites. In addition, a survey was conducted on the sewerage system of the district. Monitoring showed no significant radioactivity. (See Fig. 24.)

8.3.4. Public water supply

Goiânia's public water supply comes from a treatment plant which takes water from a tributary of the Meia Ponte upstream of Capim Puba creek. Treated water

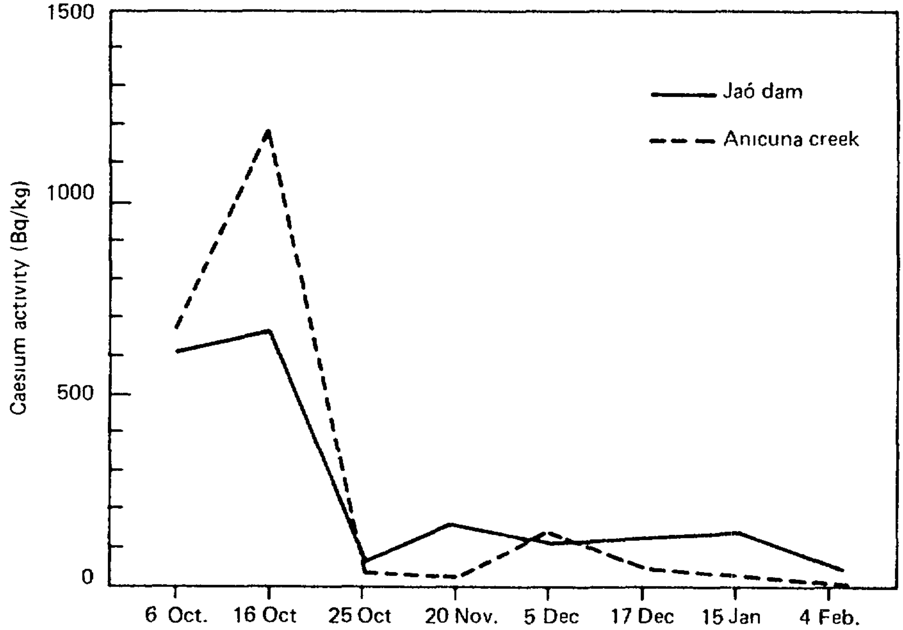

FIG 24. Time variation of radioactivity due to caesium-137 in sediments from Anicuna creek and Jaó dam

TABLE IV. AEROSOL ACTIVITY IN SAMPLES COLLECTED 50 m FROM THE MAIN FOCI OF CONTAMINATION DURING THE REMOVAL OF RADIOACTIVE WASTE

Point	Aerosol radioactivity due to caesium-137 for various sampling periods in 1987 ($mBq \cdot m^{-3}$)				
	Nov. wk 2	Nov wk 3	Nov wk 4	Dec. wk 1	Dec wk 2
1	0 9 ± 0 3	3 8 ± 0.4	<0 4	0 33 ± 0 11	0 3 ± 0 07
2	1.0 ± 0 4	75 ± 4	29 ± 2	4.4 ± 0.3	NA[a]
3	0 7 ± 0 3	<0.5	2 2 ± 0.3	2.6 ± 0.2	NA[a]

[a] NA· not available

goes to reservoirs upwind of the contaminated area. It was therefore not surprising that radioactivity levels in water from the treatment plant and from the reservoirs, both before and after treatment, were below the minimum detectable (1 $Bq \cdot L^{-1}$). Nevertheless, that the measurements bore this out greatly helped in assuaging the fears and retaining the confidence of the public in the early stage of the work.

8.3.5. Groundwater

Despite Goiânia's public water supply, many houses still draw water from wells, especially in dry periods. Thirty wells around the main sites of contamination were inspected. Only wells near the main foci had levels of radioactivity above the detection limit (1.5 $Bq \cdot L^{-1}$). The highest level of radioactivity detected, 30 $Bq \cdot L^{-1}$, was in the disused well of a residence.

8.3.6. Rainwater

To evaluate total deposition, 11 rainwater collection stations were established in the Aeroporto section. No caesium-137 was detected above the level of the limit of detection (150 $Bq \cdot L^{-1}$).

8.3.7. Air

Five high volume rate (58 $m^3 \cdot h^{-1}$) air samplers were installed near the main sites of contamination (see Fig. 16) and a control sampler was installed in a distant village. The results of weekly samples (see Table IV) indicate that peak values occurred during the third and fourth weeks of November owing to decontamination operations, but that in general levels were an order of magnitude or more lower.

8.4. RADIOLOGICAL SURVEY EQUIPMENT

Instruments of many types were used that had been collected through a co-ordinator at CNEN headquarters from various sources: CNEN and its various institutes (IRD, IEN, IPEN), FURNAS, NUCLEBRAS, universities and research facilities, and foreign aid. In total 55 dose rate meters, 23 contamination monitors and 450 QFEs (quartz fibre electrometers — dosimetric pens) were used.

As might be expected with so many monitors from so many sources, some arrived without calibration details or instruction manuals (necessary both for use and for repair). Intensive use of such equipment in the field, sometimes by people who had not had much previous experience of monitoring, inevitably meant that maintenance was continually necessary. For this reason, during the early phase an electronic and calibration laboratory was set up in Goiânia. The types of survey equipment used are summarized in Annex I, and a subjective assessment of their usefulness by the instrumentation group is presented.

9. DECONTAMINATION

Decontamination was undoubtedly the most resource intensive element of the response to the accident, with some 550 workers participating in Goiânia This section presents the salient features of this work.

Significant contamination was found in 85 houses, of which 41 were evacuated Residences away from the main foci of contamination were decontaminated first. First, a suitable uncontaminated point outside the house was found, from which objects inside could easily be monitored. The site was then covered with plastic sheeting and all movable items were brought out The items removed were monitored with a surface contamination monitor Clothes were monitored with a scintillometer (NaI) which was shielded if ambient dose rates were high. Items found to be free of contamination were wrapped in plastic Contaminated items were acceptably decontaminated or else disposed of as waste

The decontamination techniques used depended on the objects in question The decision whether to decontaminate or dispose of items depended on the ease of decontamination, except for items of special value such as jewellery or personal items of sentimental value. To see toys, photographs and other items of obvious sentimental value heaped in a yard for possible disposal had a disturbing effect on residents and technicians This is a psychological aspect of an accident that should not be overlooked.

When the contents of a house had been removed, vacuum cleaners with high efficiency filters were used to clean all surfaces. The walls, windows, floors, wash basins and water tanks were monitored. Painted surfaces could be stripped. Floors were usually red ceramic and were decontaminated with acid mixed with Prussian Blue (See Annex IV for further details)

The contamination of roofs of houses by atmospheric dispersion could significantly affect interior levels of radioactivity In such cases, the roofs were vacuum cleaned inside and washed outside with pressurized water jets This method was not very effective, since the dose rates were only reduced by about 20%, and the roofs of two houses had to be removed.

For gardens, pruning trees and discarding the fruit effectively dealt with contamination.

Contamination was removed from 45 different public places, including pavements, squares, shops and bars. There was generally less than in residential areas and it occurred in discrete spots on fabricated surfaces such as pavements and walls. Contamination was also found on various vehicles: about 50 in all. (See Photograph 17)

Major decontamination work began in mid-November with the demolition and removal of seven houses so contaminated that decontamination was not feasible. Much of the soil from enclosed gardens and yards was also removed on the basis of soil profile measurements. (See Photographs 7–19.)

The site of the greatest contamination was the house where the source capsule had been broken open (Fig. 20). This was the last and most hazardous site to be decontaminated. (See Photographs 13 and 14.) Exposure rates were very high, necessitating very short periods of work on the hot spots. The work required careful planning. More than 90% of the most contaminated soil was on the surface (with dose rates as high as 1.5 $Sv \cdot h^{-1}$) and much of the work was done during heavy rainstorms. (See Photograph 21.) This made it especially difficult during the removal of contaminated mud by machine to containers to keep within the daily dose limit of 1.5 mSv set for workers.

After demolition, rubble and soil were removed until the set criteria were met. A concrete or clean soil pad was then deposited on the site.

After Christmas, when the main foci had been decontaminated, all houses and uncultivated ground within a radius of 100 m of the foci were surveyed. Contamination was usually in the form of deposited dust, particularly for gardens. However, there was evidence that contaminated waste, probably from the houses that were the main sites of contamination, had been buried in wasteland before CNEN's intervention. The means of decontamination adopted, since urgent action was no longer required, was designed to keep to a minimum the amount of waste removed and to cause as little distress as possible to the public:

(a) the gamma dose rate was measured;
(b) the area in which the highest dose rate was found was profiled (see Photograph 19);
(c) in accordance with the criteria set previously, the soil layer indicated by the profile was removed, and then an additional layer was removed;
(d) the gamma dose rate and the soil's average specific radioactivity were measured; and
(e) if these measurements were close to derived limits, the area was covered with 30 mm of new soil.

10. WASTE DISPOSAL

10.1. SELECTION OF A WASTE STORAGE SITE

Since the response to the accident from its very inception generated radioactive waste, the technical staff recognized immediately the need to designate a suitable site in Goiânia or in the vicinity to which the waste, properly packaged, could be readily transported, to facilitate decontamination work. On the basis of their initial assessment of the probable volume of waste and of likely transport problems, the technical staff felt that any delay in choosing a site would adversely affect the work.

There was no inherent technical difficulty in constructing a waste storage site; however, the choice of a site was delayed by political considerations. In the interim, substantial public opposition was expressed to leaving the waste in Goiânia, or even in Goiás State. Nevertheless, on the basis of discussions between CNEN and the Government of Goiás State, the political decision was made that a site would be found to store the waste for up to two years and that the selection of a permanent repository would be deferred until a later date. The site eventually chosen was in a sparsely populated area 20 km from Goiânia and 2.5 km from the city of Abadia de Goiás. (See Photographs 23, 24 and 27.)

10.2. CLASSIFICATION AND CONTROL SYSTEM

From 1 October a health physics team was assigned to deal with the radioactive waste. One of its first actions was to initiate the use of a report form for radioactive waste disposal (see Table V) to identify: the waste's origins; its physical form, combustibility, compactibility and so on; and external dose rates. (This system later became an important basis for estimating the fraction of the original caesium source that had been recovered.)

Solid waste was classified, on the basis of existing legislation (Resolution CNEN-19/85, Generation of Radioactive Waste in Radiation Installations, 27 November 1985), as:

(1) Non-radioactive: radioactivity less than 74 $kBq \cdot kg^{-1}$ (2 $nCi \cdot g^{-1}$);

(2) Low level waste: dose rate less than 2 $mSv \cdot h^{-1}$ close to the surface of the package;

(3) Intermediate level waste: dose rate higher than 2 $mSv \cdot h^{-1}$ but less than 20 $mSv \cdot h^{-1}$.

Liquid waste was solidified in cement and classified in the same way.

10.3. PACKAGING

Most of the waste classed as low level was placed in industrial drums or ribbed metal boxes. (See Photographs 18, 20, 22 and 23.) The drums were of capacities 40 L, 100 L and 200 L, and made of 18 gauge carbon steel. The boxes were 1.2 m^3 in volume with a maximum load of 5 tonnes, and had corrosion resistant surfaces coated with zinc chromate and acrylic paint, and bolted rubber sealed lids. Dry cement was put in the bottom of the receptacles to absorb water. To limit the number of different sizes of package to be dealt with at the storage site and to encapsulate doubly some types of waste, the 40 L and 100 L drums were put into either 200 L drums or metal boxes. (See Photographs 18, 20, 22.)

A large volume of low level waste was in the form of contaminated bundles of paper at Junkyard III. (See Photograph 9.) The bundles were wrapped in plastic and put in roll-on–roll-off shipping containers (32 m^3), and then put in temporary deposit to await eventual recycling.

Intermediate level waste was put in 200 L drums and these were put in 'VBAs': cylindrical concentric packagings with 200 mm reinforced concrete walls.

Packaging decisions were significantly affected by the fact that the waste site was to be only for temporary storage. The waste required a total of 3800 drums (200 L), 1400 boxes, 10 containers and 6 VBAs. The drums and containers were commercially available. The VBAs were originally intended for use at the Angra nuclear power plant. The boxes were specially made at factories in Goiânia.

10.4. DESIGN OF A TEMPORARY STORAGE SITE

The storage site had to be designed to accommodate the 4000–5000 m^3 of waste initially estimated. On the assumption that half the waste would be packed in drums and the other half in boxes, the storage site had to be designed to take 12 500 drums and 1470 boxes. Open platforms were found to be best to meet local conditions, constraints on the construction time and political demands.

The design was standardized in order to be able to build the platforms quickly. Concrete plates on the platforms were sized to permit receipt of drums or boxes with full use of the area. Each plate was 0.15 m thick and 2.75 m × 2.75 m in area. With each box a 1.2 m cube, each plate could receive eight boxes or 32 drums, double stacked. Given the expected number of drums and boxes, 574 concrete plates

TABLE V REPRODUCTION OF A REPORT FORM FOR RADIOACTIVE WASTE DISPOSAL

National Nuclear Energy Commission Control of radioactive waste		Place of origin . .	File number . . .
Identification number of package		.	
Package type	.. 100 L drum 200 L drum VBA	.. Metal receptacle Concrete 40 L drum	100/200 L drum 40/100 L drum 40/200 L drum
Material			
Compactible waste	Paper .. Hard paper Plastic	Tissues Ceramic/glass Lead	.
Not compactible waste	Scrap metal Building rubble Tin	Soil Wood Furniture	Domestic utensils .. .
Nuclides with gamma/beta emission: caesium-137			
Mass of package	kg		
Exposure rate at surface of package	maximum .. minimum	$(mR \cdot h^{-1})$ . .. . $(mR \cdot h^{-1})$	
Maximum exposure rate at 1 m from surface of package		. $(mR \cdot h^{-1})$	
Surface contamination not fixed		$(\mu Ci \cdot cm^{-2})$	
Monitored by (name)	.	Date . .	
. . . . Signature		. . . . . Institution	

optimally distributed on the platforms were initially estimated to be needed. (See Photographs 23 and 24.)

On the basis of the restrictive assumptions, it was decided that only six platforms would be built initially, and these were sufficient for the 3500 m^3 of waste actually generated.

To protect the boxes and drums from the heavy rainfall, they were carefully decontaminated before transfer to the storage site and covered with plastic. (See Photograph 21.) In addition, the concrete plates were made semi-absorbent to retain any residual contamination that might result from evaporation and condensation under the plastic.

Finally, a sampling system was designed to monitor water (mainly rainwater) from the platforms continuously. (See Photograph 24.) A system of natural barriers (including a small dike used for environmental studies) was built to slow the flow of draining water and to increase the absorption of caesium within the area of the depository.

Each receptacle was numbered and its contents were described on an inventory card. The data were used with a computer programmed mathematical model to predict accessible dose rates for different arrangements of drums and boxes. The most radioactive packages were placed in the centres of the platforms to minimize the dose rates in the access corridors and at the site security fence.

In addition to monitoring workers, soil, vegetation, surface water, sediments and air were monitored and thermoluminescent dosimeters (TLDs) were used to monitor doses at the security fence. No leakage of radioactive materials has been detected but, in view of the high humidities and temperatures prevailing, some corrosion might be expected within a few years. Heavy rainfall was already eroding the underlying soil. Studies were under way to identify a means of permanent disposal, a process that was expected to be costly in both occupational exposure and economic terms.

10.5. TRANSPORT OF WASTE TO THE STORAGE SITE

Waste was transported in such a way as to meet Brazilian legal requirements, essentially identical to those of the IAEA's Regulations for the Safe Transport of Radioactive Material[7]. Before shipment the dose rate from each package was measured and a check was made that it was free of contamination. The Type A packages were transported by lorry under full load conditions. Between 25 October and 19 December, 275 lorry loads of waste were transported to the temporary storage site,

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulations for the Safe Transport of Radioactive Material, 1985 Edition, Safety Series No. 6, IAEA, Vienna (1985); and Supplement 1986 (1986).

in convoy with a police escort at speeds not exceeding 20 $km \cdot h^{-1}$ in the city and 45 $km \cdot h^{-1}$ elsewhere. Each convoy was accompanied by health physicists equipped to deal with an emergency. (Indeed, one lorry did leave the road and overturn, but without causing a radioactive release.) Lorries were monitored after use to ensure that there was no residual contamination.

10.6. INVENTORY

Data on the external dose rates for packages, recorded on the inventory cards, were used later to estimate the radioactivity of each drum, using the kernel spot method[8]. (The method assumes a homogeneous distribution of radioactivity within the cylindrical geometry of the drum, but modifying factors were introduced to take account of known shielding or inhomogeneities of the contents.) The quality of the estimates of radioactivity depended on various other estimates, particularly that of the mass. (Better estimates could only have been obtained at the cost of increased rates of occupational exposure and were not considered warranted.)

The best estimate of the radioactivity in the recovered waste, together with the radioactivity accounted for in the Marcilio Dias Naval Hospital, was about 44 TBq (1200 Ci). Although the error margins encompassed the known radioactivity of the caesium chloride source before the accident of 50.9 TBq (1375 Ci), there was some criticism in the press that contamination with a radioactivity of "hundreds of curies" was still potentially free in the environment. Under the circumstances, the estimates of the radioactivity of the waste were the best that could have been expected. Some radioactive contamination remained, on roofs or in soil for example, but not in significant amounts. The estimates of the radioactivity of the waste were intended to be confirmatory. The results of the extensive, comprehensive environmental monitoring formed the primary basis for the assurance that there was no significant residual hazard.

10.7 FOLLOW-UP ACTIVITIES

As decontamination work ended, other monitoring and research activities were initiated. Monitoring of the storage site and its surroundings to demonstrate that safety was being maintained was to continue until a decision on the final disposal of the waste permitted the release of the site. In Goiânia, the sampling network that had been set up was retained to confirm the effectiveness of decontamination work. In addition, several research projects were initiated, some undertaken jointly by universities and other national and international scientific institutions, to take advantage of the singular opportunity to investigate mechanisms of environmental migration of caesium, particularly in an urban area.

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[8] ROCKWELL, THEODORE, III, Reactor Shielding Design Manual, Van Nostrand, Princeton, NJ (1956).

Part IV

OBSERVATIONS AND RECOMMENDATIONS

The review of radiological accidents by experts is a mechanism for feeding back experience into the relevant systems of control, in order to help lessen the likelihood of accidents in the future and to be better prepared for those that do occur. Such reviews add to the fund of knowledge, and also illustrate and emphasize principles and criteria, which, however, are usually already well known. This is reflected in the observations and recommendations that follow, which derive from the international review of the radiological accident in Goiânia but not necessarily from the specific circumstances of the accident.

The accident in Goiânia shows how actions that would have been innocuous under ordinary circumstances became matters of life and death owing to the presence of radioactive material. This bears out a cardinal rule of radiological protection, namely that the security of the source is of paramount importance. Radioactive sources that are removed from the location designated in the process of notification, registration and licensing can present a serious hazard. Means to prevent such breaches of care should therefore be ensured by the person responsible for the radioactive source, including audit procedures and appropriate security arrangements. In passing, however, it should be noted that the need for security of the source has many parallels in the general area of the safety of hazardous materials, for example in dealing with poisons such as cyanide or arsenic.

The rule that radiation sources must be secure and under control must be given expression by national competent authorities in an appropriate regulatory system supported by appropriate rules and regulatory inspections; which was indeed the case in Brazil. However, such a system cannot diminish the responsibility of the person designated as liable for a radioactive source. The regulatory system cannot and must not detract from managerial responsibilities; in particular, it cannot substitute for the licensee's responsibility for safety. The system should be viewed as only a check on the effectiveness of the professional and management system; in particular, it may serve as an audit of the licensee's fulfilment of this responsibility. One way in which the regulatory system can do this is by inspections of facilities, but there are inevitably resource limits on how often periodic inspections can be made.

Suitable systems of compliance with regulatory requirements should be specific, simple and enforceable. For instance, one possibility that regulatory authorities might consider is to require a licensee responsible for a strong radioactive source to notify the regulatory authority each time the integrity of the source is checked, rather than simply maintaining a record for examination during inspections. Such notification could be made by machine readable postcard. Should a licensee fail to report at the required time, the regulatory authority would be alerted to the possible need to check on the status of the source. Such an approach would meet the test of specificity, simplicity and enforceability Moreover, good communication is required between all those engaged in implementing and enforcing radiological protection requirements, and the aforementioned requirement is a good example of how communication among parties concerned could be improved. Nevertheless, the cost effectiveness of this procedure should be assessed before its implementation.

Consideration should be given to markings for radiation hazards that would be recognizable to the wider public The interest aroused by the blue glow of the radioactive caesium chloride source markedly influenced the course of the accident in Goiânia. Clear and recognizable marks on radiation sources should help to lessen the likelihood of accidental exposures.

The physical and chemical properties of sources should be taken into account in licensing their manufacture, in view of the influence of these properties on the potential consequences of accidents or the misuse of sources. The solubility and ease of dispersion of caesium chloride had a profound effect on the course of the accident in Goiânia Many less radioactive caesium-137 sources in use are in a vitrified form that inhibits dispersion. Unfortunately, sources in such a form cannot yield the high specific radioactivity required of a radiotherapy source

If, in spite of all precautions, an accident does occur and a radiological hazard is foreseen, there should be a well understood chain of information and command. In particular, in order to respond to a serious accident, a country would probably need to engage many of its qualified personnel, possibly from many widely separated establishments, and make use of much of the equipment available to it. An emergency plan should anticipate the need for integration, and this command structure should have been set up.

In this regard it is important not only that responsibilities are assigned, but also that the necessary authority to obviate bureaucracy is conferred. For instance, the accident in Goiânia was remote from the centres of radiological expertise The logistics of mobilizing personnel and arranging for matériel were a major difficulty (air transport was found to be essential) A clear chain of command will facilitate the provision of means necessary during emergencies, including means for enabling immediate mobilization.

It follows that preparedness to respond to radiological emergencies should extend not only to nuclear accidents but to the entire range of possible radiological accidents. International and national authorities have put significant effort into preparations to respond to nuclear accidents; other types of radiological emergency have received much less attention, however. The accident in Goiânia is an example of a serious radiological accident outside the nuclear industry It was not unique in its scale, indeed, there are strong similarities with the accident in Ciudad Juárez in Mexico in 1983 (In its Nuclear Safety Review for 1987, the IAEA briefly reviewed fatal radiological accidents to date, see Appendix III.) Most fatal radiological accidents have occurred outside the nuclear industry, radiological protection in the non-nuclear sector might perhaps warrant more attention.

Moreover, in producing emergency preparedness plans, authorities should ensure that, in the event of a radiological accident affecting the public, there are well known means available to summon assistance and to notify the relevant authorities. The most effective means will depend on the infrastructure of the country concerned, but use might be made of local bodies such as the police or the fire brigade, who would have designated contacts.

Readily transportable equipment for bioassay and whole body monitoring may be needed, in addition to permanent dedicated facilities, in managing a radiological accident. Specialists trained to adapt normal procedures to the abnormal situation may also be necessary. Emergency preparedness plans might usefully be reviewed in this regard.

Prompt decorporation of internal contamination is important following an accident with radioactive materials. Prussian Blue was confirmed to be efficacious in promoting the decorporation of internal contamination by caesium-137. The threshold of effectiveness seems to be a daily dose of 3.0 g (1.0 g orally three times per day). National pharmaceutical bodies might consider permitting emergency oral doses of up to 10–12 g per day for adult patients.

Cytogenetic dosimetry is an extremely useful technique for estimating the external whole body radiation dose and the inhomogeneity of dose of the irradiated person. It is helpful in providing useful information to the physician responsible for diagnosis and prognosis. It is suggested that national authorities review their emergency plans to ensure that laboratories capable of carrying out this work are available, either internally or by international co-operative arrangements. Intercomparison programmes should be carried out to establish a desirable level of coherence among the different laboratories.

Further studies of the experimental and clinical usage of the drug granulocyte macrophage colony stimulating factor (GMCSF) are required in order to clarify the questionable results of its use following the accident in Goiânia before further application in actual radiological accidents. These results were possibly due to the fact that the optimum dosages and times of administration of the drug are not yet known.

After radiological accidents, people affected have sought medical help for the effects of exposure to radiation, usually without this being diagnosed. This difficulty in diagnosis is typical of such accidents, in which medical diagnoses have included insect bite, spider and snake bites, viral infection and exposure to toxic chemicals. Recognition of the nature of radiation injury depends on the education of non-nuclear workers as well as on trained medical and radiological protection experts, all of whom are dependent upon widely disseminated educational programmes. The accident in Goiânia would serve as a very suitable case history for inclusion in educational programmes for the health and safety professions and for those with supervisory responsibility for strong radioactive sources.

The therapy of casualties of radiological accidents in modern times is varied and complicated. Such patients must be cared for by hospitals and staffs who are engaged on a daily basis in the haematological, chemotherapeutic, radiotherapeutic and surgical treatment of patients at risk from cancer, immunosuppression and blood dyscrasias. Moreover, generally, medical personnel and facilities are not prepared for dealing with radiation injuries and radiological emergencies. Provision should be made in radiological emergency plans for immediate assistance from medical specialists trained to handle such patients.

After a radiological accident that causes widespread contamination occurs, there is usually a temptation to impose extremely restrictive criteria for remedial actions, generally prompted by political and social considerations. These criteria impose a substantial additional economic and social burden to that caused by the accident itself. The IAEA has recommended a range of reference dose levels for remedial actions which are deemed to be not unnecessarily restrictive.[9] Moreover, those managing the emergency might not be able to elaborate a sophisticated scheme of action levels, usually owing to the urgency of action, and might prefer to refer to the dose limits for normal planned exposures. This is an unnecessary restriction, since these dose limits are not intended for application to those incurring unanticipated exposures in an accident. However, as an additional parameter, peculiar to each country, the social and political pressures influencing the decision making process should not be underestimated.

In the accident in Goiânia, a number of practical problems were encountered in carrying out surveying and decontamination. These have been detailed in Sections 8 and 9 and Annexes I, III and IV. However, two observations are worthy of note here:

(a) Emergency equipment must be capable of operating in adverse ambient conditions;
(b) There will almost certainly be a need to engage workers without previous experience of radiological work, and even professional staff may not have had relevant operational experience. Provision for training should therefore be made within emergency plans.

If lessons are to be learned from the experience of accidents and fed back to improve emergency preparedness, then the facts of an accident should be documented as soon as possible, since they tend to become blurred with the passage of time. In this regard an official recorder should be an integral part of the emergency response team from the very outset, in order to facilitate subsequent reconstruction of the sequence of events and assessment of the experience gained.

The dissemination of information to the media, the public and, indeed, the response force is particularly important. In an accident, meeting information needs

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Principles for Establishing Intervention Levels for the Protection of the Public in the Event of a Nuclear Accident or Radiological Emergency, Safety Series No 72, IAEA, Vienna (1985).

is usually a drain on the resources of the people trying to deal with the consequences of the accident itself. It is therefore recommended that response teams in radiological emergencies should have administrative and public informational support appropriate to the scale of the accident. Major emergencies require prompt on-site administrative and public informational support. All individuals designated as likely to need to respond to radiological emergencies should undergo training, both formal and through drills, appropriate to their functions.

The accident in Goiânia was one of the most serious radiological accidents to have occurred to date. It resulted in the injury by radiation of many people, four of them fatally, and the radioactive contamination of parts of the city. Radiological accidents are rare events; but this should give no grounds for complacency. No radiological accident is acceptable, and the public must feel confident that the competent authorities and individuals are doing all in their power to prevent them. Part of this process is to learn the lessons of the accident in Goiânia.

PHOTOGRAPHS

(All photographs by courtesy of the National Nuclear Energy Commission (CNEN), Rio de Janeiro, Brazil)

1–3. The derelict premises of the Instituto Goiano de Radioterapia, a private radiotherapy clinic in Goiânia. A strongly radioactive source was removed from a teletherapy machine abandoned on the premises. (See Section 3.1.)

4. The physicist W.F. who discovered the accident monitors a police officer for contamination at the Olympic stadium. (See Section 4.1.)

5. Monitoring people for contamination at the Olympic stadium. (See Section 4.1.)

6. Mobile radiation monitoring: NaI(Tl) and Geiger–Müller detectors mounted on a car. More than 2000 km of roads were monitored in this way. (See Sections 7.2, 8.2.)

7. Preparing to demolish the house of E.F.2 and S.F.1. near Junkyard I. (See Section 9.)

8. Monitoring the roof of the house of E.F.2 and S.F.1 during demolition. (See Section 9.)

9. Contaminated bundles of paper that had been collected by the junkyards for recycling. Some bundles went to other towns. (See Section 9.)

10. Demolition of the house at Junkyard II of L.F.2, the six-year-old girl who died as a result of the accident. A hole has been made in the wall with the excavator to remove a radiation hot spot giving a dose rate of $0.5\ \mathrm{Sv \cdot h^{-1}}$. (See Section 9.)

11. Clearing the site at Junkyard II on 6th Street. (See Section 9.)

12. Junkyard II: cutting up contaminated girders. (See Section 9.)

13, 14 Contaminated rubble from the demolition of R.A.'s house on 57th Street, where the source assembly was dismantled and the source capsule broken open. (See Section 9.)

15. Removing contaminated items from Junkyard III. (See Section 9.)

16. Cutting up contaminated items for removal from the warehouse of Junkyard III. The fixed contamination in the floor was such that a layer of concrete had to be poured over it. (See Section 9.)

17. Decontaminating a vehicle. About 50 contaminated vehicles were found. (See Section 9.)

18. An improvised way of filling eight drums simultaneously with contaminated soil. (See Section 10.3.)

19. Monitoring soil for contamination. (See Sections 8.3, 9.)

20. One of the specially made 5 tonne waste storage boxes. (See Section 10.3.)

21. Much of the decontamination work had to be done in heavy rain. (See Sections 9, 10.4.)

22. Stacking waste containers to be taken by lorry to the temporary storage site for radioactive waste. (See Section 10.3.)

23. Boxes and drums of waste stacked and covered at the temporary storage site. (See Sections 10.1, 10.2, 10.3.)

24. The temporary storage site, showing concrete bases with channels to permit sampling of runoff water. (See Sections 10.1, 10.4.)

25. E.F., 20 October 1987. A radiation induced lesion on the thigh caused by a fragment of the caesium-137 source carried in the trouser pocket. The large eschar at the centre of the lesion is typical following prompt gamma doses in excess of 50 Gy to the dermis and underlying tissue (to a tissue depth of 1–3 cm). About 25 days after irradiation. (See Sections 5.1, 5.3.)

26. E.F., 30 December 1987. Progression of the lesion on the thigh. Injury has extended into musculature of the thigh. A series of wound debridements had been accomplished. Lesion approximately 100 mm × 120 mm. (See Sections 5.1, 5.3.)

27. Waste containers at the temporary storage site. Between 25 October and 19 December, 275 lorry loads of waste were transported to the site. (See Section 10.1.)

28. O.F.1., 11 October 1987. Large bulla on palmar surface of the hand of an individual who helped remove the caesium-137 source. Note wet desquamation on thumb and fingers. About 19 days after irradiation. (See Sections 5.1, 5.3.)

29. O.F.1., 28 October 1987. Lesion on palmar surface of the hand, showing progression of injury. Bulla has completely broken down and injury has extended to index and middle fingers. Note terminal phalanx of index finger used to extract caesium-137 from source capsule. About 36 days after irradiation. (See Sections 5.1, 5.3.)

30. O.F.1., 30 November 1987. Partial healing of lesion on palmar surface of the hand. Taken about 69 days after irradiation. (See Sections 5.1, 5.3.)

31. Superficial beta skin injury (in healing stage) to lower extremities of an individual who underwent extensive contamination with caesium-137. About 60 days after irradiation. (See Sections 5.1, 5.3.)

32. The improvised whole body counter used in Goiânia. Note the unusually large separation between patient and detector and the use of a leisure chair. (See Sections 5.2, 6.1.)

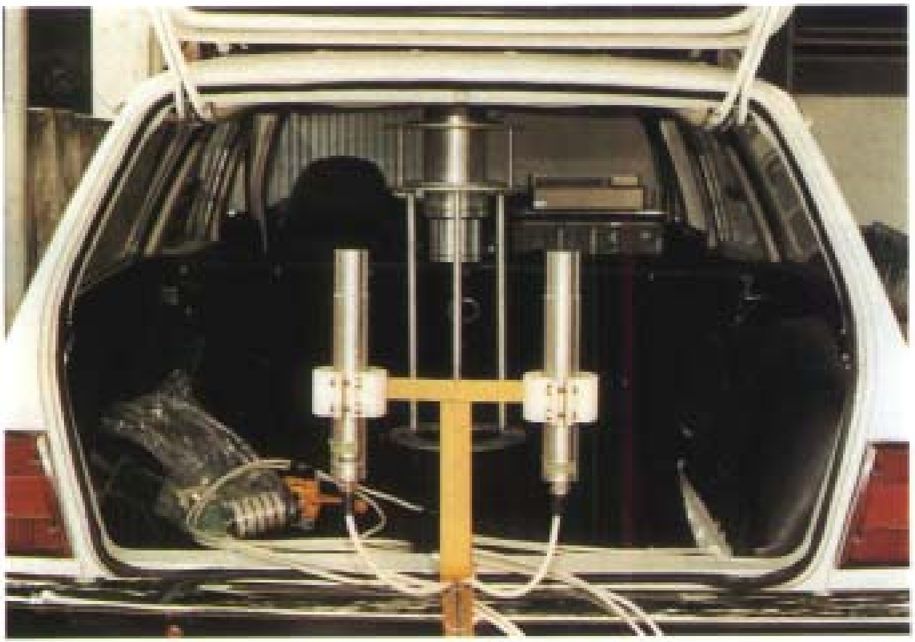
1. *The derelict radiotherapy clinic in Goiânia from which the caesium source was taken.*

2. *The derelict radiotherapy clinic in Goiânia from which the caesium source was taken.*

3. *The derelict radiotherapy clinic in Goiânia from which the caesium source was taken.*

4. *The physicist W.F. monitoring for contamination at the Olympic stadium.*

5. *Monitoring people for contamination at the Olympic stadium.*



6. *Mobile radiation monitoring: NaI and GM detectors mounted on a car.*

7. *Preparing to demolish the house of E.F.2 and S.F.1. near Junkyard I.*

8. *Monitoring the roof of the house of E.F.2 and S.F.1 during demolition.*

9. Contaminated bundles of paper that had been collected by the junkyards for recycling.

10. A hole is made to remove a radiation hot spot giving a dose rate of 0.5 $Sv \cdot h^{-1}$.

11. Clearing the site at Junkyard II on 6th Street.

12. Junkyard II: cutting up contaminated girders.

13. Contaminated rubble from the demolition of R.A.'s house on 57th Street.

14. The same site after removal of the contaminated rubble.

15. *Removing contaminated items from Junkyard III.*

16. *Cutting up contaminated items for removal from the warehouse of Junkyard III.*

17. Decontaminating a vehicle. About 50 contaminated vehicles were found.

18. An improvised way of filling eight drums simultaneously with contaminated soil.

19. Monitoring soil for contamination.

20. One of the specially made 5 tonne waste storage boxes.

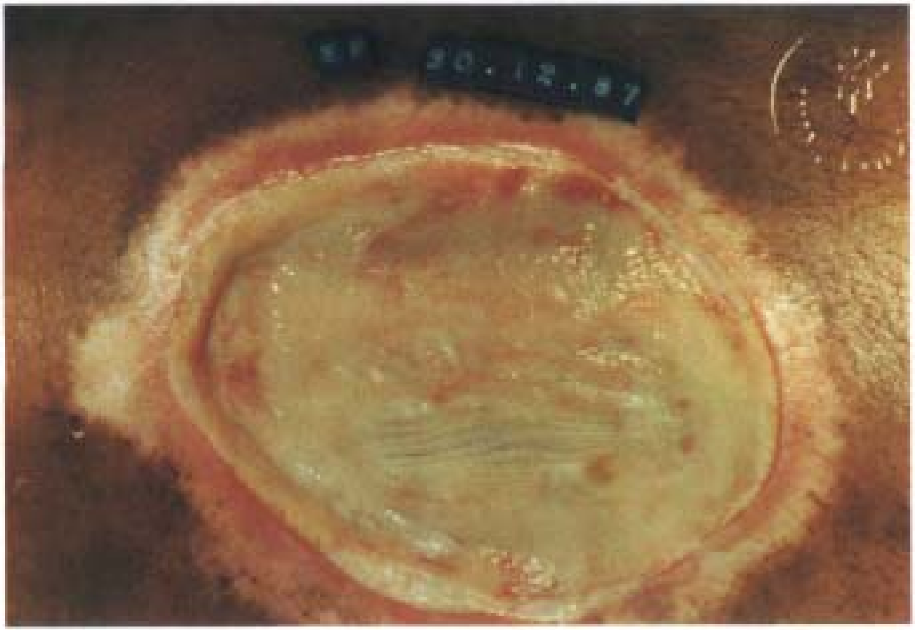
21. *Much of the decontamination work had to be done in heavy rain.*

22. *Stacking waste containers to be taken to the temporary storage site.*

23. Boxes and drums of waste stacked and covered at the temporary storage site.

24. The temporary storage site, showing concrete bases with runoff sampling channels.

25. *A radiation induced lesion on the thigh about 25 days after irradiation.*



26. *Injury has extended into musculature of the thigh. Lesion 100 mm × 120 mm.*

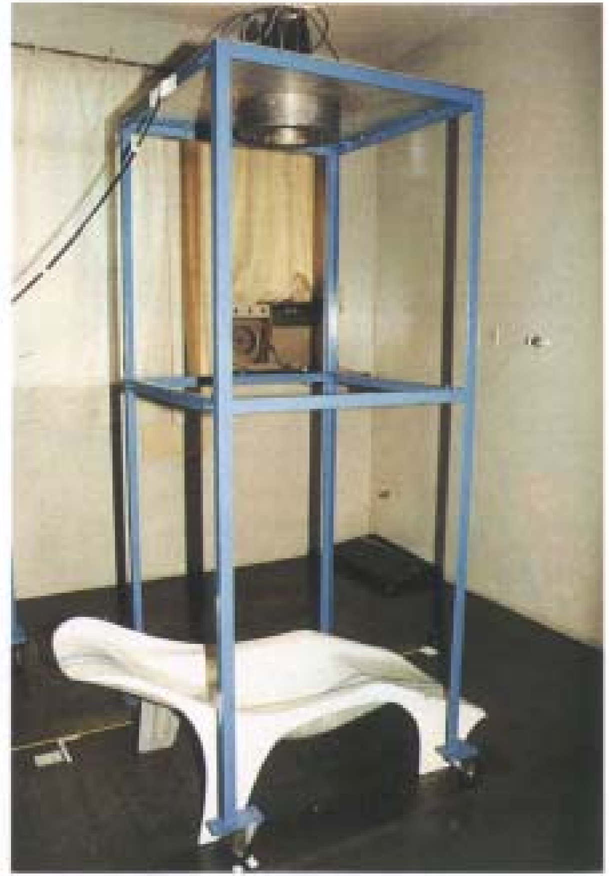
27. Waste containers at the temporary storage site.

28. Large bulla on palmar surface of the hand. Note wet desquamation.

29. *Bulla completely broken down and injury extended to index and middle fingers.*

30. *Partial healing of lesion on palmar surface of the hand.*

31. *Superficial beta skin injury (in healing stage).*



32. *The improvised whole body counter used in Goiânia.*

Appendix I

INTERNATIONAL CO-OPERATION

Before the accident in Goiânia

The institutes of CNEN were capable of doing what was necessary to manage the accident in Goiânia, including the assessment of radiation doses, the diagnosis, prognosis and treatment of the overexposed persons, and dealing with the severe environmental contamination.

An IAEA–Brazil co-operation programme on emergency preparedness had made a significant contribution to their preparedness. This programme started with an expert mission to Brazil well before the accident in Goiânia, and led to the construction of laboratories and the training of staff through fellowships and expert missions. The first project included the training of a physician in dealing with radiological accidents, a capability that proved extremely useful in responding to the accident.

In the response to the accident

The Brazilian authorities informed the IAEA of the accident soon after its discovery, and requested assistance under the terms of the international Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. The assistance given included the provision of experts and equipment. (See Table VI for details.)

Since the accident

Since the accident, numerous collaborative activities have been undertaken by Brazilian and other experts to evaluate the experiences and to learn lessons from it. The international review upon which this report is based is one such activity. Among others, the experience of providing and co-ordinating international assistance will be evaluated to determine how such an operation might be improved in the future.

The accident in Goiânia has generated a large database that can yield information of continuing value in a wide range of fields. A number of scientific research projects are under way, others are planned and more may be proposed. It should be the task of international organizations to foster the exchange of information on the lessons learned from the accident.

TABLE VI. INTERNATIONAL CO-OPERATION IN THE RESPONSE TO THE ACCIDENT IN GOIÂNIA

Country/ organization	Type of collaboration	Type of assistance	Field of work	Institution of origin
Argentina	Bilateral	Expert	Medicine	National Atomic Energy Commission
Argentina	Bilateral	Expert	Radiation protection and waste disposal	National Atomic Energy Commission
CEC, Ispra	Technical co-operation	Equipment	Radiation protection	
France	IAEA	Equipment	Radiation protection	
France	Bilateral	Expert/equipment	Medicine/radiation protection	
Germany, Federal Republic of	Bilateral	Expert/equipment	Radiation protection	Institut für Strahlenschutz, Munich
Germany, Federal Republic of	IAEA	Equipment	Radiation protection	
Hungary	IAEA	Equipment	Radiation protection	
IAEA	Technical co-operation	Expert/equipment	Radiation protection	
Israel	IAEA	Equipment	Radiation protection	

Japan	Voluntary	Expert	Medicine	Institute of Therapeutically Difficult Diseases
Netherlands	IAEA	Equipment	Radiation protection	
USSR	Voluntary	Expert	Medicine	Central Hospital No. 6, Moscow
United Kingdom	IAEA	Equipment	Radiation protection	
USA	Voluntary	Expert/equipment	Medicine	University of California
USA	Voluntary	Expert	Medicine	Boston City Hospital
USA	IAEA	Expert	Radiation protection	Department of Energy Radiation Emergency Assistance Center/ Training Site, Oak Ridge (REAC/TS)
USA	IAEA	Expert	Medicine	REAC/TS
World Health Organization	Technical co-operation	Expert	Radiation protection	WHO

Observations

- The IAEA should consider providing more emergency preparedness training at the regional level that would include: participation by persons experienced in emergency response within the region, and practical field exercises under conditions typical of the region.
- The IAEA should co-ordinate arrangements for periodic regional exchange of information on respective strengths and weaknesses in emergency response preparedness.
- The IAEA should continue in its aim to provide unbureaucratic assistance in an emergency.

Appendix II
PUBLIC COMMUNICATIONS

The accident in Goiânia had a great psychological impact on the Brazilian population owing to its association with the accident at the Chernobyl nuclear power station in the USSR in 1986. Many people feared contamination, irradiation and damage to health; worse still, they feared incurable and fatal diseases.

Some of the inhabitants of Goiânia were discriminated against, even by their relatives, and sales of cattle, cereals and other agricultural produce, and of cloth and cotton products, the main economic products of Goiás State, fell by a quarter in the period after the accident.

CNEN technicians conducted an inquiry in the period after the accident. They obtained the following results:

(a) About 90% of the inhabitants of Goiânia suffered no significant deterioration in their standard of living or in their circumstances at work.
(b) Of the persons involved in the accident, there were significant effects on the home environments of about 30% and on the work environments of about 30%.
(c) Of the individuals monitored for radioactive contamination, 74% had spontaneously gone to be monitored for fear of radiation.

In order to allay these fears, the working team was encouraged to explain to people what they were doing and why, and, for example, to accept offers of drinking water and food from people's houses. They thus gained people's confidence and raised the credibility of official statements.

Team workers made frequent appearances on television. Their approach was to draw analogies in simple language with common applications of radiation, such as for medical X-rays, and to recount as much as was known of the situation at the time.

In addition, if the co-ordinators found it difficult to explain some aspect of radiological protection to the public, talks were given for journalists, explaining in basic terms the applications and effects of radiation. A pamphlet was produced on 'What you should know about radioactivity and radiation', and 250 000 copies were distributed. A telephone service was operating 24 hours a day to answer inquiries or receive information about other possibly contaminated people or sites.

Several talks were given to different sections of the population and to community groups in order to restore confidence so that public life could proceed normally.

There were two distinct phases in the reaction of the communications media (the press, radio and television). The first was characterized by sensationalism, misinformation and criticism of the authorities. In the second phase there was a much more responsible coverage of events, seeking to inform the public and describing more clearly what was happening and what actions were taken by CNEN and the Federal and State Governments.

In order to encourage a more responsible presentation of events, CNEN personnel went to great lengths to clarify matters for the communications media, demonstrating and explaining their work. News reporters could accompany CNEN technicians engaged in decontamination work and attending to casualties.

Appendix III

THE ACCIDENT IN GOIÂNIA IN PERSPECTIVE

(excerpted from the IAEA's Nuclear Safety Review for 1987)

Serious radiation accidents

"Considerable information has been documented about accidents since 1945 with significant overexposure to radiation.[10] [See Tables VII and VIII.] Most of the accidents at nuclear facilities occurred early in the development of the applications

TABLE VII. SERIOUS RADIATION ACCIDENTS REPORTED (1945–1987)

Type of facility	No. of events	Overexposures[a]	Deaths
Nuclear facilities	27 (34%)	272 (64%)	35 (59%)
Non-nuclear facilities			
Industry	42 (52%)	84 (20%)	20 (34%)
Research	7 (9%)	10 (2%)	- (-)
Medical	4 (5%)	62 (14%)	4 (7%)
	80 (100%)	428 (100%)	59 (100%)

[a] An overexposure is taken here as exposure of the whole body, blood forming organs or other critical organs to 0.25 Sv or more; of skin to 6 Sv or more; other external exposure of 0.75 Sv or more; and internal contamination of half or more of the 'maximum permissible organ burden'. (The concept of the 'maximum permissible organ burden' has now been superseded by the concept of the 'annual limit of intake'.) The table excludes patient related events and off-site exposures at Chernobyl.

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[10] The Medical Basis for Radiation Accident Preparedness (Proc. REAC/TS Int. Conf. Oak Ridge, TN, 1979) (HÜBNER, K.F., FRY, S.A., Eds), North-Holland, New York (1980); UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Ionizing Radiations: Sources and Biological Effects, Report to the General Assembly, United Nations, New York (1982).

TABLE VIII. FATAL RADIATION ACCIDENTS REPORTED (1945-1987)[a]

Year	Location	Radiation source	Fatalities	
			Worker	Public
1945	Los Alamos, USA	Critical assembly	1	
1946	Los Alamos, USA	Critical assembly	1	
1958	Vinča, Yugoslavia	Experimental reactor	1	
1958	Los Alamos, USA	Critical assembly	1	
1961	Switzerland	Tritiated paint	1	
1962	Mexico City, Mexico	Lost radiography source		4
1963	China	Seed irradiator		2
1964	Germany, Federal Republic of	Tritiated paint	1	
1964	Rhode Island, USA	Uranium recovery plant	1	
1975	Brescia, Italy	Food irradiator	1	
1978	Algeria	Lost radiography source		1
1981	Oklahoma, USA	Industrial radiography	1	
1982	Norway	Instrument sterilizer	1	
1983	Constituyentes, Argentina	Research reactor	1	
1984	Morocco	Lost radiography source		8
1986	Chernobyl, USSR	Nuclear power plant	29	
1987	Goiânia, Brazil	Removed teletherapy source		4
Total: 17 events with 59 fatalities			40	19

[a] In nuclear facilities and non-nuclear industry, research and medicine (excluding patient related events).

of nuclear energy. Some were criticality accidents and several were at experimental reactors. Although the incidence of radiation accidents in nuclear facilities has decreased considerably over the years, the number of such accidents elsewhere has risen. Several accidents have affected members of the public. Some resulted in deaths when control was lost over high strength sources, which, unrecognized for what they were, ended up in the public domain.

"The general picture seems clear and well documented, even though some serious radiation accidents (for example, hand exposures of industrial radiographers) may not have been reported and, to that extent, information that would be useful for preventing similar accidents is unavailable. In comparison with the number of deaths caused by other types of industrial accidents every year, those due to accidental radiation exposure reported worldwide over 40 years are not many [see Table VIII]. However, the relatively good safety record for applications of radiation gives no grounds for complacency, especially where practicable, effective steps can be taken to reduce the risks of such accidents."

Appendix IV

LESSONS LEARNED BY CNEN

The following lessons were drawn by CNEN from the accident in Goiânia:

(1) A radiological accident entailing contamination due to the breaking up of a radioactive source can be aggravated if much time elapses before the discovery of the accident.

(2) The physical and chemical properties of a radioactive source are important factors in an accident. The records of sealed sources should contain that information. It is suggested that physical and chemical properties of sources should be taken into account in the licensing for manufacture of such sources, emphasizing the possible consequences of accidents or misuse.

(3) An adequate system of information is essential to avert panic on the part of the public. In general the public should be made aware of what radiation is and of its applications. A booklet explaining the special terms and units related to radiation should be available to the communications media. In the event of a radiological emergency, a group should be set up to present information in the legislative assembly, schools, churches and community associations, and so on, as well as to the news media. Personnel working in decontamination and attending to casualties should be instructed on how to convey information comprehensibly to the population. Their contacts with the individuals affected in the accident in Goiânia proved very important: people would gauge the seriousness of contamination by the reactions of the workers. The people most affected by the accident would judge whether their houses were really free of contamination by whether the CNEN personnel accepted water or coffee from them.

(4) An adequate system of social and psychological support should be provided following a radiological accident causing serious contamination. The psychological support should be provided to those individuals directly and indirectly affected and the personnel working in response to the emergency. Psychologists should be available for counselling, joining the group responsible for making quick decisions and planning action to be taken, and evaluating the possible stress to the casualties.

(5) The effectiveness of international assistance following a radiological accident depends on the infrastructure of the country concerned. Emergency training courses should be held in developing countries as well as in developed countries where facilities are available and work well. In general, these

programmes deal with emergencies responded to by strong organizations under a priori known conditions. In many countries circumstances are very different, equipment is diverse, the climate is adverse and matters are administered differently.

(6) A mobile system of first aid transportable by air should be available at all times.

(7) Appropriate international organizations should consider having ready for use a record of radiological equipment available. Such organizations should also consider having a set of radiological equipment at hand ready to be shipped. Customs regulations should be amended to facilitate the import and re-export of material and/or equipment. The establishment of regional centres for emergency attendance in every continent should be considered.

(8) Instrumentation should be capable of being adjusted to withstand field conditions, so that it can be used in high humidities, high temperatures and unstable environmental conditions. Personnel using instruments should be trained to be able to obtain a clear indication of dose rate response, for a wide range of doses; and to know the most suitable equipment in different conditions and its calibration factors.

(9) Records of available personnel resources according to field of work should be kept. Experts in each area of action should be available to be contacted in the event of an emergency to give support to the local radiological protection teams. These experts should be ready to advise actively in decision making and on intervention measures, and to participate in all the work that needs to be done. The experience of the accident in Goiânia indicated that supposedly 'better' reports had in fact been prepared by specialists who had not participated in the response.

(10) The provision of a temporary waste storage site near the area affected by a radiological accident is considered indispensable. A delay in the decision, usually a political one, on where to construct a site could permit greater dispersion of radioactive material in the environment.

(11) An infrastructure of civil engineering personnel should be available to participate in decontamination work.

(12) For decision making and the organization of working teams following a radiological accident, the hierarchy should be well defined. The assigning of responsibilities in the decision process, from planning to action and evaluation of consequences, should be very clear, and each group should be sure of its function. If possible, teams should be formed with a leader who heads the group in normal working conditions.

(13) In general, a programme of inspection of radiological equipment and facilities is very important; however, it is only effective if coupled with some kind of enforcement system, such as assigning civil or professional liability in licensing sources.

Annex I

RADIOLOGICAL SURVEY EQUIPMENT

This annex details the radiological survey and monitoring equipment used following the accident in Goiânia, with an assessment by the instrumentation group which supervised their use and its observations on the use of the equipment. Table IX gives an assessment of the performance of dose rate monitors. Table X presents a similar assessment for contamination monitors.

Observations

From their experience of using the equipment the CNEN team made the following observations:

(1) In order to protect monitors against the ambient environment, particularly radioactive contamination and rainwater, it was necessary to put them in plastic bags. This in itself caused some difficulty in taking readings and in general handling.

(2) There were continual problems with the cables of instruments having remote probes. Often they could be repaired, but it was necessary to acquire a large stock of replacement cables.

(3) Audible signals were found to be very useful in contamination monitoring, but in the presence of the public (such as in the monitoring of houses) it was necessary to mute the monitors, as the audible clicks gave rise to alarm.

(4) The proportional counters and ionization chambers were found to be sensitive to the high humidities encountered and were therefore less useful. The ionization chambers were also sensitive to high temperatures.

(5) Equipment with digital readouts was found to be sensitive to temperature and was difficult to read in bright sunlight, particularly when the monitors were in plastic bags.

(6) Rainwater (often heavy) got into the telescopic sections of the Teletector monitors, which then needed to be dried. This was done with a hair dryer.

(7) Lighter fuel gas was used to run the proportional counters. Unfortunately it was found that the quality of this gas available in Brazil was inadequate; the counters became clogged, resulting in a high failure rate.

(8) A number of the monitors had slow response times; this became important in the later phases of the response to the accident when lower dose rates and contamination levels were prevalent.

(9) Subsequently, scintillation dose rate meters became available. These were designed for geological survey work. They could readily measure down to the level of background radiation and had a very fast response time. They were found very useful in quickly identifying small hot spots. As an indication of the usefulness of the speed of response,

TABLE IX. ASSESSMENT OF PERFORMANCE OF DOSE RATE MONITORS

Type	Number used	Robustness	Resilience in adverse conditions	Response	No. of failures or repairs
GM tubes	27	Very good	Very good	Very good	3
Proportional counters	2	Very good	Acceptable	Excellent	1
Ionization chambers	16	Very good	Acceptable	Poor at low dose rates	1
Teletectors (telescopic)	7	Very good	Acceptable	Excellent	1
Teletectors (articulated)	3	Very good	Very good	Good	0

TABLE X. ASSESSMENT OF PERFORMANCE OF CONTAMINATION MONITORS

Type	Number used	Robustness	Resilience in adverse conditions	Response	No. of failures or repairs
End window GM tubes	11	Very good	Very good	Excellent	3
Proportional counters	7	Poor	Good	Excellent	5
Side window GM tubes	2	Very good	Very good	Adequate	0
Scintillation detectors	3	Very good	Very good	Very good	0

a contaminated bundle of paper was detected on a lorry passing by at 60 kilometres per hour. Their sensitivity was such that they could also be used for contamination monitoring in certain circumstances.

(10) The personnel in the initial response group were familiar with monitoring techniques but subsequently had to use equipment with whose characteristics and capabilities they were unfamiliar. Moreover, as the work progressed it was necessary to engage many health physics staff who had had little direct practical experience of monitoring work. There was therefore a need to provide basic training. Some problems nevertheless arose owing to the adoption of different measurement protocols.

Annex II

GUIDELINES FOLLOWED FOR THE DISCHARGE OF PATIENTS

Protocol adopted by the Brazilian authorities for the discharge of patients with internal contamination due to intake of caesium-137 on the basis of criteria relating only to the radiological protection of other persons and of the environment

Recommended limits

It is recommended that monitoring in whole body counters and 24 hour urine collection be carried out for individuals potentially having, or on patients admitted to hospital with, internal contamination. It is further recommended that only those persons whose levels of in-body radioactivity are lower than the applicable values given in Table XI, and the mean radioactivity of whose urine is less than 15 $kBq \cdot L^{-1}$ (0.4 $\mu Ci \cdot L^{-1}$), should be discharged from hospital to rejoin the community.

Theoretical basis

The limit for the release of caesium-137 into the sewerage system in compliance with the Brazilian standard CNEN-ME-6.05, Management of Radioactive Releases in Radiological Installations (1985), is 0.4 $\mu Ci \cdot L^{-1}$ (15 $kBq \cdot L^{-1}$). In fact this limit refers to the quantity which, on dilution with the average daily volume of sewage released by the installation, would result in a mean concentration of 0.4 $\mu Ci \cdot L^{-1}$.

It is suggested that this limit of 0.4 $\mu Ci \cdot L^{-1}$ be applied to the radioactivity of urine as a criterion for the discharge from hospital of patients with internal contamination. This limit does not take into account dilution of the urine in sanitary fittings and drains.

It was confirmed that the maximum effect of Radiogardase^R (Prussian Blue) is to bring about a rate of faecal excretion of caesium more than three times greater than the rate of excretion of caesium in urine; that is, a discharge rate of 15 $kBq \cdot L^{-1}$ in urine could correspond to up to 45 $kBq \cdot L^{-1}$ or more in faeces. However, in the case of faecal excretion, dilution in the sanitation system should be taken into account. The volume of diluent in this case would amount to at least 4 L. Hence faecal matter at this level of radioactivity can be released into the sanitation system without exceeding the limit for radioactive releases.

The limits suggested on radioactivity due to caesium-137 in the body are low enough for individuals in compliance with them to present no hazard to others due to external exposure.

Table XII gives the dose rates in contact with and at 0.3 m from a cylinder exhibiting the levels of radioactivity given in Table XI in uniform distribution, the dimensions of the cylinder being adapted for modelling in accordance with the respective age group.

TABLE XI. SUGGESTED MAXIMUM IN-BODY RADIOACTIVITIES FOR DISCHARGE FROM HOSPITAL, AS A FUNCTION OF AGE AND TIME SINCE INCORPORATION OF CAESIUM-137

Time after incorporation (days)	Maximum in-body radioactivity (μCi)[a]					
	Newborn	One year old	Five years old	Ten years old	15 years old	Adult
15	4.4	4.2	8.1	19.2	51.8	105.4
30	4.4	4.2	10.2	28.9	60.0	110.7
45	4.4	4.4	11.8	34.4	69.0	110.7
60	4.4	4.6	12.8	36.4	69.0	110.8
75	4.4	4.7	13.3	37.0	69.0	110.7
90	4.4	4.8	13.5	37.2	69.0	110.7
105	4.4	4.9	13.6	37.3	69.0	110.7
120	4.4	4.9	13.7	37.3	69.0	110.7
135	4.4	5.0	13.7	37.3	69.0	110.8
150	4.4	5.0	13.7	37.3	69.0	110.8
165	4.4	5.0	13.7	37.3	69.0	110.8
180	4.4	5.1	13.7	37.3	69.0	110.8
240	4.5	5.7	13.7	37.3	69.0	110.8
300	4.5	4.1	13.7	37.3	69.0	110.7
360	4.4	0.79	13.9	37.3	69.0	110.7

[a] 1 μCi = 37 kBq.

TABLE XII. EXPOSURE RATES CORRESPONDING TO THE MAXIMUM IN-BODY RADIOACTIVITIES GIVEN IN TABLE XI

In-body radioactivity (μCi)[a]	Exposure rate ($mR \cdot h^{-1}$)[b]	
	In contact	At 0.3 m
Newborn		
4.4	0.13	0.008
One year old		
4.2	0.05	0.005
4.4	0.05	0.005
4.6	0.06	0.006
4.7	0.06	0 006
4.8	0.06	0.006
4.9	0.06	0.006
5.0	0.06	0.006
5.1	0.06	0.006
5.7	0.07	0.007
4.1	0.05	0.005
0.79	0.01	0.001
Five years old		
8.1	0.04	0.007
10.2	0 05	0.008
11.8	0.06	0.010
12.8	0.07	0.011
13.3	0.07	0.011
13.5	0.07	0.011
13.6	0.07	0.011
13.7	0.07	0.011
Ten years old		
19.2	0.06	0.011
28.9	0.09	0.017
34.4	0.10	0.020
36.4	0.11	0.021
37.0	0.11	0.021
37.2	0.11	0.021
37.3	0.11	0.021

TABLE XII. (cont.)

15 years old		
51.8	0.09	0.021
60.0	0.10	0.024
69.0	0.12	0.028
Adult		
105.4	0.13	0.034
110.7	0.14	0.036
110.8	0.14	0.036

[a] 1 μCi = 37 kBq.

[b] 1 mR = 0.258 $\mu C \cdot kg^{-1}$.

Annex III

RADIOLOGICAL PROTECTION

Operational protection at medical installations

Almost all the patients admitted to the Goiânia General Hospital and to the Marcilio Dias Naval Hospital in Rio de Janeiro as a result of the accident had significant amounts of internal contamination, particularly those at the latter. This gave rise to both external irradiation and significant contamination problems. For example, gamma dose rates close to the patients on their arrival at the hospital varied from about 10 $\mu Sv \cdot h^{-1}$ to 15 $mSv \cdot h^{-1}$ (close to contaminated wounds). An extensive monitoring and health physics supervisory programme that had to be integrated with the overriding medical requirements was therefore necessary. Controlled areas with appropriate barriers and working procedures had to be set up for the wards and a separate decontamination facility had to be provided.

Bioassay monitoring of excreta was clearly necessary. The samples themselves, with levels of radioactivity of up to 30 $MBq \cdot L^{-1}$ (urine) and 75 $MBq \cdot L^{-1}$ (faeces), posed a contamination problem, both at the hospital and at the monitoring facility (see Section 6.1). However, of more relevance in health physics terms was the fact that caesium-137 was being excreted in the patients' sweat. Although the patients could be periodically decontaminated, they were thus acting as mobile regenerable sources of contamination.

Routine contamination measurements were made to determine the need for decontamination, and the patients, when this was medically acceptable, used showers to decontaminate themselves. The basic data on levels of radioactive contamination in controlled areas were recorded. Variations in the measurement protocols make it difficult to interpret the results, but levels of 10^5–10^6 $Bq \cdot m^{-2}$ were frequently found in the controlled areas. In view of the potential for resuspension, air monitoring was also undertaken in some wards at the Marcilio Dias Naval Hospital, but radioactivity levels were found to be low. Water and solid effluents were also monitored.

Where possible, plastic sheeting was put on floors and walls to facilitate decontamination. Experience in the first week or so necessitated changing some of the working procedures. Special procedures had to be followed in performing autopsies on the four casualties who died.

In order to provide appropriate health physics cover at the Naval Hospital, two 12 hour shifts of four health physics staff were needed for the wards, for access control and monitoring of personnel and waste. A further four were required also, to deal with decontamination of areas and clothes, and to arrange the transport and movement of patients.

Personnel who entered the controlled area were monitored with film badges and QFE pens, and where there had been contact with patients, with TLD finger dosimeters. During the period when patients were in hospital, no occupational dose exceeded 5 mSv.

Operational protection in Goiânia

The remedial actions in Goiânia gave rise to a significant potential for occupational exposure, both externally and internally, and as such required resources to be dedicated to the control of exposure. The basic principles observed and the procedures adopted were those that are common to most establishments concerned with radiation. However, the circumstances under which they were put into practice, in adverse environmental conditions and in facilities not designed for radiological uses, were unusual. This required a pragmatic approach, combining flexible thinking with a sound understanding of radiological protection.

At the main foci of contamination, there were numerous spots where dose rates were of the order of tens of millisieverts per hour and some where they exceeded 1.0 $Sv \cdot h^{-1}$. Work in these areas during the decontamination had to be planned, often with the predicted doses a limiting factor. To help in this planning and in the general control of doses, authorized dose limits were set for various time periods, namely:

1.5 mSv per day;
5.0 mSv per week;
15.0 mSv per month;
30.0 mSv per quarter.

Occupational doses were monitored using film badges, but continuing dose control was mainly on the basis of the daily readings from QFE pens. In total some 450 of these were used (75 of them coming from the IAEA and 221 from France). The problem of high ambient humidity was exacerbated by their being worn between two sets of clothes, causing them to be easily discharged if care was not taken with the end caps. The provision of dose instruments with direct readout that work in the ambient environments of accidents is an important point for emergency response planners to consider.

Contamination control was a major difficulty, requiring the use of suitable protective clothing and the adoption of good working practices. The ambient environment was such that the usual disposable coveralls were found to be unsuitable, and cloth coveralls were used instead. A dedicated laundry, albeit somewhat primitive, had to be set up. Good working practices were promoted by supervision, training and the use of written procedures. Training was particularly important since, as is likely to be the case in any major accident, the workforce included a large body of people who had had little or no previous experience of work with radiation (in this case about two thirds of the workers). Even many of the professional people had had no direct operational experience and required some training.

Personnel monitoring

External exposure

In total, 755 workers participated in some way in the response to the accident in Goiânia. They were working at Junkyards I, II and III; in 57th Street where the source capsule was ruptured; where the bundles of contaminated paper were found; at the waste repository; at the Tropical Diseases Hospital; at other hospitals in Goiânia; and at the Marcilio Dias Naval Hospital in Rio de Janeiro. Different groups were working in the areas of instrumentation and dosimetry, administration, decontamination, residences, and searching for further contamination sites and receiving complaints from the public.

Of these workers, only 262 had previously worked in or had received some training in radiological protection work. The others had occasionally worked with ionizing radiation, and were called upon in the response to the accident or owing to their specialities (dosimetrists, for example).

Personal dosimetry for all workers was by the use of dosimetric film badges that were changed after one month or at the end of each period of work. The badges were sent to the Institute of Radiation Protection and Dosimetry (IRD) in Rio de Janeiro and the results were sent back to a central control system in Goiânia.

The use of QFE pens was initially restricted to a very small group, but eventually some 450 people wore them. The dosimetric control of the QFEs was done daily. Each morning, each worker took two QFEs (0–200 mR and 0–5 R), and at the end of the day the dose was registered in an individual file, which also recorded the worker's area of work. Every day this file was processed with a computer program that compiled the data.

The dosimetric film badges were supplied by IRD. The QFEs came from various laboratories and some were calibrated in the institutions they came from (more than half were calibrated at IRD) In order to check the QFEs, eight would be chosen at random every day and exposed to caesium-137 sources overnight. The next morning their readings were registered, as well as the variation. Any that were more than 20% in error were removed.

The 583 accumulated dose values recorded from a total of 755 workers in the period from 30 September to 21 December 1987 show that 67.6% of the workers received doses of less than 1 mSv and 100% received less than 16 mSv. The latter value is smaller than 30 mSv, the CNEN quarterly authorized limit for this accident. The mean dose was determined for each specific task group. The largest value was 4.7 mSv in three months for the group working on the decontamination of the main foci.

Internal contamination

A total of 194 persons who occupationally participated in the response to the accident were monitored for internal contamination in IRD's whole body counter. Of these, 38 people had contents of radioactive material in the body that exceeded the minimum detectable level of radioactivity (74 Bq in a counting time of 30 min) The highest level of in-body radioactivity was 2.0 ± 0.3 kBq, corresponding to a committed dose equivalent of about 10 mSv.

Exposure of the public

The radiometric research and the external exposure estimates indicated that the exposures of the public were as follows in sites identified as foci of contamination:

(a) Near the foci

— In the house in 57th Street behind No. 68, estimated external doses of between 0.08 and 0.12 Sv were obtained (taking into account the time period from the rupture of the source to the isolation of the area) Five people lived in this house.

— In the other adjoining houses in 57th Street, the integrated external doses were estimated to be between 0.8 mSv and 0.012 Sv;

— In the vicinities of the other principal foci, the integrated external doses were estimated at between 0.2 and 9 mSv.

(b) Distant sites

— In Anapolis, three houses had hot spots at up to 250 $mR \cdot h^{-1}$ (1 R = 258 $\mu C \cdot kg^{-1}$) and in three others in Aparecida de Goiânia there were spots with rates of up to 30 $mR \cdot h^{-1}$. These houses were exceptional in that they were visited by people who had been in direct contact with caesium-137.

(c) In the streets

— The integrated doses in the streets in this period were estimated at between 1 12 mSv and 1.73 mSv.

(d) Transport of the remnants of the source assembly

— A reconstruction was made of the interior of the bus in which the remnants of the source assembly were taken by M.F.1 and G.S. from Junkyard III in P-19 Street to the Vigilância Sanitária in 16A Street. This enabled an estimate to be made of the maximum dose that a hypothetical passenger in the most disadvantageous disposition to the source would receive in 15 minutes, the estimated maximum time period for the journey. It was determined that this dose would not have exceeded 0.3 Sv to the legs. At a separation of 1.40 m from the source, this figure would fall to 0.04 Sv, with no account taken of any additional shielding of the beam.

(e) Vigilância Sanitária

— Investigations were made to identify workers at the Vigilância Sanitária who could have been in direct contact with the source or who had been in the neighbourhood of the courtyard where the remnants of the source assembly were deposited on 28 September

On the basis of this information, the conclusion was reached that many people could potentially have been exposed. From the assessments of these people, only four had measurable doses estimated by cytogenetic analysis; namely, 0.2 Gy, 0.3 Gy, 0 5 Gy and 1.3 Gy. The only person with a detectable level of internal contamination reached 0 74 GBq. These people are being closely supervised by specialists in radiological medicine from CNEN, together with the staff of doctors of the Health Ministry of Goiás State in a regular clinical and analytical evaluation.

Fewer than 1000 people were found to have incurred doses due to external exposure higher than one year's dose due to exposure to natural background radiation. The preliminary reconstruction of conditions based on the inventory of the source in these places enables it to be stated that more than 97% of these 1000 people were exposed to doses between 0.2 Sv and 0.01 Sv.

From 30 September to 22 December, the station centre of CNEN in the Olympic stadium in Goiânia monitored around 112 000 people. Of these people, 249 were identified

TABLE XIII. DOSES INCURRED IN THE ACCIDENT IN GOIÂNIA

Number of people	Committed dose (70 years) (Sv)
45	<0.005
42	0.005–0.05
33	0.05–1.0
4	1–2
2	2–3
1	3–4
1	5–6
1	7

with external or internal doses indicative of contamination. Of these, 129 people exhibited both internal and external contamination. Bioassays and monitoring in the whole body counter installed by CNEN in Goiânia gave the results shown in Table XIII.

Of this last group, 49 people were admitted to hospital. Of these 49, 20 casualties needed intensive medical care. Among these patients, ten were in critical condition with complications in the clinical course and radiodermatitis. Four patients died, and the forearm of one patient had to be amputated. The surviving patients were discharged after treatment for internal and external decontamination, and are now under medical supervision as out-patients.

Annex IV

CHEMICAL DECONTAMINATION

(The following is a summary of technical notes provided by Brazilian experts on chemical decontamination techniques used in the Goiânia accident. It is assumed that a more detailed technical description of such techniques will be published in the literature.)

Caesium contamination in Goiânia: chemical aspects

The mechanism of contamination with caesium is discussed before the discussion of methods of decontamination. Caesium-137 chloride from the original source (mixed with a support matrix) is leachable by water and aqueous solutions or layers. The crystalline energy of caesium chloride is low, and its solubility in water is very high (approximately 2 kg per kg water, at 30°C). $(Cs^+)_{aq}$ ions are somewhat smaller than $(K^+)_{aq}$ ions, and readily substitute for these in compounds of low solubility, such as silicates and ion exchangers, mineral or organic. These processes involve equilibrium thermodynamics and, although Cs^+ compounds with large anions are less soluble than K^+ compounds, and Cs^+ ions substitute readily for all alkali ions in ion exchangers, Cs^+ ions can be dislocated by K^+ ions and even Na^+ ions in concentration effects.

The main materials affected by Cs^+ ion transport and contamination were people and animals, soils (several silicate materials, mainly clay, a double sheet silicate with ion exchange properties, especially for Cs^+ ions), aqueous solutions, concrete and cement.

The original caesium chloride was hydrated and liberated Cs^+ ions. These were absorbed by people's skin, by aqueous layers of soils and by buildings. (This may be termed 'primary contamination'.) In soils, Cs^+ ions were retained by clay silicates by ion exchange, as they were by silicates in concrete and cement.

People were contaminated very seriously by this primary process. From the skin, Cs^+ ions were transferred to the muscles and the blood stream. In some cases caesium was ingested, taking Cs^+ ions directly to the stomach and intestines and to the blood stream.

Secondary processes occurred from contaminated soil: people and animals and rainwater transferred contamination to buildings, causing transfer of Cs^+ ions by competitive mechanisms. Contaminated soil formed dust that transported Cs^+ ions to skin and to buildings and roofs and so on. There, with the help of aqueous layers or rainwater, equilibration again caused secondary contamination. People inhaled air contaminated with dust, leading to secondary contamination.

Significant primary and secondary contamination were caused by people and animals carrying the original source and transferring Cs^+ ions in sweat, urine, saliva and faeces. These carriers yielded Cs^+ ions in a very soluble form, adsorbed more intensively than if carried by soil or dust. This contamination interacted much more strongly with cement, concrete, paint coatings, synthetic organic materials and phenolic resins. Some oil coatings contain Prussian Blue as a pigment It is known that this pigment strongly accepts Cs^+ ions as a result of ion exchange with K^+ ions (or Fe^{3+} ions, in a less favourable process).

Preparatory laboratory work

IRD's Laboratory of Mineral Analysis provided supporting chemical analysis and a study of the kinetics of the removal of Cs^+ ions by hexacyanoferrate ions (Prussian Blue), $[Fe(CN)_6]^{4-}$, in suspension, for the purposes of washing contaminated people at the Marcilio Dias Naval Hospital. A 0.5% suspension of Prussian Blue showed 99.9% retention of Cs^+ ions by the exchange of K^+ ions. The product (of the Pharmaceutical Laboratory of Marinha, Rio de Janeiro) was found to be $K \cdot Fe \cdot Fe(CN)_6$ (termed PBK), with a solubility of less than 10^{-12}. By contrast, tests of commercial Prussian Blue used as pigments gave only 30% retention. Further studies of Prussian Blue were then done on caesium-137 sorption and desorption in high clay content soils; on decontaminating urine and liquid wastes; and on reagents for personal decontamination.

Soil sorption and desorption

Urine containing caesium-137 was passed through one litre columns of soil similar to the soil in Goiânia. (Parallel batch experiments were run.) Potassium alum and Portland cement suspensions were proposed to fix Cs^+ ions on soils like the soil in R.A.'s yard, where perhaps 18 TBq (500 Ci) remained. Tests showed that alum solutions (containing K^+, Al^{3+} and SO_4^{2-} ions) desorbed Cs^+ ions completely by exchange with K^+ ions and by coagulation of clay minerals. The best retention was achieved by PBK precipitation. (A proposal to use kaolinite was rejected, as such suspensions are filtered by soil, slow down percolation and have a lower capacity for caesium uptake.)

Decontamination processes for urine and liquid wastes

In tests of ion exchangers, caesium-137 was very effectively removed with strong acid and PBK loaded cation resins, even in the presence of high concentrations of Na^+ ions, Ca^{2+} ions and Al^{3+} ions. Anion exchange resins loaded with PBK had a lower efficiency. Columns of one litre volume (2 in × 0.5 m) made of polyvinyl chloride (PVC) tubes were used in Goiânia at hospitals and in the decontamination work.

Products for the external decontamination of people

Creams and gels containing ion exchangers were applied to the skin. Cs^+ ions on the surface of the skin and, by means of transport and chemical equilibration, transferred internally, are replaced by Na^+ ions, H^+ ions or K^+ ions, depending on the exchange material: *Na^+ cation exchange resin (RNa, sulphonated polystyrene type); H^+ ion resin (RH)*; or PBK resin (RAPK). Carboxymethylcellulose, glycerine and kaolinite yielded consistent creams, easily forming layers 2–5 mm thick on the skin. RNa, exchanging Na^+ ions for Cs^+ ions, was gentler on the skin, but RH produces HCl on the skin, causing irritation. RAPK was the most active resin. (On the basis of these tests, the Goiânia General Hospital used RAPK to treat contaminated patients.)

Chemical decontamination work

A 20 person chemical decontamination group was set up in Goiânia with staff from IRD, IPEN, IEN, NUCLEBRAS, FURNAS and the Federal University of Rio de Janeiro, with a field laboratory in 57th Street. Field training dealt with the kinds of problems they would face and with selecting the most suitable processes in each situation.

As circumstances required, each subgroup of two to four people usually designated one member for monitoring. Surface contamination detectors were the instruments used most widely. Chemical decontamination was performed for contamination causing exposure rates of up to 15 $R\cdot h^{-1}$ (1 R = 258 $\mu C\cdot kg^{-1}$).

The following illustrates the variety of items that had to be dealt with:

— Vigilância Sanitária: floors, walls, tables, typewriters, chairs, concrete;
— Goiânia General Hospital: rooms, decontamination room, bathrooms, floors, windows;
— Tropical Diseases Hospital: bedrooms, ceramic floors, bathrooms;
— COOJ institute for children and youth: rooms, chairs, walls, doors, restaurants, bathrooms, swimming pool;
— A bar: metal tables, chairs, cement floors;
— Building not demolished at Junkyard I: concrete floor, walls, roofs, cars, tools, machines, motors;
— Junkyard II: the remnants of the rotating assembly (excluding the source capsule) that had been taken from the IGR clinic, asphalt paving, neighbouring walls;
— Junkyard III: trucks, bicycles, heavy tyres;
— Yard of house at No. 68, 57th Street: soil (treated with acid solutions of alum, followed by PBK loaded cotton towels, using fixed and lead shielded polyurethane foam rectangles; during work with back-loaders, PBK suspension minimized the draining of Cs^+ ions in heavy rain; back-loaders, trucks, tools and the street were decontaminated by water jet, sometimes including HCl–Al–PBK);
— Olympic stadium: bathrooms, sanitation systems, asphalt street, cars, drum press;
— Private houses: floors, walls, bathrooms, kitchens, windows, gardens, household goods, refrigerators, furniture;
— Nos 58 and 80, 57th Street: houses, furniture, roofs (roofs were vacuum cleaned inside and washed with water jets outside; about 50% of surface radioactivity was removed by washing; inside, dust accounted for more than 90% of the radioactivity; radioactive solutions were chemically processed);
— Personal or valuable items: jewellery and clocks; money, documents and photographs; clothes;
— Marcilio Dias Naval Hospital in Rio de Janeiro;
— Excreta collected from hospital patients.

Methods of chemical decontamination

In view of the great variety of materials to be decontaminated, several decontamination processes were developed to achieve the fastest possible results with a minimum of destruction and waste:

— K-alum solutions, acidified with HCl (K-Al-HCl), for clay or cement floors and walls and for soil or soil contaminated materials and roofs (waste solutions collected and processed subsequently);
— Organic solvents, then K-Al-HCl: for wax or grease on floors or tables;
— Caustic solutions (NaOH) with detergents, then K-Al-HCl: for synthetic floors, some machines, typewriters, personal objects;
— Hexylene glycol or propylene glycol with HCl: for greasy cement floors, personal objects, jewellery;
— Halogenated hydrocarbons, then solvents: to blister then remove paint;
— HCl plus Prussian Blue plus K-alum (PBK-HCl-Al): for soils, concrete, cement, asphalt, papers (photographs, documents, money), clothes;
— Creams or gels with RAPK: for skin and delicate materials such as furniture, television screens;
— Hydrofluoric acid (HF) with HCl and APK: for vitrified ceramic surfaces (kitchens, bathrooms) and enamel coated surfaces (ovens, refrigerators, washing machines), granite and other silicate materials;
— Water jets: for dissolving and abrading surfaces (floors, roofs, walls, vehicles, back-loaders);
— Mechanical and chemical action (with K-Al-HCl and PBK-HCl-Al) with brushes and industrial polishing machines;
— Aspirators and polyurethane sponges: for recovering liquid waste from contamination;
— Chemical processing of solutions and suspensions with RAPK or APK (supernatant caesium was produced).

Processing of excreta at the CNEN laboratory in Goiânia

Two systems for processing contaminated urine were installed in Goiânia. They consisted of a sand plus active carbon filter, a reservoir (20 L, PVC) and two 1 L PVC columns 0.5 m long, in series, containing PBK loaded cation exchange resin. Diluted and acidified urine was allowed to percolate at a low flow rate through the columns, shielded with lead foil. The radioactivity and the dose rate were monitored regularly. After 50 L of urine had percolated (100 L of 1:1 solution or 100 column volumes), the caesium distribution had still not reached the end of the column. The distribution of radioactivity was measured with a Geiger-Müller detector with a lead window. The maximum radioactivity, corresponding to 7 $mR \cdot h^{-1}$, is centred at 0.1 m from the top of the column. When the flow is directed to the second column the first is replaced. Caesium free urine is yielded with the background level of radioactivity.

Faecal matter was processed in batch operations in 60 L drums, by dilution and reaction with PBK loaded resin to collect Cs^+ ions. Contaminated resins were sent to the storage site and the supernatant liquid was released at background levels of radioactivity. All faecal matter collected at hospitals and sent for analysis was so processed.

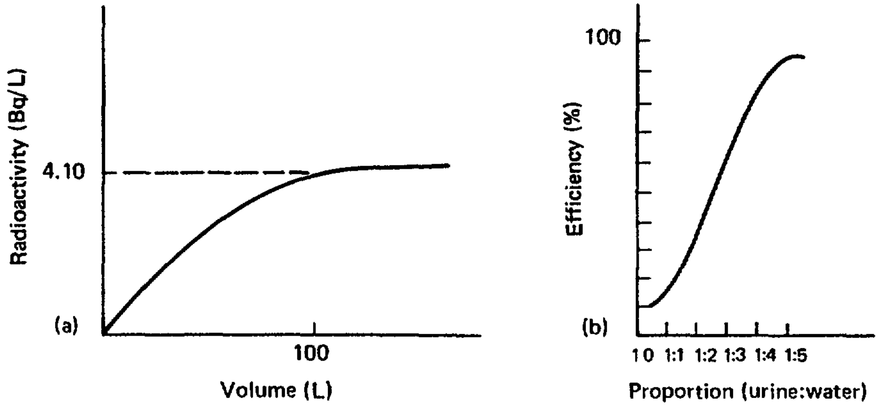

FIG. 25. (a) Quantity of caesium-137 retained by a volume of cationic resin as a function of the volume of dilute urine (one part urine to four parts water). (b) Variation of the efficiency of retention of caesium-137 as a function of the dilution of urine (at a flow rate of 6 $L \cdot h^{-1}$).

Radioactive wastes produced at the Marcilio Dias Naval Hospital

Radioactive wastes of many types were produced at the Marcilio Dias Naval Hospital following the accident in Goiânia. These wastes comprised hospital materials used for the medical care of patients and excreta of internally contaminated persons.

These wastes were segregated and treated. The method employed to treat faeces was to aggregate them with quicklime and cement; for urine, an ion exchange resin was used. Other types of radwaste were compacted or simply conditioned.

These wastes totalled nearly 3.5 tonnes of solids, 3 m^3 of urine and 350 kg of faeces, which were stored in a small installation for this purpose at CNEN/IEN in Rio de Janeiro.

The total radioactivity of caesium-137 released into the sewerage system between October 1987 and May 1988 was about 2×10^8 Bq.

S100-Lewatit cationic resin was used to decontaminate urine. The maximum efficiency obtained in this process was about 90% using a flow rate of 6 $L \cdot h^{-1}$ and a dilution of four parts water to one part urine. The saturation curve of the resin and the variation in its efficiency as a function of dilution are shown in Fig. 25.

Other materials were decontaminated, in the majority of cases, by normal washing with water and detergent. The total quantities of materials sent from the Marcilio Dias Naval Hospital to IEN for decontamination in the period from October to December 1987 were as follows: two ambulances; 1000 items of clothing (protective and hospital); 150 surgical instruments; 50 items of hospital equipment; and 50 objects for personal use.

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Emergency procedures adopted in the
Goiânia radiological accident

Radiological protection planning for people and the environment at the temporary waste repository site
Procedures for the packaging and collection of the radioactive waste generated.
Identification and classification of the contaminated areas
Methodology for packaging waste contaminated with caesium-137
Criteria for the classification of waste contaminated with caesium-137.
Criteria for the disposal of waste contaminated with caesium-137.
Determination of drinking water standards for caesium-137.
Establishing a dose limitation system for and assessing the doses of occupationally exposed personnel participating in the emergency response.
Criteria for the classification of contaminated areas and for their return to unrestricted use
Determination of the methods to be used for the classification of contaminated areas.
Determination of acceptable levels of surface contamination for the classification of contaminated areas and their return to unrestricted use.
Determination of the counting efficiency and calibration of the beta/gamma survey meter Eberline model E520 supplied with the probe model HP210 (Pancake)
Determination of the counting efficiency and calibration of the beta/gamma survey meter Eberline model E120 supplied with the probe model HP270 Series Nos 20 and 23.
Procedures for evaluating radioactivity levels in soils
Procedures for the normal operation of the washing machine SITEC, model SLEX-3

Criteria for the use of the washing machine owned by FURNAS with a capacity for washing 30 kg of clothes.

Criteria for segregating the clothes to be washed or decontaminated.

Criteria for storage in hospitals and disposal of excreta of the casualties of the radiological accident in Goiânia.

Evaluation of the source inventory.

Criteria for releasing clothes owned by the public and not contaminated with caesium-137.

Criteria for discharging patients contaminated with caesium-137 from hospital.

Procedures for collecting drums of radioactive wastes from the triage areas.

Radioactive waste management procedures for the site of triage and transport to the waste storage site.

Procedures for the transport of collected radioactive wastes.

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A:	IGR clinic	G	Physicist W F 's house
B:	Source first exposed	H:	Olympic stadium
C·	Junkyard I	J·	General Hospital
D·	Junkyard II	K, L:	Other contamination points
E	Junkyard III	M:	Initial CNEN command post
F·	Vigilância Sanitária	N:	Present CNEN office

FIG. 7. Plan of Goiânia showing the principal sites of contamination.

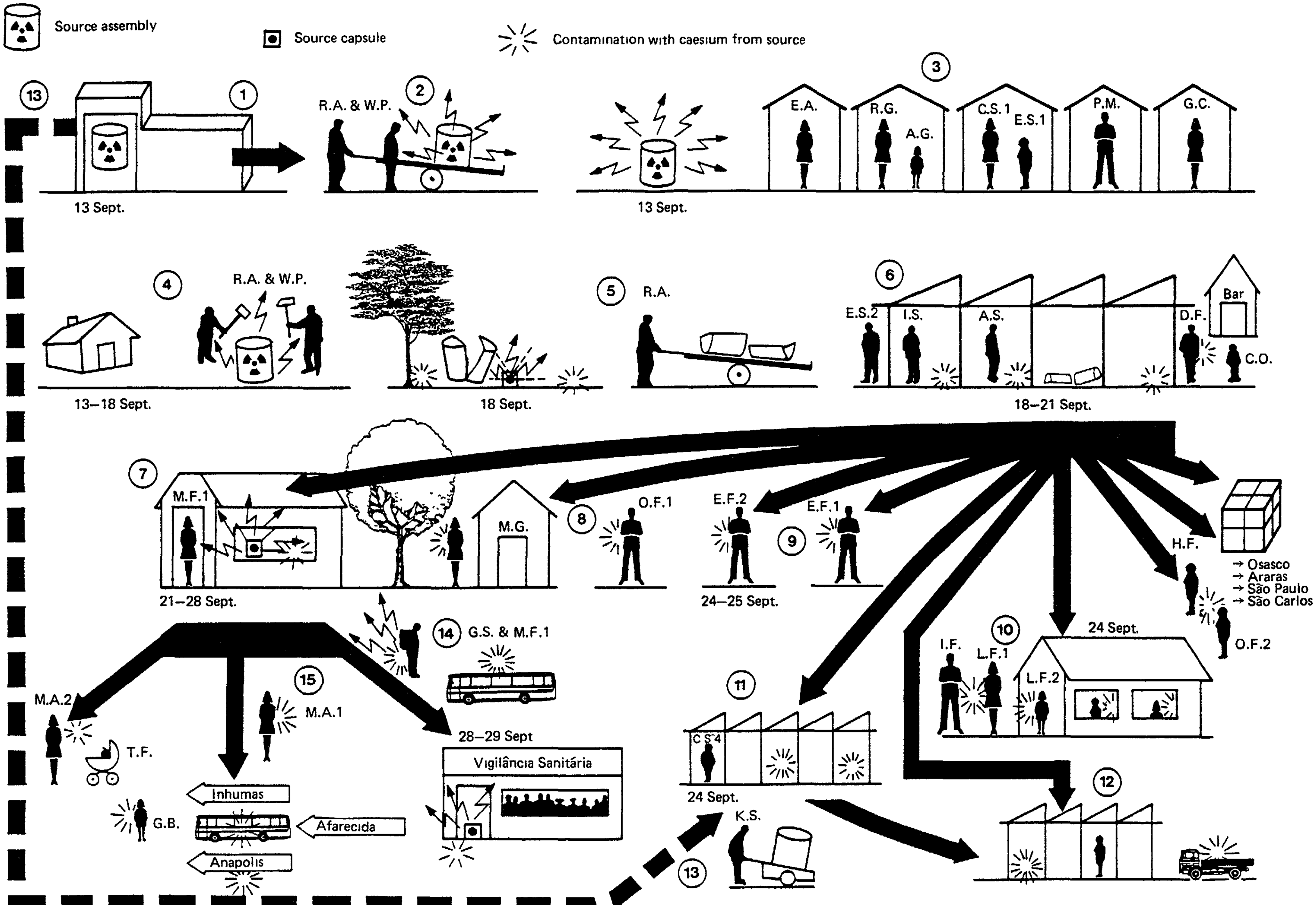

FIG. 8. Schematic diagram of the dispersal of caesium-137 in the accident in Goiânia. The diagram is based on a drawing made shortly after the discovery of the accident in attempting to reconstruct what had happened. It is reproduced in the format in which it was originally drawn even though it differs in minor details from what is now considered to be the best description of events (see the text of the report). Key: (1) the derelict clinic of the IGR; (2) removal of the rotating source assembly from an abandoned teletherapy machine by R.A. and W.P.; (3) source assembly placed in R.A.'s yard near houses rented out by R.A.'s mother E.A.; (4) R.A. and W.P. break up source wheel and puncture source capsule; (5) R.A. sells pieces of the source assembly to Junkyard I; (6) Junkyard I. the caesium chloride is fragmented and dispersed by I.S. and A.S. via public places; (7) D.F.'s house: contamination is further dispersed; (8) visitors and neighbours, e.g. O.F.1, are contaminated; (9) E.F.1 and E.F 2 contaminated; (10) I F.'s house; other arrows indicate dispersion via visitors and contaminated scrap paper sent to other towns; (11) contamination is spread to Junkyard II; (12) contamination is spread to Junkyard III, (13) K.S returns to the IGR clinic to remove the rest of the teletherapy machine to Junkyard II; (14) M.F.1 and G.S. take the source remnants by city bus to the Vigilância Sanitária; (15) contamination transferred to other towns by M.A.1. (By courtesy of CNEN, Brazil.)

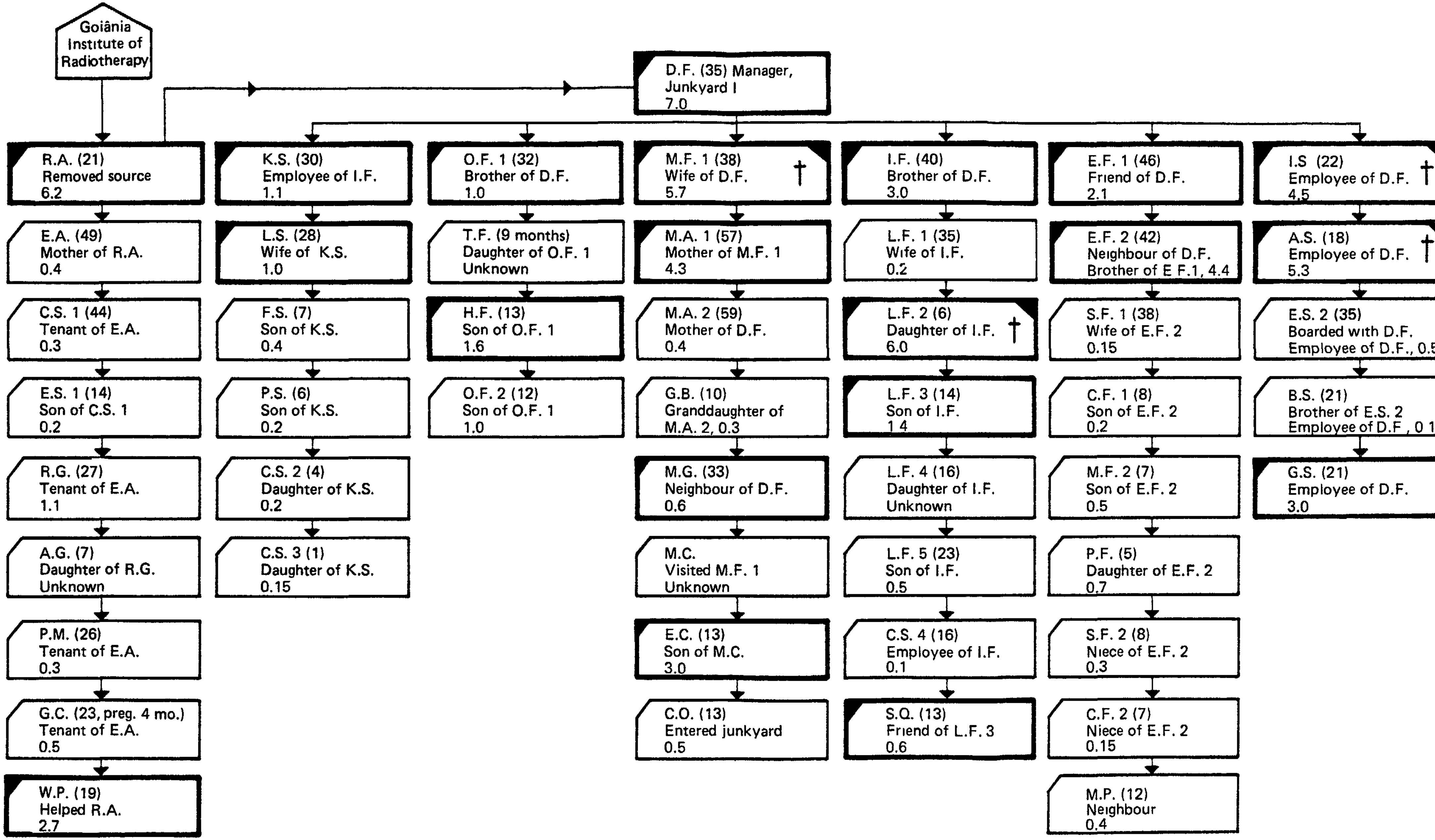

FIG. 9. The persons most highly contaminated in the accident in Goiânia, listed by site of exposure and family membership. Estimates from cytogenetic data of doses incurred (in grays) and information on those admitted to hospital and on the four fatalities are also given. (A thick black border indicates who was hospitalized; the other individuals were treated as out-patients.)