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Nature and magnitude of the problem of spent radiation sources

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FOREWORD

Various types of sealed radiation sources are widely used in industry, medicine and research. Virtually all countries have some sealed sources. The activity in the sources varies from kilobecquerels in consumer products to hundreds of petabecquerels in facilities for food irradiation. Loss or misuse of sealed sources can give rise to accidents resulting in radiation exposure of workers and members of the general public, and can also give rise to extensive contamination of land, equipment and buildings. In extreme cases the exposure can be lethal.

Problems of safety relating to spent radiation sources have been under consideration within the Agency for some years. A "spent source" means, in this context, a source which is no longer in use and for which no further use is foreseen.

This question received higher priority after the tragic accident in Brazil in 1987 which caused the death of four people and caused extensive contamination in the city of Goiânia. As a result the Agency has, in its plan for 1990 (GC(XXXIII)/875), included a special project to "review and assess both the magnitude and the nature of the radiological and disposal problems associated with old medical radium sources in Member States and the role the Agency should play in this connection". The project has since been extended to include other spent radiation sources which can be considered a potential hazard.

The first objective of the project has been to prepare a comprehensive report reviewing the nature and background of the problem, also giving an overview of existing practices for the management of spent radiation sources. This report is the fulfilment of this first objective.

The safe management of spent radiation sources cannot be studied in isolation from their normal use, so it has been necessary to include some details which are relevant to the use of radiation sources in general, although that area is outside the scope of this report.

The report is limited to radiation sources made up of radioactive material. It does not refer to radiation generated by particle acceleration.

It is intended to support the Agency's programme to improve management of spent radiation sources throughout the world, especially in the developing countries, but it can also be of use to national Competent Authorities and others concerned with the safe management of spent sources. During its preparation by Mr C. Bergman of the Waste Management Section, Division of Nuclear Fuel Cycle and Waste Management, valuable contributions were given by Staff Members of the Waste Management Section, Radiation Protection Section, Radiation Protection Service, and the former Head of the Agency's Seibersdorf Laboratories, Mr C. Taylor.

To facilitate reading the report there is a summary paragraph at the beginning of each chapter. This summary gives the main content of the chapter without giving any background or explanation.

EDITORIAL NOTE

CONTENTS

1. USE OF SEALED RADIATION SOURCES

1.1 What is a sealed radiation source?

Summary of 1.1 **A sealed radiation source is a small entity containing encapsulated radioactive material of high specific activity. Usually, it has the appearance of a small harmless piece of metal.**

A radiation source is any source capable of emitting ionizing radiation. The sources considered here are those which have radioactive material as their primary source of ionizing radiation (other sources can be X-ray tubes or particle accelerators).

Whenever the type of use allows this, the radioactive material is enclosed by non-radioactive material ("encapsulated") to improve radiation protection and safety by reducing the risk of loss of radioactive material during use. This combination of radioactive material and encapsulation is called a "sealed radiation source".

There are a number of different definitions of the term "sealed radiation source" (which is often abbreviated to "sealed source"). In the IAEA Glossary [1] a sealed source is defined as:

> "A source whose structure is such as to prevent, under normal conditions of use, any dispersion of the radioactive material into the environment."

The Commission of European Communities [2] has a slightly different definition:

> "A source consisting of radioactive substances firmly incorporated in solid and effectively inactive materials, or sealed in an inactive container of sufficient strength to prevent, under normal conditions of use, any dispersion of radioactive substances."

A third definition can be found in the ISO (International Standards Organisation) standard for sealed sources [3]:

> "Radioactive source sealed in a capsule or having a bonded cover, the capsule or cover being strong enough to prevent contact with and dispersion of radioactive material under the conditions of use and wear for which it was designed."

In an ISO standard [4] there are also specific requirements and test procedures specified for sealed radiation sources.

Although the IAEA definition is short and concise, the ISO definition, which is in no way in contradiction to the IAEA definition, gives a better understanding of what is meant by "source" in this report, since it specifically mentions the encapsulation.

In sealed radiation sources the encapsulation is, with very few exceptions, made of stainless steel, titanium, platinum or other inert metal. The sealed radiation source may be marked with an engraved serial number, and for sources with sufficiently large dimensions the radionuclide, activity and date may also be given. In most cases, however, the small size of the source prevents marking. This gives many sealed radiation sources the deceptively harmless appearance of a small smooth piece of metal.

1.2 Applications

Summary of 1.2 The first use of sealed radiation sources dates back to 1901. Up to the 1940s only radium sources were used, mainly for medical purposes. Today sealed radiation sources are used in medicine, research, agriculture and industrial applications, in mobile as well as stationary devices. Large numbers of old radium sources, which are of special health concern, have been, and many still are, in use for brachytherapy. Other sources which cause particular concern are those used in mobile industrial radiographic units, and medical teletherapy sources. The largest number of sealed sources, apart from those in consumer products, are those in industrial gauges. The largest individual sources are those used for sterilization and food preservation.

A short history of the production and use of radium sources is given in Appendix I. Before 1940 the only sealed radiation sources which were widely distributed were the radium sources used in hospitals. After 1940, when it became possible to make new types of source, with different characteristics, using particle accelerators and nuclear reactors, a large number of new applications were developed in medicine, research and industry.

Medical applications

Hospitals are still among the largest users of sealed radiation sources. They are mostly used for teletherapy and brachytherapy. The radionuclide used in teletherapy sources is ^{60}Co, but some ^{137}Cs sources are also in service. Because of the large activity of these sources, 0.1 - 0.5 PBq (one petabecquerel equals 10^{15} becquerels)[5], they are always used in heavily shielded "radiation heads" which weigh of the order of one tonne. Since these are usually not designed or approved for use in transport there can be problems when obsolete or unusable units, still containing the radiation source, have to be moved. The fact that the shielding material in the radiation head can have high scrap value adds to the risk.

Today most of the old radium sources previously used for brachytherapy have been replaced by sources containing ^{60}Co, ^{137}Cs, ^{192}Ir or other radionuclides. Because the replacement of radium can be expensive, and because some radiotherapists have not yet learned the new techniques, radium sources are still in use in some hospitals.

Brachytherapy sources are small, and are often handled one by one without any shielding during use. The number of sources in a hospital can be considerable, a typical radium set in a large hospital consisting of more than 100 sources. There is real risk of losing a source if very strict procedures are not followed, and losses have in fact occurred at most large hospitals.

Old radium sources represent the largest single problem in the management of spent radiation sources. An additional problem with these sources is that they are often leaking, due to internal overpressure, or mishandling, and many are not registered with the national Competent

Authority. Their small size, easy portability, and high apparent value (their outer casings are often made of platinum) increase the risk that they will be stolen.

Research applications

Almost any radionuclide may be required for research, especially in physics, and this includes alpha emitting radionuclides. Due to limited funds scientists sometimes make their own sources, or use an old source which has previously been used for another purpose. In both cases there is a risk that the encapsulation will not be satisfactory. Alpha and some beta sources are particularly at risk as part of the closure has to be very thin, so that the particles emitted can escape from the source.

A source is often bought for a specific research project, and once that is finished it may be set aside and abandoned. There may also be a high rate of turnover of scientists, especially in a university, leading to early loss of information about old sources.

During the 1960's many irradiators, each containing up to 1 PBq of ^{60}Co, were set up for research work around the world, and many of these are no longer in use. These irradiators were constructed with heavy lead shielding, making them difficult to move but also attractive to scrap dealers. There may be no safe way to remove the sources from such an irradiator without taking the whole unit to a major nuclear research centre.

Two radionuclides frequently found in sealed sources in agricultural research institutes are $^{241}Am/Be$ and ^{137}Cs. They are used in soil moisture and density gauges. These are small portable units which have been used all over the world for more than 30 years.

Industrial applications

The industrial sources giving most cause for concern are those used for industrial radiography. Worldwide ^{192}Ir is the most common radionuclide in this context, but ^{60}Co and ^{137}Cs are also used, and in some special applications ^{169}Yb and ^{170}Tm. The activity ranges from 0.1 up to many TBq [5].

Radiographic sources are often used in mobile units for nondestructive testing (NDT) of welds on site, during the construction of industrial plant, pipe lines, etc. Serious problems may arise when international construction companies do radiographic work in countries with insufficient radiation protection and waste management infrastructures. It has been reported that significant numbers of such sources have been left behind after use, without proper care for their management.

Many portable radiography units contain 10-50 kg of valuable heavy metals, which makes them attractive for scrap. The way this equipment is used, in an industrial environment and with the source frequently exposed, adds to the risk of loss of the source, which is a metal cylinder only a few millimeters in diameter and length. If such a source is found by someone who does not realize what it is, there is evident risk of over-exposure.

Large neutron and gamma sources are used for well-logging in the oil and mining industries. These are similar to the sources used for moisture and density measurements but are of higher activity. Although the number of these sources is small in comparison with the number used for NDT, they represent the same type of high risk sources due to how and where they are used.

A still growing application for large sealed radiation sources in developing as well as in developed countries is in industrial facilities for sterilizing medical products or preserving foodstuff. About 150 such units are in operation around the world. Fortunately, due to their extremely high activity (up to a few hundred petabecquerels of ^{60}Co or ^{137}Cs) these installations have always been controlled very carefully by the authorities in the countries where they are installed. Although there is a great potential risk for radiation accidents during operation, the risk is decreased when the sources are spent, as they are unlikely to be abandoned or forgotten, but will be returned to the supplier in a developed country.

The most widely used industrial sources are in level and thickness gauges, which are usually used in fixed installations. If not immediately removed when an industry or a factory is closing down, they can end up in a scrap yard, where they can cause serious accidents.

An overview of sealed radiation sources and their areas of application is given in Appendix II and Fig 1.2-1, which also indicates the relative magnitudes of the problems associated with the different types of sources.

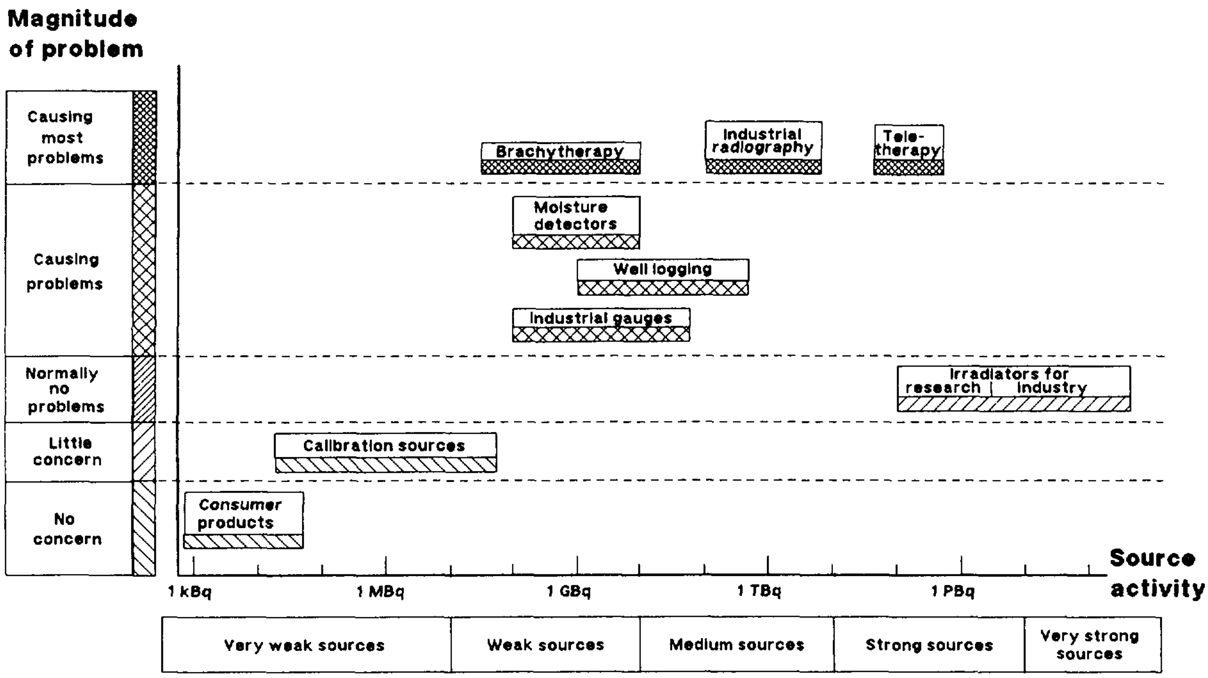

FIG. 1.2-1. Activity range for some important applications of sealed sources and the magnitude of problems caused when they are spent.

In an internal IAEA-report on RAPAT-activities there is an estimate of the number of sealed radiation sources used in the world. A break-down is given for different types of use. According to this, industrial gauges are the most widely spread sources with half a million units around the world, followed by brachytherapy sources. Industrial irradiators have the highest activity content. Table 1.2-I is a slightly modified version of a Table from the above-mentioned IAEA report.

TABLE 1.2-I

SOME ESTIMATES REGARDING SEALED RADIATION SOURCES

Industrial Radiography	
USA data for 1988	3,500 devices
Gulf countries estimate	5,000 devices
Total World estimate	25,000 devices
Sources: Co-60, Ir-192, Cs-137, ...	
Commercial Irradiators	
Worldwide 1988	142 units
Average Co-60 activity	40 PBq
Average Cs-137 activity	400 PBq
Teletherapy Devices	
Worldwide 1988	2,600 units
Average Co-60 activity	220 TBq
Average Cs-137 activity	40 TBq
Brachytherapy Sources	
Cs-137, Ra-226, Ir-192, ...	100,000 sources worldwide
Industrial Gauges	
USA data 1988	90,000 units
World estimate 1988	500,000 units

Consumer products

Normally, equipment used by the general public does not contain any radiation sources of activity high enough to cause concern. There have however been exceptions in the past. One example of this was the use of radium, or more recently ^{241}Am, in lightning arrestors. In most countries their use is now not permitted or at least not encouraged, but thousands have already been distributed and in some countries their use is not yet forbidden.

1.3 Distribution

<u>Summary of 1.3</u> Sealed radiation sources are in use worldwide, in total more than half a million sources. By far the largest numbers are in the developed countries. As well as through normal sale, which is the main route, sources have also reached developing countries via international co-operation programmes, international firms, medical practitioners, and as gifts and donations. The IAEA has provided more than 550 sealed radiation sources of significant activity since 1957, including more than 1.5 grams of radium, to developing countries. International engineering firms have brought large numbers of industrial sources into developing countries in the course of their work. Developed countries have donated whole hospital stocks of radium brachytherapy sources.

During the first 40 years of use of sealed radiation sources only radium sources were available. These were expensive and only the wealthiest countries could afford them. It was not until the 1950s, when relatively cheap new types of sources came on the market, that significant numbers were spread globally. The large number of new applications in industry and research also contributed to their rapid and wide distribution.

Most sources used today are produced commercially and distributed by a few large companies. Many other companies buy sources from a primary producer to include them in their own products, for example gamma radiographic equipment, moisture-, level-, or thickness-gauges.

Some of the old major producers no longer exist, or have ceased operation in this field. This is for example so for all the major producers of radium. Because of this, and perhaps also because of commercial secrecy, it is difficult to get an accurate picture of the present whereabouts of sealed sources by asking producers and distributors.

A few sources are produced for special purposes in research institutes. Most of these are used only by those who produce them, but a few may be sent elsewhere for testing and use, even in developing countries.

Sealed radiation sources can enter a country by many different routes: normal commercial trade, international technical co-operation programmes, international companies or industrial groups working in developing countries, medical practitioners, and as gifts and donations. A general discussion of these routes is given below.

All the points made may not be relevant for every country. There are for example developing countries which already have a comprehensive control programme for all imported sources. However, since the aim here is to point out risks it is useful to emphasize the unsatisfactory side of the problem.

Normal commercial trade

The normal way of obtaining a sealed radiation source is to buy it directly from a supplier. The deal is made under strictly commercial conditions. Most sources in the developed countries were acquired in this way. For developing countries, notably those with small economic resources, other routes may be more important.

IAEA Technical Co-operation

Within its terms of reference "to seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" the IAEA operates an extensive Technical Co-operation Programme. This includes supply of equipment as well as training programmes and the services of experts. Since it was formed in 1957 the Agency has purchased many sealed sources for use in developing countries. Until a project is completed the sources delivered within it remain the property of the Agency. When the project is closed the ownership is transferred to the Government of the receiving country. It is only recently that the Agency has given adequate consideration to the safe management of the sources when they are no longer in use. Many sources have been delivered to developing countries which lack radiation protection and waste management infrastructure, or indeed any other provision for ensuring the safe management of spent sources.

In an IAEA report dated September 1989 [6], the authors list all significant gamma and neutron sources (omitting those which emit only low energy gamma radiation or have short half-lives) purchased over the period 1979 to mid-1989. This list was compiled from information in the Agency's computerised data base.

By going through manual files held in the Agency it was possible to get an estimate of the number of sources provided before 1980. These are not in the computer data base and so were not included in the 1989 report. Some details may have been missed because of the difficulty of manual search, but in most cases enough information was found to establish what was supplied. During this search some additional sources purchased after 1980 were also identified.

Because sources are seldom useful for more than ten years, and often less than this, it is of interest to separate sources purchased before and after 1980. 250 sources were provided before 1980 and 315 after, in total 565 sources. A summary of the sources supplied, divided between six types of application, is given in Fig. 1.3-1. From the Figure it can be seen that sources provided before 1980 were for roughly the same purposes as those supplied after 1980, and also that the numbers are in

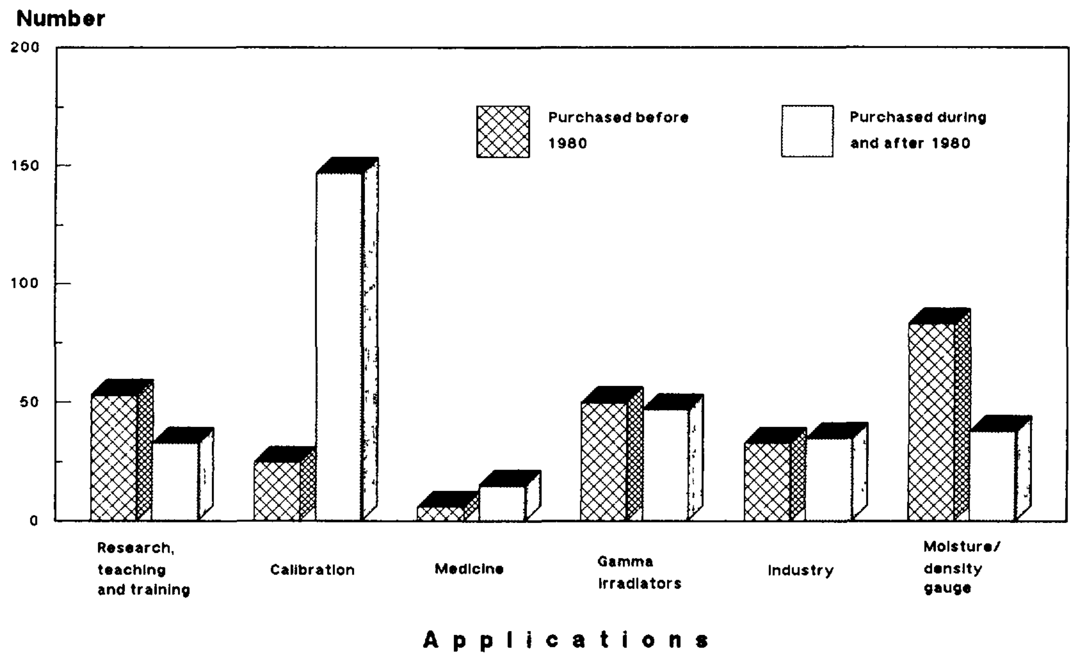

FIG. 1.3-1. Sealed radiation sources purchased by the IAEA.

most cases similar. The large number of calibration sources provided after 1980 may be explained by the fact that from the late 1970s onwards the IAEA intensified assistance to establish a network of Secondary Standards Dosimetry Laboratories. The low figure for sources in moisture/density gauges purchased after 1980 may be partly explained by the fact that these sources do not easily show up when going through the computerized data base.

Although only six radium sources, each with an activity of 37 MBq, were purchased after 1980, at least 23 radium sources, with a total activity of more than 65 GBq, were purchased before 1980. One of these, a ^{226}Ra/Be neutron source, had an activity of 55 GBq, corresponding to 1.5 grams of radium. A list of radium sources purchased before 1980 is given in Table 1.3-I.

It should be noted that ten ^{238}Pu/Be neutron sources have been provided, with a total activity of more than 4 TBq.

The World Health Organization, which has a large medical programme in developing countries, reports that it has not supplied radiation sources to any significant extent.

International firms

In many developing countries international firms, with headquarters in developed countries, are constructing or operating mines, oil production installations, large processing and production facilities, and other major industrial complexes. When radiation sources are needed these firms have often brought them in without any formal clearance or approval by the national authorities. In some cases there was no Competent Authority in the country to consult, but in many cases it seems that existing national rules were regarded as too complicated or troublesome to follow. Although most international firms follow the national radiation protection rules and practices in the country in which they are operating, or those of their home country, there are certainly exemptions. Due to inadequate control by national authorities, large problems can also arise when a firm, for one reason or another, leaves a country without taking proper actions to guarantee safe management of the spent sources.

For example, in one African country a mining company has, according to its records, brought in more than 100 radiation sources for its own use. Most of these contained ^{60}Co or ^{137}Cs.

Large exploration or construction works can also result in radiation sources entering a developing country in an uncontrolled way. As a result of inadequate control of construction companies during construction of oil pipelines in the deserts in the Middle East it is thought that at least a hundred radiographic sources have been abandoned where they were last used. Fortunately most of these contained ^{192}Ir, which has a half-life of only 74 days and thus will be harmless within a few years.

Medical practice

In the past, when a medical practice was set up in a developing country, it was common for all equipment to be supplied from outside the country. In some cases this included radium brachytherapy sources.

TABLE 1.3-I

RADIUM SOURCES PURCHASED BY THE IAEA BEFORE 1980 FOR USE IN DEVELOPING COUNTRIES (data from IAEA files)

No. of sources	Source	Year of delivery	Activity in GBq	Receiving country
1	Ra/Be	1965	55	Brazil
2	Ra/Be	1968	1.7 (total)	Chile
1	Ra/Be	1960	unspecified	Thailand
4	Ra	1960	0.6 (total)	Brazil
1	Ra	1962	unspecified	Burma
1	Ra	1963	"	Indonesia
2	Ra	1963	"	Thailand
1	Ra	1964	0.2	Chile
1	Ra	1964	1.8	Peru
1	Ra	1965	unspecified	Ethiopia
1	Ra	1965	1.8	Lebanon
1	Ra	1967	0.7	Saudi Arabia
1	Ra	1968	0.7	Nicaragua
1	Ra	1969	1.8	Ecuador
1	Ra	1970	unspecified	Indonesia
1	Ra	1972	"	Syrian Arab Republic
1	Ra	1973	0.07	Guatemala

Often the practice grew into a hospital and the sources entered into hospital inventory lists and came under control of the national Competent Authority, but there are also other cases. Sometimes when a medical practitioner returned to his home country, or retired, the sources were left in unattended or inadequate storage. Sometimes hospitals using radiation sources have been closed without the sources being properly taken care of.

The number of radiation sources brought into developing countries in this way was probably quite moderate, but it can be very difficult to learn about them. If all records are lacking the only way to get information is to speak with people who may remember where treatment by brachytherapy was given, and then to follow this up by further enquiries.

Gifts and donations

When ^{137}Cs and other radionuclides began to replace radium in brachytherapy in the 1960s, many hospitals in developed countries found themselves with stocks of radium sources for which they had no further use. In some cases entire radium stocks were donated to hospitals in developing countries which could not afford to buy the new safer sources. Sometimes handling and storage facilities were included in the shipment, and basic training was provided for the staff. The fact that the donating hospital at the same time could solve a future waste management problem gave advantage to the donating hospital even if that, at that time, probably was not considered.

Universities and research institutes have also received gifts of radiation sources from developed countries, through personal contacts or co-operation with other research centres. The number of sources received this way has probably been small, however, and the sources have usually had low activity content.

2. RISKS WITH SEALED RADIATION SOURCES

2.1 Characteristics of sealed radiation sources

Summary of 2.1 **Sealed radiation sources have small dimensions and are thus easily lost or misplaced. They are encapsulated in such a way that, with the exception of radium and some other old sources, they will not be destroyed even if incinerated. They will be unaffected after many years in repositories. Sources containing very long-lived radionuclides, such as ^{226}Ra and ^{241}Am, will still be dangerous to human health after hundreds of years. Some sources contain only short-lived radionuclides, however, and will become safe within a few months or years.**

Many applications of radiation sources require the activity to be concentrated into as small a volume as possible ("point source") or to approximate to a line ("line source"). To achieve this the sources are made as small or thin as possible, with material of high specific activity. The volume of radioactive material is usually of the order of a cubic centimeter or a few cubic millimetres, which gives the source very small dimensions even though the overall volume is increased by encapsulation.

Today most commercially produced sources are manufactured and tested to internationally agreed standards. Double encapsulation may be used, although alpha, beta and low energy gamma sources need a thin window through which the particles or photons can leave the source without unacceptable attenuation.

The material used for encapsulation is usually stainless steel, but sometimes platinum, titanium, or other metals are used. Gold, brass, silver and even glass capsules were used for early ^{226}Ra and ^{222}Rn sources.

In modern practice the radioactive material inside the encapsulation should be in an insoluble form, for example metal in the case of ^{60}Co and ^{192}Ir or a ceramic for ^{137}Cs and ^{241}Am. This is to reduce the risk of contamination if the encapsulation should be damaged. Fig. 2.1-1 gives examples of the form and dimension of ^{226}Ra sources [7] and Fig. 2.1-2 shows the construction of ^{60}Co teletherapy sources. The Agency has a programme aiming at further improving the design and control of sealed radiation sources.

Old sources, many of which are still in use (especially old radium sources) were manufactured to standards lower than would be acceptable today. The radioactive substance in these sources may be a powder or soluble salt which could readily disperse if the encapsulation were to be damaged.

Most modern sealed sources are produced in such a way and with such materials that they would remain intact even during incineration in a municipal incinerator. They can survive without losing their radioactive contents if stored in a repository for hundreds, maybe thousands, of years. Radium sources are however unlikely to survive incineration as they would rupture because of internal overpressure created during incineration.

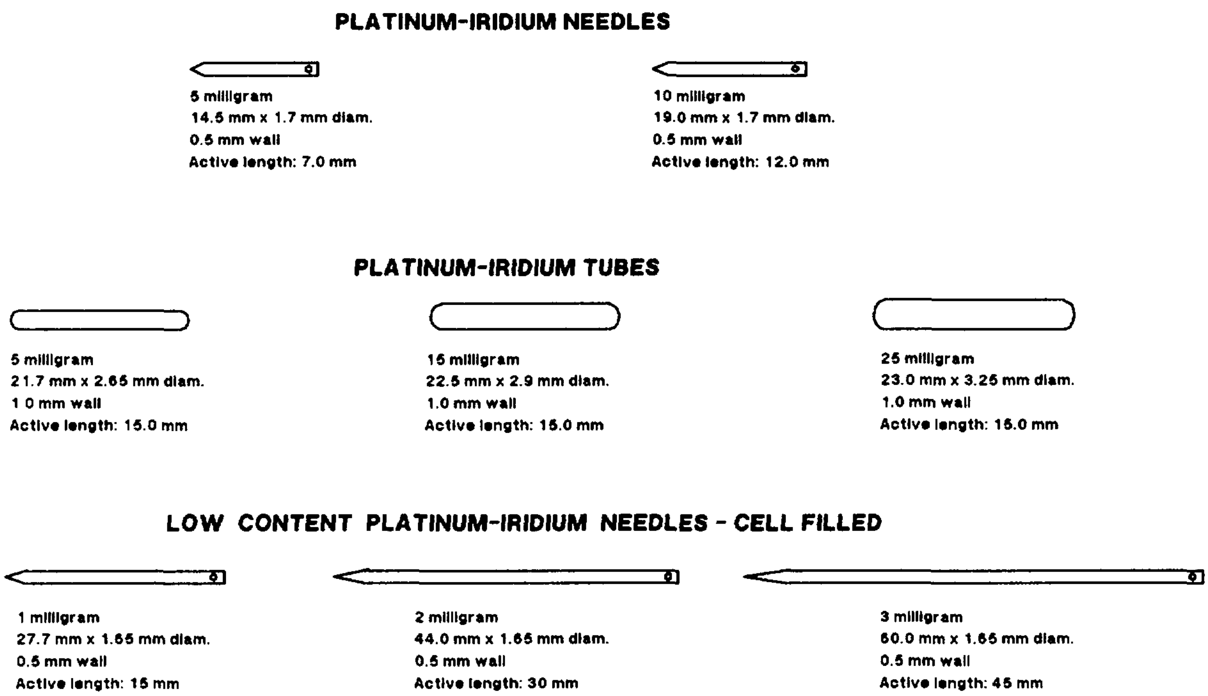

FIG. 2.1-1. Typical radium brachytherapy sources.

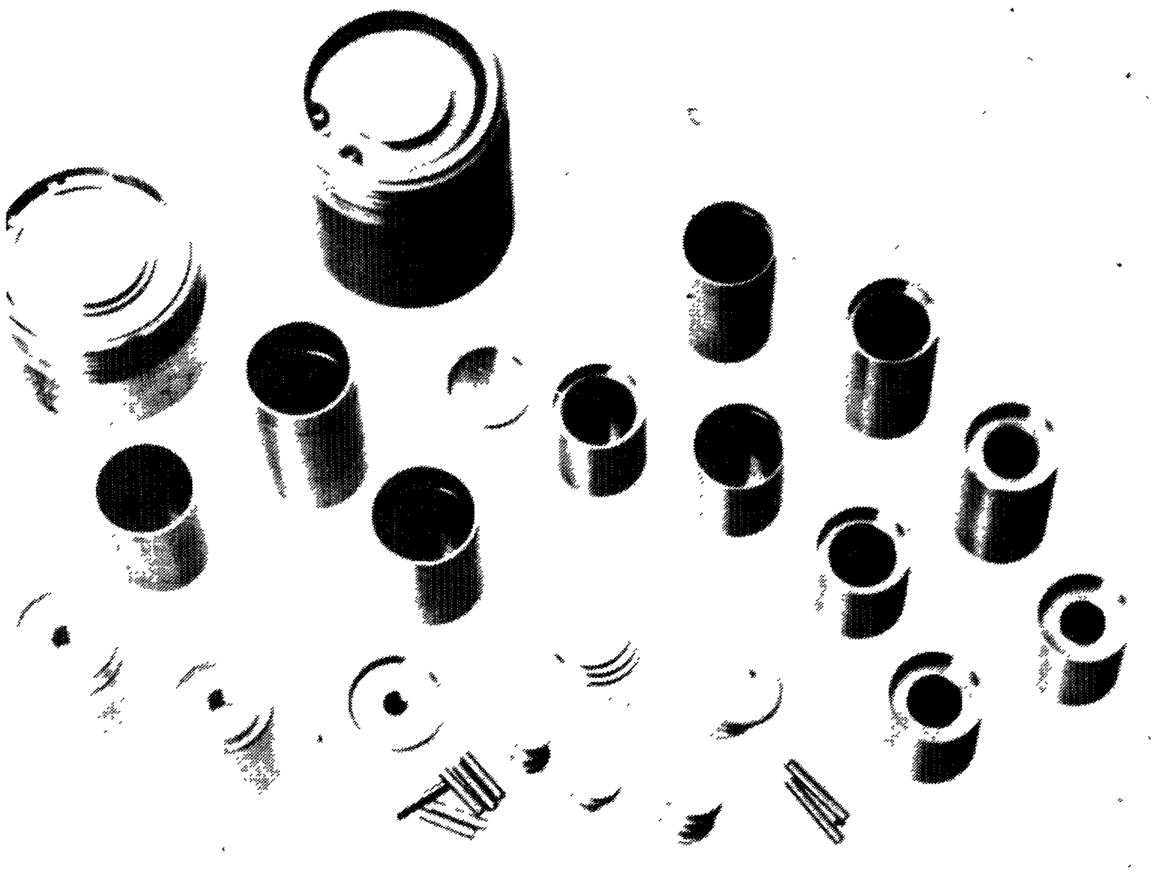

FIG. 2.1-2. Components for fabricating sealed radiation sources.

Strong radiation sources containing radionuclides with long half-lives, such as ^{241}Am and radium, will still be dangerous even if found after a thousand years. For other radionuclides the source may become safe, due to natural radioactive decay, in a more acceptable time. After 10 half-lives the activity is reduced by a factor of 1000. Thus a ^{60}Co teletherapy source with an initial activity of 100 TBq will become safe after little more than 100 years, while a corresponding ^{137}Cs source would require 700 years. A strong ^{192}Ir industrial radiography source will have decayed to a safe level already after 4 years.

The radioactive material in a radiation source should be in a form which minimizes the risk of spread of contamination if the encapsulation is damaged. This means that the radioactive material should be a solid piece of material which is not affected by air, even at elevated temperatures, and is not soluble in water. Of the frequently used radionuclides, ^{192}Ir and ^{60}Co are two of the few which can readily be obtained with such characteristics. ^{137}Cs and ^{241}Am can be prepared with characteristics giving rather good inherent safety, but ^{226}Ra can only be obtained with very poor characteristics. Appendix III gives further details of the characteristics of these five important radionuclides.

2.2 Effects of ionizing radiation

Summary of 2.2 **If not properly managed, spent radiation sources can be a threat to human health and cause contamination of the environment. Exposure to large whole body doses of ionizing radiation can be lethal to man, and large organ doses can cause severe acute effects. Lower doses can induce cancer.**

For deterministic (non-stochastic) effects on man there are threshold doses below which specific effects are not apparent. Whole body exposure above 3 Sv can be, and above 7 Sv is, lethal to man. If only part of the body is exposed, the individual can survive higher doses, but the damage may be so severe that the exposed part may have to be removed. A summary of deterministic effects is given in Fig. 2.2-1. For stochastic effects, mainly the induction of cancer and genetic effects, there is no threshold; the risk for an effect is regarded as proportional to the dose. The risk for induction of potentially lethal cancer is 2 - 4 X 10^{-2} per Sv, while for severe hereditary effects the risk is smaller, about 10^{-2} per Sv.

Accidents due to radiation from spent radiation sources have led to amputation and death. If the source is damaged the effect on the environment may be contamination of buildings and of the area generally. The high specific activity of the material in sealed sources means that the spread of as little as microgram quantities of its contents into the environment can generate significant risk to man and inhibit the use of buildings and land. The cost of decontamination can be very high. Accidents with spent sources have already given rise to extensive and costly contamination of the environment.

A fuller discussion of the effects of ionizing radiation on man and the environment is given in Appendix IV and in Refs.[8-10].

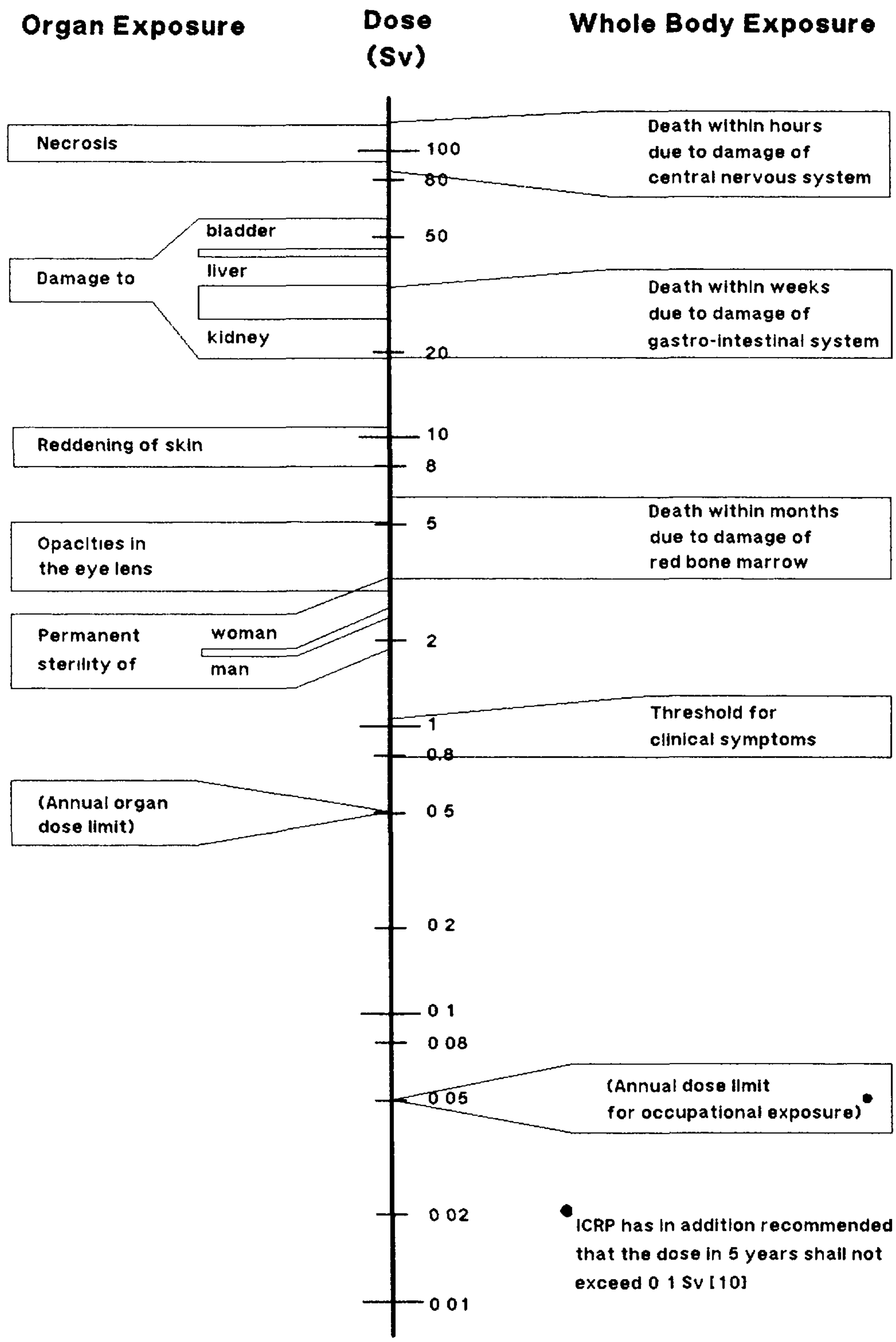

FIG. 2.2-1. Summary of the deterministic effects in man.

3. SPENT RADIATION SOURCES TO BE CONSIDERED

3.1 What is a spent radiation source?

Summary of 3.1 A spent radiation source is a source for which no further use is foreseen. The reasons for which a source may be considered spent are many: its activity has decayed to a level below which the source is no longer useful; the equipment or the technique used may have become obsolete; the equipment may be worn out, or damaged so it has to be taken out of service; or the source may be lost or stolen. Sometimes, but not often, a new use can be found for a spent source, or the radioactive material in it may be recovered and used in other sources.

Reasons for a source to be considered spent are discussed briefly below. A "spent source" means, in this context, a source which is no longer in use and for which no further use is foreseen. It is not easy to define exactly when a source should be regarded as spent. To ensure that a source will not be outside both the control system for sources in use, and that for spent sources, it is better to have an overlap between the definitions of "spent source" and "source-in-use" than to have a gap. Radiation protection procedures for sources-in-use and spent sources must be compatible with each other, and thus an overlap need not cause any problems, while a gap might.

Reasons for considering a source to be spent are:

Decay

For all applications of sealed radiation sources there is a minimum activity content below which the source is no longer useful. Due to natural radioactive decay the activity is constantly decreasing, and if the half-life is short the useful lifetime of the source is also short. In most applications the source must be replaced when the activity has fallen by a factor of two or more i.e. after about one half-life. Industrial radiography sources containing ^{192}Ir, which has a half-life of only 74 days, usually become spent because of decay.

Obsolete equipment and technique

A sealed radiation source is used in an instrument or technique which has a specific function. The purpose may be to treat a cancer tumour, to measure the density of a product in a pipe, or the moisture in soil, or the level of liquid in a tank. The source provides the ionizing radiation required by the system. Even if the source still gives the required radiation output the system may be taken out of use because there are new ways to achieve the desired results which are cheaper, more accurate, or give additional information. There may be new techniques which use a safer type of source, or a lower level of radiation, or do not use ionizing radiation at all.

During the development of new techniques the time for a new generation of equipment to come onto the market will be short, at most a few years. For mature systems, such as the level gauges now in use, equipment can remain up to date for much longer times, more than ten years.

The replacement of radium by ^{137}Cs in brachytherapy is an example of a new and safer technique which has made existing sources obsolete.

Worn out equipment

All equipment will sooner or later be worn out. A good maintenance programme can extend the lifetime, but eventually the equipment and source can no longer be used in a safe and effective way. It should be taken out of operation and so its source will become "spent".

Damage

Equipment or sources which suffer damage must not be used again until their safety can be guaranteed. If this guarantee cannot be given the source must be considered spent and proper action taken for its safe management.

Loss and theft of sources

If a radiation source becomes detached from the equipment in which it is used, and this is not immediately noticed, the source may be lost. The fact that sources are small in size can make them difficult to find and recover. Lost radiation sources are not recognized as such by inexperienced persons and may anyway be difficult to locate without proper instruments.

Equipment containing sources may also be stolen, usually without knowledge that there is a radiation source in the equipment. Such sources should be considered as spent radiation sources as long as they have not been recovered. If, after recovery, it is proposed to put the equipment back into use, this should not be done until the source and equipment have been thoroughly checked. If the check is not satisfactory the source must from then on be managed as a spent source (and not left in the equipment in the hope that a way will be found to repair it later).

3.2 Sources and Member States to be considered

<u>Summary of 3.2</u> **A programme for the management of spent radiation sources should include sources with activity greater than 10 MBq, or for radium sources, greater than 1 MBq. Except in a few special cases, in particular ^{192}Ir used in gamma radiographic sources, the half-life should be longer than 1 year. Priority should be given to improving the situation in developing countries.**

To ensure safe management of spent radiation sources it is necessary to exercise control of all sources during their entire lifetime until they are finally safely disposed of or have decayed to exemption levels. Systems which give the possibility of individual control of all sources are complex in nature and are also costly and time consuming to implement. The complexity increases with the number of sources. To avoid unnecessarily large and unmanageable systems, it is necessary to restrict the individual sources included in the control programme to those which represent the main risks. This can be done by setting an activity limit below which spent radiation sources are considered to be of little concern. As a principle the limit should be set as to avoid deterministic effects, which means that local doses should be below a few Sv. (The limiting scenario with small sealed radiation sources will be local exposure, due to handling of a source without proper protective measures, or putting it in a pocket for a couple of hours, rather than whole-body exposure.)

A small gamma emitting source with an activity of 1 MBq may give a gamma dose rate of up to a few mSv/h at 1 cm, which is a suitably short distance in the present context. If beta particles are emitted, and are not absorbed in the encapsulation, the dose rate at such short distance could be increased by a factor of at least 10.

It is very unlikely that any local area of a person will be exposed for more than a couple of hours at such short distance. This means that sources with activities less than 10 MBq will in general not give rise to serious effects due to external radiation, since the local dose will not exceed 1 Sv. This cutoff is adequate for the most frequently used radionuclides (^{60}Co, ^{192}Ir, ^{137}Cs and ^{226}Ra) and includes a safety factor for others.

Even in the extreme situation when radioactive material from a damaged source is applied directly to the skin, as happened in the Goiânia accident in 1987, sources with activity below 10 MBq are not likely to give local exposure exceeding a few Sv. If for example 1% of a 10 MBq ^{137}Cs source is applied on the skin, many hours of exposure would be required to give a skin dose of one Sv.

Internal exposure due to inhalation or ingestion of small amounts of radioactive material leaking from a spent source is not likely to give deterministic effects if the activity of the source is less than 10 MBq, assuming that at most 1% of the activity in the source is available for intake. It may however be prudent to set a lower limit for radium sources, due to the long half-life of ^{226}Ra and its unfavorable radiation protection characteristics. 1 MBq per radium source would be an appropriate lower limit.

It is not necessary to include sources containing radionuclides which have short half-lives as it may be assumed that they will decay to harmless levels while still under proper administrative control. By setting a one year lower limit on the half-life most radionuclides of concern will be included. Consideration should however also be given to those few radionuclides which are used with high activity but for which the half-life is only a few months. The most important example of this is ^{192}Ir when used for industrial radiography, for which a single source may have an activity of many TBq.

Risk from spent radiation sources exists both in developed and in developing countries. Many aspects of the problem are the same for both, but there are some major differences.

In developed countries the main problem arises from the large number of sources which are and have been in use, and thus if even a small percentage of them is lost or unaccounted for it can nevertheless amount to a large number.

In the developing countries it is possible that many sources were imported before proper national legislation and control were introduced (in one third of Member States proper radiation protection and waste management infrastructures have still to be implemented), so there is likely to be a higher percentage of lost and unaccounted sources.

Expertise and experience in management of spent radiation sources is also limited in these countries.

It may be assumed that the developed countries have all the legal, technical and expertise resources needed to implement a programme for managing their spent sources, which is in marked contrast to the situation in many developing countries. It is therefore much more pressing for the Agency to assist the latter, and the highest priority should be given to improving the situation in these countries.

4. INVENTORY OF SPENT RADIATION SOURCES

<u>Summary of 4.</u> From records available in the IAEA about 2,500 spent radiation sources have been identified in developing countries, but this figure is a serious under-estimate. A better figure would be close to 30,000. The number of spent radiation sources in developed countries is more than 100,000. All medical ^{226}Ra sources in the world will be spent sources within a decade. The identified inventory of ^{226}Ra sources in developing countries is 122 grams. The addition of unidentified sources should not more than double that figure. The world inventory of ^{226}Ra sources is estimated to be a few kg.

In 1989 the IAEA sent a questionnaire to Member States asking for information for setting up an international Waste Management Data Base (WMDB). Among the questions was one on spent radiation sources in storage, but this was limited to sources of activity greater than 18.5 GBq. Up to September 1990, 32 developing countries and 21 developed countries had responded. 15 of the developing and 9 of the developed countries gave details of spent sources, but most gave the impression that the listing was incomplete. For example the Federal Republic of Germany 1/ estimated its number of spent sources to be 1000, while Norway reported only 7. No estimates at all were received from many countries, like Sweden and the USA, perhaps because they have no central register from which reliable numbers can easily be obtained. Detailed lists of more than 100 spent sources were given by Mexico (798, all ^{226}Ra sources), Indonesia (397), Malaysia (220) and Zambia (107). Many countries presented lists with less than 100 spent sources.

In about 70% of the WAMAP reports there is specific information on spent sources, and in all these reports there is some general information about sources. The RAPAT reports also give information on spent sources, but most of the information in these reports refers to sources in use.

Information from WMDB, WAMAP, RAPAT, discussions with IAEA Staff Members, and letters and memoranda in the Agency's files, is summarised in Table 4-I.A. Because there is more detailed information in the IAEA's files on developing countries, and they are most in need of assistance, the Table includes only information relevant to those countries. Summaries are given for the four regions LA (Latin America), ME&E (Middle East and Europe), Afr (Africa) and A&P (Asia and the Pacific). When reading the Table it must be borne in mind that there is probably not a full list of spent sources for any country, and only a few have a comprehensive list covering most sources. The true number of spent sources is thus much larger than is shown in the Table. In 30 of 84 developing countries altogether 2600 identified spent sources are listed, of which the majority are radium sources, and in 13 other countries spent sources are said to exist but no details are given.

1/ This information was obtained before the unification of Germany in October 1990.

TABLE 4-I. ESTIMATED NUMBER OF SPENT SOURCES IN DEVELOPING COUNTRIES

Region a/	LA	ME&E	Afr	A&P	Total
Number of countries in region	20	22	26	16	84
A. NUMBER OF SPENT SOURCES, FROM INFORMATION AVAILABLE AT IAEA					
Number of countries giving quantified information on spent radiation sources	6	7	12	5	30
Number of spent Ra-226 sources identified	798	100	395	168	1461
Number of other spent sources identified	223	94 b/	260	560	1137
Number of countries giving unspecific information on spent radiation sources	4	4	2	3	13
B. SOURCES PURCHASED BY IAEA BEFORE 1980					
Number of countries having received sources	13	14	17	12	56
Sources received	59	40	71	58	228
C. RADIUM INVENTORY FROM INFORMATION AVAILABLE AT IAEA					
Number of countries for which quantified information is available	19	7	4	10	40
Identified quantity of radium c/ [grams]	39.6	37.3	8.9	36.0	121.8
Countries with unspecified radium inventory	0	3	9	4	16
Number of countries for which no information is available	1	12	13	2	28

a/ LA = Latin America, ME&E = Middle East and Europe, Afr = Africa, A&P = Asia and Pacific

b/ 3000 spent sources reported by one country have not been included.

c/ For many countries the quantity given refers only to one or a few locations and thus the total inventory may well be larger.

Information on spent sources may also exist in some of the 41 countries for which no information has been found at the Agency, and it is likely that there are spent sources in most of those countries. As an illustration of the uncertainty in the numbers, it may be noted that more than 100 industrial radiography sources are said to have been abandoned in the deserts of the Middle East after construction work, but mention of these sources is not to be found in any register.

It is thus not possible to make an accurate estimate of the total number of spent sources existing in the developing countries. Considering that 2600 have been identified in 30 countries, and that this is not the total inventory for those countries, and that there are 54 other countries for which no detailed information exists, the total number may well exceed 10,000. A rough estimate based on the number of sources in use gives a figure of about 30,000 for the total number of spent sources in developing countries. The regional distribution of this estimate is shown in Fig. 4-1.

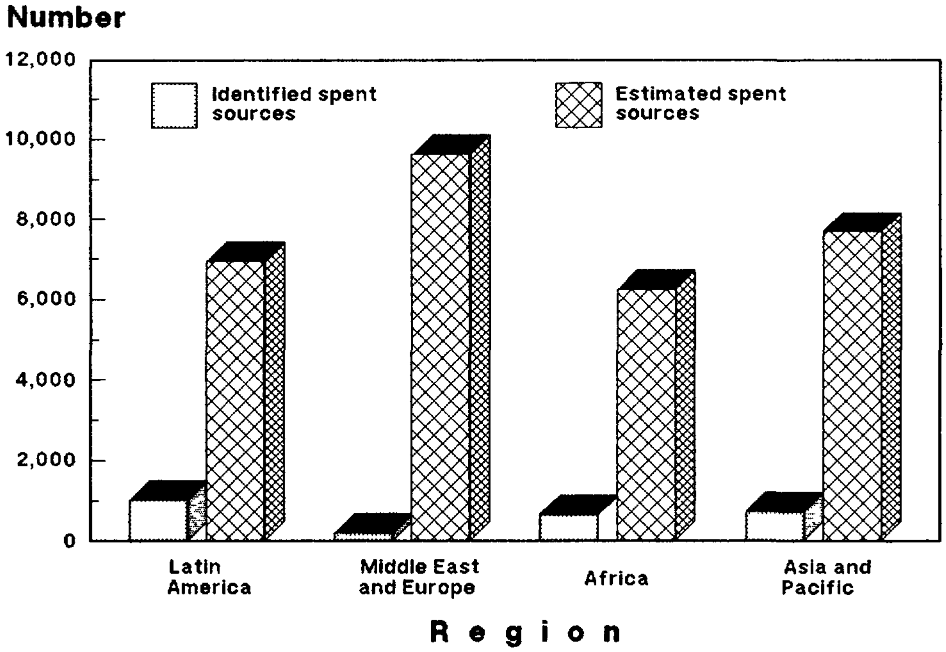

FIG. 4-1. Regional distribution of spent sources in developing countries.

Sources provided to developing countries through Agency programmes during the 1960s and 1970s are now so old that most of them must be regarded as spent. In total more than 200 sources were delivered in these programmes before 1980, mostly to African countries. Table 4-I.B gives the regional distribution of these early deliveries.

The process of replacing ^{226}Ra brachytherapy sources by sources containing other radioisotopes is in progress around the world, and most radium sources will be replaced within a decade. All medical radium sources will therefore soon be spent sources.

Table 4-I.C shows the available information on radium sources, which are mostly medical sources, in the developing countries. In 40 countries some 122 grams of radium, equivalent to an activity of 4.5 TBq, have been identified. Assuming a mean quantity of 8 mg of radium per brachytherapy source this corresponds to approximately 15,000 sources.

While for many countries the inventory given is no doubt correct, there are others for which only a small part of the total stock has been reported. Further, there are 16 countries known to have radium but for which detailed information is not available, and still another 28 for which it is not known whether they have radium or not. It is thus not possible to give a correct figure for the whole radium inventory in the developing countries. We may however guess that the total is unlikely to be more than twice the identified quantity, which means it is less than 250 grams, perhaps in the range 200-250 grams.

The developed countries have very many sources in use; more than half a million. These are regularly replaced by new ones when they decay to low activity or exceed their working lives. In most cases there are established routes for returning the spent sources to the supplier, or to interim storage or to a repository. Most sources are placed in interim storage awaiting conditioning and disposal. Based on the number of sources in use, the number of spent sources in the developed countries can be estimated to be at least 100,000.

The inventory of radium is much larger in the developed countries than in the developing countries. The largest registered inventory, in the USA, amounts to about 700 grams, but the quantity produced for domestic use or imported has been estimated to be 2,000 grams [11]. Although part of this quantity has been used for consumer products there is still a large difference between the figures, indicating that significant quantities are not accounted for.

In the United Kingdom "more than 100 grams" were identified in the beginning of the 1960s, and in Sweden the inventory registered by the Competent Authority is 24 grams. On the assumption that there are two countries each with an inventory of 500 grams, half a dozen which have 100 grams, some 30 with inventories of the order of 10 grams and the rest with one gram or less, the world inventory of sealed ^{226}Ra sources should be a few kilograms. To illustrate the magnitude of the quantity of radium which has to be stored and eventually disposed of, world-wide, it may be noted that 2.5 kg of radium corresponds to only 100 TBq, and that this level of activity can be found in a single teletherapy unit (although of another radionuclide) and is entirely negligible in comparison with the inventory in even a small nuclear reactor.

5. ACCIDENTS WITH SEALED RADIATION SOURCES AND THEIR CONSEQUENCES

5.1 Review of accidents with sealed radiation sources

Summary of 5.1 Reported accidents with spent radiation sources have caused the death of 19 persons in five accidents since 1960. In more than 100 registered accidents with sealed radiation sources, about 700 persons have been exposed to a whole-body dose larger than 0.25 Sv or to a local skin dose above 6 Sv. In addition there have been accidents which were not reported, the number of which probably are equally large. On average there have been more than two accidents reported per year. The number occurring per year has been about the same during the period, but the number of individuals exposed in each accident is increasing. Since the beginning of 1980s there have also been reports on accidental melting of sealed sources in steel foundries, causing extensive contamination of both the steel and the foundries.

In all countries with a mature radiation protection infrastructure there is a follow-up of accidents involving radiation sources. This requires a Competent Authority, a national reporting system, and a special register for the accidents. Analysis of the details of the accidents helps the national authority and the users of radiation sources to understand the causes of such events and helps in the design of measures to prevent similar happenings in future. An early review of accidents involving radium sources was made in the USA in 1937. Information from this and other early reports of incidents with radiation sources is presented in Appendix V.

To make good use of experience collected in this way it is important to spread the information not only to the national user but also to the international community. Presentations at international conferences and reports in the open literature help with this. In 1969 and 1977 the IAEA arranged symposia specifically devoted to the handling of radiation accidents, and in other IAEA conferences, most recently in 1988, there were special sessions dealing with the subject [12-14].

Another way to facilitate the spread of information is to collect data about accidents in a central register, which is then made generally available. A first approach to such a register was made by the Radiation Emergency Assistance Centre/Training Site (REAC/TS) at Oak Ridge Associated Universities [15]. Its central register consists of four sub-registers, three with data on accidents in the USA and one for accidents in other countries. The main purpose for the register, which was established in 1976, is to facilitate the follow-up of accidentally exposed individuals. As might be expected, it has full coverage only of major US accidents. In many other countries, especially in developing countries, the existence of this register is not always known.

In order to be noted in the register an accident should give doses above 0.25 Sv to the whole body, blood-forming, or other critical organs; or above 6 Sv locally to the skin; or above 0.75 Sv to other tissues or organs from external sources; or an intake of more than half of the maximum permissible organ burden.

According to information published in the register 10 accidents with lethal consequences have occurred with sealed radiation sources. (Accidents caused by X-rays, accelerators, medical treatment, and reactors or critical assemblies are not included.) In five of these, each of which caused one death, the accident occurred with sources which were still in use. In the other five accidents, which altogether caused the death of 19 persons, spent sources were the cause (Table 5.1-I). On this evidence the consequences of accidents with spent radiation sources may be more severe than accidents with sources still in use. Accidents with sources in use are usually discovered immediately, or at least very soon, whereas accidents with spent sources occur because people are not aware that they are handling a radiation source. It can be a long time before this is recognised, allowing high exposure before protective action is taken.

TABLE 5.1-I. REPORTED FATAL RADIATION ACCIDENTS WITH SEALED SOURCES

(accidents caused by X-rays, accelerators, medical treatment, and reactors or critical assemblies are not included)

Year	Location	Sealed radiation source	Fatalities	
			Worker	Public
1962	Mexico City, Mexico	Lost radiography source		4
1963	China	Seed irradiator		2
1975	Brescia, Italy	Food irradiator	1	
1978	Algeria	Lost radiography source		1
1981	Oklahoma, USA	Industrial radiography	1	
1982	Norway	Instrument sterilizer	1	
1984	Morocco	Lost radiography source		8
1987	Goiânia, Brazil	Stolen teletherapy source		4
1989	El Salvador	Sterilization facility	1	
1990	Israel	Sterilization facility	1	
			5	19

Total: 10 events with 24 fatalities

In a review of accidents with sealed radiation sources presented at an IAEA Conference in 1988 [16] it was shown that although there has been a decrease in the number of accidents reported there has been no corresponding decrease in the number of over-exposed individuals (Fig. 5.1-1).

Two accidents, one in Juarez, Mexico, in 1983, and one in Goiânia, Brazil in 1987, caused the exposure of many people. The Juarez accident may have over-exposed several thousand persons. It has not been possible to evaluate the doses to all these individuals, but it is estimated that those exposed to biologically dangerous levels do not exceed 275. In the Goiânia accident about 245 persons are thought to have been over-exposed. Due to these uncertainties the two last bars in Fig. 5.1-1 should be taken as an indication of the magnitude rather than of the exact number of over-exposed individuals.

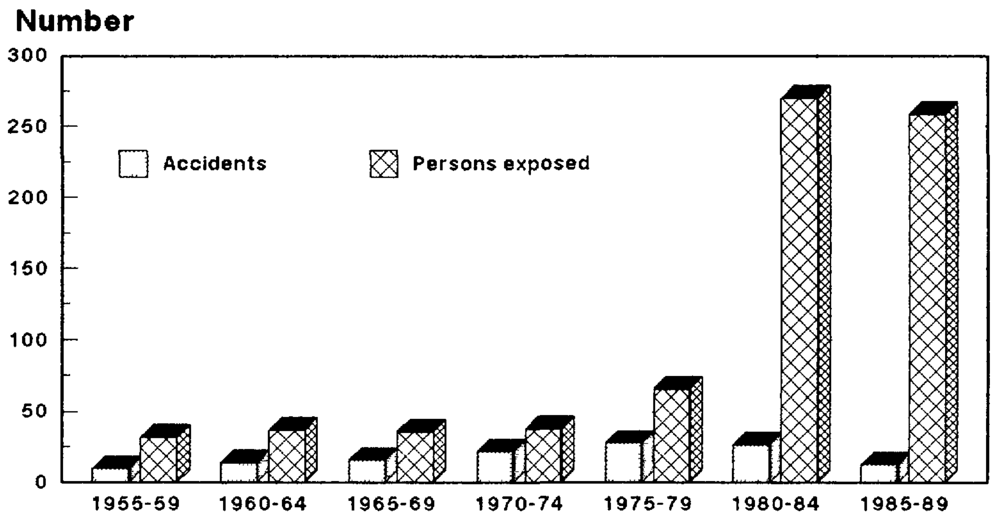

FIG. 5.1-1. Reported accidents with sealed radiation sources and persons exposed.

From the information available it is not always possible to distinguish between accidents caused by spent sources and by sources still in use, but it is likely that, as for accidents with lethal consequences, the number of accidents is about the same, while the number of over-exposed individuals is larger with accidents caused by spent sources.

There have not been any official reports on accidents with spent radiation sources in Eastern European countries, but in recent years a number of newspaper articles have suggested that such accidents have in fact occurred.

Over the last 20 years there have been on average more than two registered accidents with spent radiation sources annually, each exposing one to ten persons (excluding the accidents in Juarez and Goiânia, where hundreds of persons were exposed). The real number of accidents is probably about double the registered number.

Although the REAC/TS register is the most comprehensive world-wide data base on accidents with radiation sources, it does not cover countries outside the USA in a fully comprehensive way. Information is fed into it from the open literature and from reports sent to REAC/TS, and for the latter there must be knowledge of its existence and also willingness to give information. Since the register is not officially recognised by international organizations there are many countries which do not know about it, and no doubt there are some which for other reasons do not report their accidents to REAC/TS. The IAEA recognises the need for a truly international register and is now discussing different options, one of which is to establish co-operation with REAC/TS. Discussions with REAC/TS have been initiated.

One type of accident which may not give rise to large individual exposure but can give large collective doses and also be very costly to clear up, is when a spent radiation source is accidentally melted down together with scrap metal. The radioactive material is then dispersed in the melted metal, usually steel or lead, and in the slag. No such accident was reported before 1983 but since then there have been several, the most serious being that in Juarez, Mexico, in 1983, when the main part of a spent 16 TBq ^{60}Co teletherapy source was melted down with steel scrap. Besides the over-exposure of many individuals, there was primary contamination of 7300 tonnes of steel [17]. No other accident of this type is known to have caused high individual exposure, but several have caused extensive contamination needing costly clean-up.
Table 5.1-II summarizes eight reported cases of contamination by accidental melting of sealed sources [18,19]. In seven cases the sources were melted together with steel and in one case with aluminum.

TABLE 5.1-II. CONTAMINATION BY ACCIDENTAL MELT-DOWN OF SPENT SEALED SOURCES

Year	Radionuclide	Activity	Probable origin
1983	Co-60	0.9 TBq	Industrial radiography or old teletherapy source
1984	Co-60	15 TBq	Teletherapy source
1984	Co-60	0.4 - 0.7 GBq	Gauge
1985	Co-60	?	Furnace wall ?
1985	Cs-137	56 GBq	Gauge
1985	Cs-137	0.4 - 1.9 TBq	Gauge
1986	Cs-137	0.7 - 0.9 TBq	Gauge
1986	Ra-226	?	Medical source

It is interesting to note the way by which these accidents were discovered. Only in one case was action taken because sources (four level gauges containing ^{137}Cs) were reported lost. In this case one source was retrieved from a scrap yard 46 km from where it had been used and the rest were found by an aerial radiation survey over scrap yards, steel mills, and other selected sites. Two accidents were discovered because of abnormal response by radiation monitors when contaminated items were being checked, two because contaminated items entered controlled areas, two when a truck with flue dust and one with slag passed a radiation monitor, and one was detected by a monitor installed at a weighing station on a highway. Table 5.1-III summarizes how the accidents were discovered.

TABLE 5.1-III. MEANS OF DISCOVERY OF ACCIDENTAL MELT-DOWN OF SPENT RADIATION SOURCES

Year	Means of Discovery
1983	Abnormal response of plant level gauge
1984	Object passing radiation monitor at another site
1984	Object passing radiation monitor
1985	Abnormal response of a gamma-log
1985	Passing state highway radiation monitor
1985	Reported lost source
1986	Flue dust passing radiation monitor
1986	Slag passing radiation monitor

The fact that all reported cases except one were recognised by chance, and not by any systematic control measure, makes it likely that there have been similar incidents in the USA and other countries which have not been recognised at all. There have been isolated reports of metal objects which had elevated activity content without any reasonable explanation.

A computer code has been developed to predict the activity distribution in commercial steel caused by recycling of contaminated scrap from the nuclear industry [20]. This has been expanded to cover contamination by spent sources, notably by those used to check the ceramic brick walls in steel smelters (^{60}Co with activity of the order of 1 GBq). A calculation of the activity concentration expected in steel due to recycling and spent sources indicates that cases of contamination above 0.1 Bq/g are mainly caused by spent sources. A pre-study to verify the calculated activity concentration distribution based on measurements of samples chosen at random has indicated that the number of samples having activity concentrations above measurable levels are 5-10 times higher than expected. Although the results are preliminary and the analyses of the causes are yet to be completed, it is likely that spent radiation sources, which have been melted together accidentally with scrap metal, are the main cause.

An unusual case of metal contamination came to light in New York in the 1950s, when contaminated gold was used in jewellery [21]. The activity originated in spent medical radon sources. Some of these were encapsulated in gold, which became contaminated by decay products of the radon. Eventually some of these gold capsules found their way to the jewellery industry. Although the contamination was low it could give significant exposure if the gold came into direct contact with the skin, as was found when people wearing contaminated rings developed skin lesions. In a major campaign in 1981, 170 pieces of contaminated gold were identified, and nine people were found to have squamous cell cancer. These individuals had worn their jewellery for an average of 17 years. It was also reported that a 2.5 kg batch of gold, containing gold from radon encapsulations and thus also contaminated, was missing from a radium processing company. This batch has not been found. As late as 1989 three new cases of contaminated gold rings were discovered, two of which had resulted in skin cancer on the wearer's finger.

Radium needles, of which several thousand remain as spent sources in Third World hospitals, are made of platinum and so are very attractive as a source of scrap for jewellers. The problems which could follow are much more severe than those experienced in New York as these needles are fully loaded with radium, whereas the gold was only incidentally contaminated with decay products from radon.

5.2 Economic consequences of accidents with spent radiation sources

Summary of 5.2 **The most costly clean-up operation, after the accident in Mexico in 1983, is estimated at about 34 million US dollars. There are also others which have cost more than one million, but for most accidents no total cost estimates have been made. Costs for medical treatment of a seriously exposed individual can exceed US$ 500,000. Although no figures are available for the costs for lost equipment, damage to property, and disposal of decontamination waste, it is obvious that these can also be high. Very large sums may thus be saved if actions are taken which prevent an accident from occurring.**

Damage to health cannot be measured in purely economic terms, but there may be other consequences for which economic evaluation is appropriate.

Before the 1940s, when all sealed radiation sources contained radium, and the health consequences were not fully recognised, the main economic consequence of an accident was considered to be the loss of valuable material. Little effort was made to decontaminate after a spread of activity. It is only during the last 10 to 20 years that extensive measures to clean up have been taken without the cost determining whether or not the work should be done.

The components in the costs of an accident include:

- loss of sources
- medical treatment of exposed individuals
- radiation surveillance, including search for lost sources and contamination
- decontamination/dismantling
- loss of production capacity

- waste management and disposal

- costs for monetary compensation to over-exposed individuals

For spent radiation sources the economic value of the source is usually negligible.

Specialist treatment of highly exposed individuals is very expensive. The hospital costs alone may be at least a couple of thousand US$ per day. Total medical treatment costs for a seriously exposed person can exceed 500,000 US$.

Depending on the area to be covered by a radiation survey the costs can be anything from negligible up to more than 100,000 US$. For example, the US state radiation protection authorities estimated their costs for locating contaminated objects after the 1983 Mexico accident, when a ^{60}Co source contaminated a large batch of steel, to be more than 200,000 US$ [17].

Decontamination costs can also vary, depending on where the contamination occurs and how big the affected area is. The costs can be anything from zero to more than a million US$. In one case, when a steel plant was contaminated by a ^{60}Co source, the decontamination cost was reported to be 2.2 million US$ [18].

If it is not possible to decontaminate, or if decontamination is unsuccessful, the contaminated items must be treated as waste and their value will be lost. The higher the value of the object the more effort may be made to achieve full decontamination. Sometimes decontamination will not be possible. After the Goiânia accident there were several buildings, including residences, which had to be demolished because they could not be decontaminated. After the accident in Mexico in 1983 many new pieces of furniture had to be regarded as radioactive waste, and some houses had to be demolished because their construction included reinforcement bars made from the contaminated batch of steel.

If industrial plant is contaminated it may be necessary to shut it down during the period of investigation and clean-up, causing indirect costs through disruption of operation and loss of production.

During decontamination large volumes of radioactive waste can be generated and this must eventually be disposed of. The cost of disposal varies depending on the type of repository, the pricing policy, and the type of waste to be disposed of. For modern repositories the cost per cubic metre varies from around 1,000 up to 10,000 US$. At such prices, the cost of disposing of waste generated at Goiânia must be several million dollars.

The only published cost estimates for remedial action after accidents with spent sources are for decontamination of steel plants in which sources have accidently been melted. The reported costs, which may run to millions of dollars, are summarised in Table 5.2-I [18]. In addition there must also have been costs for disposal of the waste.

According to unofficial estimates the remedial actions after the Goiânia accident cost 2.8 million US$. Hire of heavy equipment for handling radioactive material, cleaning up large areas, dismantling buildings, and transporting wastes, accounted for more than half the total. In addition to these 2.8 million US$ there are costs for medical treatment and for disposing of the wastes, which at present are still stored.

TABLE 5.2-I. REPORTED COSTS FOR DECONTAMINATING STEEL PLANTS AFTER ACCIDENTAL MELTING OF SPENT RADIATION SOURCES

Year	Source involved	Costs (US $)
1983	0.9 TBq Co-60	2,200,000
1984	0.4 - 0.7 GBq Co-60	relatively minimal
1985	? Co-60	" "
1985	56 GBq Cs-137	1,000,000

In total the direct and indirect costs in Mexico for the remedial actions after the accident in 1983, when a teletherapy source was accidentally melted, is estimated to be about 34 million US dollars. Of that sum the largest fraction, 46%, was spent on transport and disposal of 7,450 tonnes of steel and 17,500 tonnes of other contaminated material. Contaminated items, which had been sold to the USA before the accident was discovered, were returned to Mexico. Table 5.2-II gives the break-down of the total cost.

TABLE 5.2-II. BREAK-DOWN OF THE COST OF REMEDIAL ACTIONS AFTER THE ACCIDENT IN MEXICO IN 1983

Actions taken	Percent
Transport and disposal of contaminated material	46%
Demolition and reconstruction to remove contaminated reinforcement bars in buildings	25%
Loss of production capacity	11%
Value of contaminated material	6%
Technical and operational personnel and equipment	2%
Security and surveillance by police and army forces, legal or political problems, etc.	10%
Total cost: US$ 34 million	

Luckily, most accidents do not give rise to such high costs. It is however clear that costs for a single accident can be very high, especially if the accident is not immediately recognised as such and preventive action is delayed, allowing further exposure of individuals and further spread of radioactive material. Very large sums could thus be saved by properly implemented measures for preventing future accidents.

6. PERCEPTION OF RISKS ASSOCIATED WITH SPENT RADIATION SOURCES

__Summary of 6.__ **The perception of risks from spent radiation sources is lower in developing countries than in developed countries, but even in the latter the full extent of the risk is not always appreciated. It certainly cannot be assumed that all decision-makers in developing countries will fully recognise the problem. To improve the situation in those countries will require initiative and assistance, including financial support, from international organizations.**

The word "risk" can mean:

- the probability of an event to occur (e.g. the risk to be exposed from a spent radiation source)
- the consequence or severity of an event once it has occurred (e.g. the risk of developing cancer as a result of a given radiation exposure)
- the product of the probability of an event and its consequences.

In radiation protection the third meaning of risk is normally used, although it has created, and still does create, problems because of the different ways in which the words may be understood (for this reason ICRP has recently proposed the use of new terminology for discussing risk in radiation protection [10]). The advantage of the third interpretation, which is used in this report, is that it offers the possibility of calculating a risk figure using "scientific methods". This is also the reason why this meaning of risk is sometimes called "objective risk", in opposition to "perceived risk" or "subjective risk". The word "objective" is intended to indicate that the risk value being calculated is independent of who is making the assessment, so long as the best knowledge and scientific methods are used. Studies have however shown that there is no such thing as a really objective risk. Sometimes the perceived risk, as expressed by laymen, may even represent a better understanding of complex problems of risk.

The calculated risk levels can be considered totally meaningless for an individual in a group. For him the effect will either occur, or will not occur. If the calculated risk from an event is 0.1 lethal cancer, it will most probably be 'no effect' for the individual but it may also be a lethal cancer; it will never be 0.1 cancer.

The case history for a spent radiation source will either be that there is no serious health effect, or that an accident resulting in significant radiation exposure occurs. The number of spent sources will not influence the consequences of an individual accident, only the probability that it will occur. The consequences are governed by the characteristics of the source, the way the accident develops, the people involved, and the countermeasures taken.

Perceived risk is not only, and sometimes not even mainly, governed by calculated risk levels. If a risk has its cause in a voluntary activity, such as for example horse riding, smoking or rock climbing, the risk may be perceived as similar to that of an activity having up to 1000 times lower objective risk but which is forced upon an individual, such as occupational exposure to ionizing radiation.

If a practice giving rise to risk is regarded as unnecessary or undesirable, the perceived risk from that practice is seen as much larger than the corresponding objective risk. Also, an unfamiliar risk is considered worse than a familiar risk.

If there has been an accident having severe consequences which have been given extensive publicity, so that there is an increased awareness of the problem, there will also be an increase in the perceived risk in the practice giving rise to the accident. The closer to the time and location of the accident, and the more the publicity, the larger will be the risk perceived.

Even though well educated and informed individuals may show smaller differences between perceived and objective risks, many examples can be given in which this difference amounts to many orders of magnitude.

Decision makers must consider not only the objective and perceived risks when making their decisions but also, especially if the decision maker is a political institution, the political consequences of the decision. That this "recognised risk" may differ from the other risks is illustrated by the situation regarding radon in houses. There are countries where many houses have high radon concentrations. It is possible to take measures to reduce the concentration to any desired value, but this may be very expensive. For example, in one country 50 percent of the houses have radon concentrations which result in doses to the inhabitants in excess of what would have been permitted if the dose were generated by the industry. The average cost per house of measures to reduce the radon concentration is at least 1000 US$. With two million houses the total investment required would thus exceed two billion dollars. If it were decided to reduce domestic radon concentrations to the levels required in industry, the economic consequences would be unacceptably large, and the decision would be unpopular because it would affect private property and personal expenditure. For these reasons the acceptable domestic radon concentration was set at a higher level.

Because the risk-concept has so many dimensions, it is not possible to make a clear statement of the perceived risk from spent radiation sources within a limited study. There are no published studies on the subject to refer to. Based on discussions with representatives from developed as well as developing countries, and some scattered information on relevant subjects, it is however possible to make some general observations:

- Countries lacking radiation protection and waste management infrastructure do not properly recognise the risks from spent radiation sources.

- Highly industrialised western European countries, which have made extensive use of medical and industrial sources over a long period, do not have full control of their spent radiation sources, even though they have had proper legislation and radiation protection and waste management infrastructures for a long time. They still underestimate the risks from spent radiation sources in their countries.

- There are developing countries which cannot afford to recognise the problem because there are larger and more urgent risks to be reduced which take the available resources.

- The Agency cannot expect all developing countries to recognise their national problems with spent radiation sources or take the necessary steps to reduce the risk of this type of accident. It is therefore necessary to take action to improve the situation.

7. EXISTING PRACTICES FOR THE MANAGEMENT OF SPENT RADIATION SOURCES

Summary of 7 **There exists today experience and means for all steps in the management of spent radiation sources, except disposal of long-lived sources. However, all countries do not have the resources needed to implement existing methods. Assistance is therefore required.**

The safe management of spent radiation sources includes the following topics:

- identification
- collection and transport
- return to supplier
- conditioning
- interim storage
- disposal

Ideally all necessary manpower, equipment and facilities for safe management should exist within a country before a practice giving rise to spent radiation sources is initiated. Sealed radiation sources for which no further use is foreseen should, without undue delay, be:

- (if short-lived) transferred to interim storage for decay until exempted levels for disposal are reached, or

- (if long-lived) conditioned in such a way that the source is made safe and then transferred to a proper interim store while awaiting eventual disposal.

As illustrated in Appendix VI, countries differ widely in their experience of the steps in the safe management of spent radiation sources. Good facilities and experience exist mainly in the developed countries, elsewhere they may be completely lacking.

An alternative to conditioning and storing a spent radiation source is to return it to a supplier or other organization having proper interim storage and disposal facilities. This option is often the preferred practice.

In summary, the situation in the developing countries is as follows:

Collection and transport

Most developing countries do not have the necessary equipment, expertise, and experience for the safe collection and transport of spent radiation sources. These countries need Agency assistance, including advice, training, equipment and sometimes economic support.

Return to supplier

Return of spent sources to the supplier is often the best option and is strongly recommended by the Agency. Most new contracts for purchase of sources contain a clause for the return of the sources once they are spent. This method is however not available for many old sources as the original supplier is unknown or no longer exists. Also, lack of money has in some cases hindered the return of spent sources as the cost of packaging and transport can be considerable.

Conditioning

All spent radiation sources should be conditioned as soon as practicable once they are identified, unless the half-life of the radionuclide is short enough to guarantee decay to exemption levels while the source is still under strict control. There are simple methods for conditioning spent sources in cement, and these can be applied in developing countries. Large sources used for sterilization and irradiation should always be sent back to the supplier. In some countries there are facilities for encapsulating spent radium sources in welded steel capsules. Two thirds of the developing countries do not have any experience of conditioning operations.

Interim storage

All countries using nuclear power or having large nuclear research centres have some interim storage facility for radioactive wastes, and these may also be used for the long-term storage of properly conditioned spent radiation sources. In most other countries no storage of this type is available. For some developing countries there is thus an urgent need for international or regional interim storage to be established, to which they can send those sources, notably radium sources, which require a long storage time.

Disposal

Disposal of spent radiation sources, including radium sources, has been done by sea dumping or by disposal in shallow land repositories. There are only a few repositories anywhere in the world which are sited, constructed and operated in compliance with the safety principles laid down by the IAEA. However, some spent radiation sources, which have a high activity and/or contain long-lived radionuclides, need for radiation protection reasons disposal in deep geological repositories or sea disposal. Neither option is available at present.

From the radiation protection as well as from the economic point of view, the establishment of <u>regional</u> shallow land repositories for countries having small waste volumes is favourable.

It must be appreciated that it is necessary to get agreement with some developed countries to use their deep repositories (when they have been constructed) for disposing of the small quantities of long-lived spent sources from those developing countries which have no possibility to establish their own repository.

8. CONCLUSIONS

The present global situation as regards the management of spent radiation sources is unsatisfactory. Accidents caused by spent sources occur every year, causing unnecessary exposures (sometimes even lethal exposures) and requiring extensive and costly contamination cleanup.

Most developed countries have proper legislation and all necessary technical and personnel resources for the safe management of spent radiation sources, except for facilities for final disposal, which are still rare. The main lack in these countries is a proper system for keeping track of the sources at all stages of their existence; a national database for all major radiation sources is needed. The people who make and use radiation sources realize that the problem exists, but this may not be recognized by the decision makers. There is extensive knowledge and experience of the management of radiation sources, but accidents still occur.

In the developing countries there is often a lack of both proper legislative framework and of technical resources. There is little knowledge or experience of the management of spent radiation sources. The degree of awareness of the problem covers a whole spectrum, from full recognition to ignorance. Financial resources are inadequate. There is an urgent need for Agency assistance in the form of training, equipment, financial support, and practical work affecting all aspects of the safe management of spent sources. There is also a need for advisory documents which can be used by Member States to improve their performance without other outside assistance. A beginning in all these directions has already been made in the Agency's current programmes.

Many of the spent sources in developing countries were originally brought into the country by firms operating from developed countries, or were given by governments, institutions or other organisations in developed countries. The supplying countries carry a certain responsibility for helping the developing countries to improve their management of these sources when they become spent.

The role of the IAEA is "to seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Within this role the Agency has supplied many radiation sources to developing countries. All will eventually become spent: some already are. The Agency must have been aware that many of the receiving countries did not, and many still do not, have the capacity to manage their spent sources. Many have no established radiation protection or waste management infrastructures. Despite this, it is not until recently that the Agency has considered the problems these sources will cause once they are no longer in use.

The Agency is implementing a comprehensive action plan for assistance to Member States, especially the developing countries, in all aspects of the safe management of spent radiation sources. The Agency is further seeking to establish regional or global solutions to the problems of long-term storage of spent radiation sources, as well as finding routes for the disposal of sources when it is not feasible to set up safe national solutions.

The cost of remedial actions after an accident with radiation sources can be very high indeed: millions of dollars. If the Agency can help to prevent even one such single accident, the cost of its whole programme in this field would be more than covered.

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Appendix I

EARLY HISTORY OF THE PRODUCTION AND USE OF RADIUM

In 1896 Henri Becquerel found that uranium salts affected photographic plates. In 1898 Pierre and Marie Curie isolated an element they called "radium" from pitchblende, an element which was much more effective in darkening photographic plates than any uranium salt.

The first pitchblende the Curies used was a gift from the US government, but the quantities were small. Larger quantities came to their laboratory from the Joachimsthal mine, located in an area which at that time belonged to Austria and is now in Czechoslovakia. Between 1898 and 1903 Pierre and Marie Curie obtained a total of 11 tonnes of pitchblende from this mine (from old pitchblende tailings which were stored at the mine after previous uranium mining), most of it as a gift from the Austrian government [1].

When radium became available uses were soon found for it. Its first application as a sealed source of ionizing radiation was in 1901, when Pierre Curie provided a physician at a Paris hospital with a radium source to be used for medical treatment. The source was to be applied to a malignant surface tumour. Two years later the first successful treatment was reported. In 1904 the first attempt to treat a tumour inside the body was made by inserting a glass capsule containing radium. Commercial interest in radium grew as its usefulness was demonstrated.

The concentration of a commercially interesting metal in its ores is usually a few percent, but the concentration of radium was at least a million times lower. To extract an element at such low concentration is time-consuming and expensive. To produce 100 mg of radium, by one of the processes [2] used at the beginning of this century, the following raw materials were needed: ten tonnes of ore, three tonnes of hydrochloric acid, one tonne of sulphuric acid, five tonnes of sodium carbonate, and ten tonnes of coal. After that came two months of laboratory work to purify the radium.

When the high economic value of radium was recognised the Austrian government put an embargo on the export of pitchblende from the Joachimsthal mine (in 1903) and established its own radium extraction plant. For the following 10 years this Austrian plant was the world's main supplier of radium, and for a further 10 years it was the main European supplier. There was also some commercial production in Paris, with ores from Sweden, Hungary and Canada, but only small quantities were produced.

Between 1913 and 1922 the main production of radium was in Colorado, USA, but radium was also extracted from ores in Portugal, Australia, Madagascar and the Soviet Union. In 1915 a high grade uranium ore was discovered in the Belgian Congo by the Belgian company Union Minière. This company set up its extraction plant at Olen in Belgium and produced its first radium in 1922. Since the African ore was 30 to 40 times richer in radium the American companies could not compete and left the market a few years later.

For ten years Union Minière dominated the world market, but in 1932 it faced competition from the Canadian company Eldorado, which established a radium extraction plant in Port Hope, Ontario, using high grade ores from Great Bear Lake. After a few years of competition the two companies made an agreement in 1938 to fix the price of radium and divide the market between them on a 60 to 40 basis, with Union Minière taking the larger share [3,4].

At the beginning of the century the price of radium was extremely high, up to 100,000 US dollars per gram. This made radium production very profitable. As more companies entered the market, and larger and richer ore bodies were discovered, the price fell to 75,000 dollars per gram in 1930 and down to 20,000 in 1937. After the 1938 agreement between Union Minière and Eldorado the price was stabilised between 20,000 and 26,000 dollars per gram, depending on quantity.

After the second world war the radium market contracted rapidly. New radiation sources could be made using artificial radioisotopes produced in accelerators or nuclear reactors, with better characteristics, including being much safer to use.

From the beginning little consideration was given to safety in the use of radium, and there are numerous examples of medical applications recommended by medical doctors which would be considered totally unacceptable today. Many commercial products containing radium were put on the market, often as consumer products. It was not until some of the radium pioneers died from causes which could be associated with their work, that its dangers were properly considered. This was during the 1930s. After being considered solely as beneficial during its first 20 to 30 years radium became recognised as a hazard, and in 1941 it was established as a standard for radiotoxicity. The Maximum Permissible Body Burden (MPBB) for radium, 0.1 μCi, was used for the calculation of MPBBs for all other radionuclides. Radium had become a risk standard.

There are some figures in the literature for the quantities of radium produced. Up to 1902, when Pierre and Marie Curie were separating the element, only 0.1 g was produced. From Joachimsthal 13 g were produced up to 1913 and in Colorado 196 g up to 1926. Figures given for the first ten years of production by Union Minière vary between 396 and 700 g. Production by Eldorado was smaller. The total estimated production of radium up to 1940, mainly by the two latter firms, is 1.4 kg. No estimate is found for production after 1940 or for production in the Soviet Union, China and other countries. Production by Eldorado stopped in 1954 and by Union Minière in 1960. Fig. A.I-1 summarizes radium production.

Once treatment methods were established, the medical use of radium increased rapidly, despite its high price. The great advantage of radium, in comparison with treatment by X-rays, which was the alternative method of treatment, was that radium sources could be placed directly onto or inside a tumour, whereas X-rays could only be applied from outside the body and not in direct contact with the tumour. Radium was usually encapsulated either in needles, of which a number could be inserted directly into a tumour, or in "tubes" (small sealed cylinders) which could be applied to tumours on the surface of the body or placed in body cavities. The high price of radium sources made it the most valuable item of equipment in many hospitals. At least 100 mg of radium was required for a full set. Many donations were made and special funds were raised between 1920 and 1940 to acquire radium for medical use.

Another widespread early use of radium was in luminous compounds, which were made by mixing radium with zinc sulphide. Its main use was in clocks and watches, but it was also used in other consumer products.

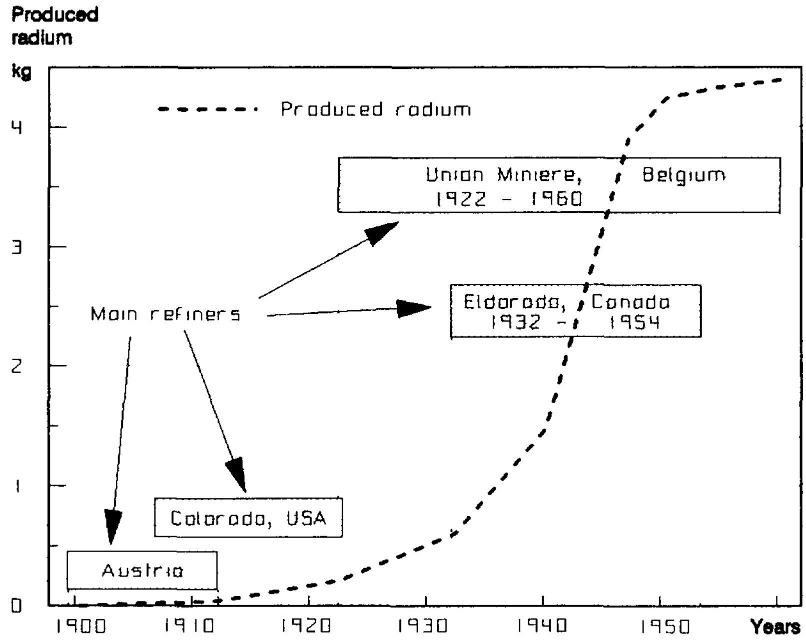

FIG. A.I-1. Main radium refiners and their periods of operation.

Although the quantity used in each item was small, only a few micrograms, the total quantity was significant. In the USA for example, 70 grams of radium were produced for manufacturing luminous compounds between 1913 and 1920.

During the 1920s radium emanators were designed for producing "radon water" and were sold to the general public. One of these could contain up to 0.5 mg of radium. The use of the "radon water" was advertised as being healthy, and said to be supported by medical recommendation. Other medical products containing radium were sold to the public, for example Radium Salve, and cloth impregnated with radium. According to one advertisment [2]:

> "Radium Rays have proven highly valuable in the treatment of the following conditions: anaemia, arteriosclerosis, arthritis, catarrhal conditions, diabetes, dental conditions, general debility, goitre, high blood pressure, menopause and menstrual disorders, nephritis, neuralgia, neurasthenia, nervous conditions, obesity, prostatitis, rheumatism, senility, sexual conditions and skin disorders."

Products of this type can still be found for sale in antique shops or stored in attics or cellars.

Until the late 1940s no radionuclide other than radium was available in significant quantities for use as a sealed radiation source. When particle accelerators and research reactors became widely available, during the 1950s, sources with many different radiation characteristics could be produced. These were safer and easier to handle than those containing radium, and could be used for many new purposes. Most of the modern applications of sealed sources in industry, agriculture and research, such as level and thickness gauges, soil moisture gauges, or irradiation facilities, were developed during these years.

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Appendix II

EQUIPMENT CONTAINING SEALED RADIATION SOURCES USED IN INDUSTRY, RESEARCH AND MEDICINE

The table gives the most frequently used types of equipment and the corresponding radionuclides. Alternative radionuclides are given in brackets. Different activities may be used depending on the specific application. Figures in the Table represent a typical range.

Application	Radio-nuclide	Half-life	Source strength	Comments
I. Industrial application				
Belt gauge	Cs-137	30 y	0.1- 40 GBq	Fixed installations
Density gauge	Cs-137 Am-241 (Sr-90)	30 y 433 y	1 - 20 GBq 1 - 10 GBq	Fixed installations
Industrial radiography	Ir-192 Co-60 (Cs-137, Tm-170, Yb-169)	74 d 5.3 y	0.1- 5 TBq 0.1- 1 TBq	Often portable units
Level gauge	Cs-137 Co-60 (Am-241)	30 y 5.3 y	0.1- 20 GBq 0.1- 10 GBq	Fixed installations
Moisture detector	Am-241/Be (Cf-252, Ra-226/Be)	433 y	0.1- 10 GBq	Portable units
Roentgen fluor-escence analyser (XRF)	Fe-55 (Pu-238, Am-241)	2.6 y	0.1- 5 GBq	Often portable units
Sterilization and food preservation	Co-60 Cs-137	5.3 y 30 y	0.1-400 PBq 0.1-400 PBq	Fixed installations
Thickness gauge	Kr-85 Sr-90 (C-14, P-32, Pm-147, Am-241)	10.8y 28.1y	0.1- 50 GBq 0.1- 2 GBq	Fixed installations
Well logging	Am-241/Be Cs-137	433 y 30 y	1 -500 GBq 1 -100 GBq	Portable units

Application	Radio-nuclide	Half-life	Source strength	Comments
II. Research applications				
Calibration sources	Many different		< 0.1 GBq	Small portable sources
Electron capture detector	H-3 (Ni-63)	12.3 y	1 - 50 GBq	Can be used in portable units
Irradiator	Co-60	5.3 y	1 -1000 TBq	Fixed installations
Tritium targets	H-3	12.3 y	1 - 10 TBq	Fixed installations for neutron production
III. Medical applications				
Bone densitometer	Am-241 I-125	433 y 60 d	1 - 10 GBq 1 - 10 GBq	Mobile units
Brachytherapy	Cs-137 Ra-226 (Co-60, Sr-90, Ir-192)	30 y 1600 y	50 - 500 MBq 30 - 300 MBq	Small portable sources
Teletherapy	Co-60 (Cs-137)	5.3 y	50 - 500 TBq	Fixed installations

Appendix III

CHARACTERISTICS OF ^{226}Ra, ^{60}Co, ^{137}Cs, ^{192}Ir AND ^{241}Am USED IN SEALED RADIATION SOURCES

^{226}Ra is part of the decay chain of ^{238}U. Radium decays with alpha emission to ^{222}Rn, a noble gas with a half-life of 3.6 days. Before the decay chain ends, with the stable isotope ^{206}Pb, it has generated a further eight radionuclides of which four are alpha emitters. Each decaying ^{226}Ra atom thus gives rise to five alpha particles. During the decay many high as well as low energy gamma quanta and beta particles are also emitted. In a radium source there are always not only ^{226}Ra but also its daughter products. ^{226}Ra is a very radiotoxic radionuclide with a correspondingly low Annual Limit of Intake (ALI). A simplified scheme for the ^{238}U series, which includes ^{226}Ra, is shown in Fig. A.III-1. Some important characteristics of ^{226}Ra are given in Table A.III-I.

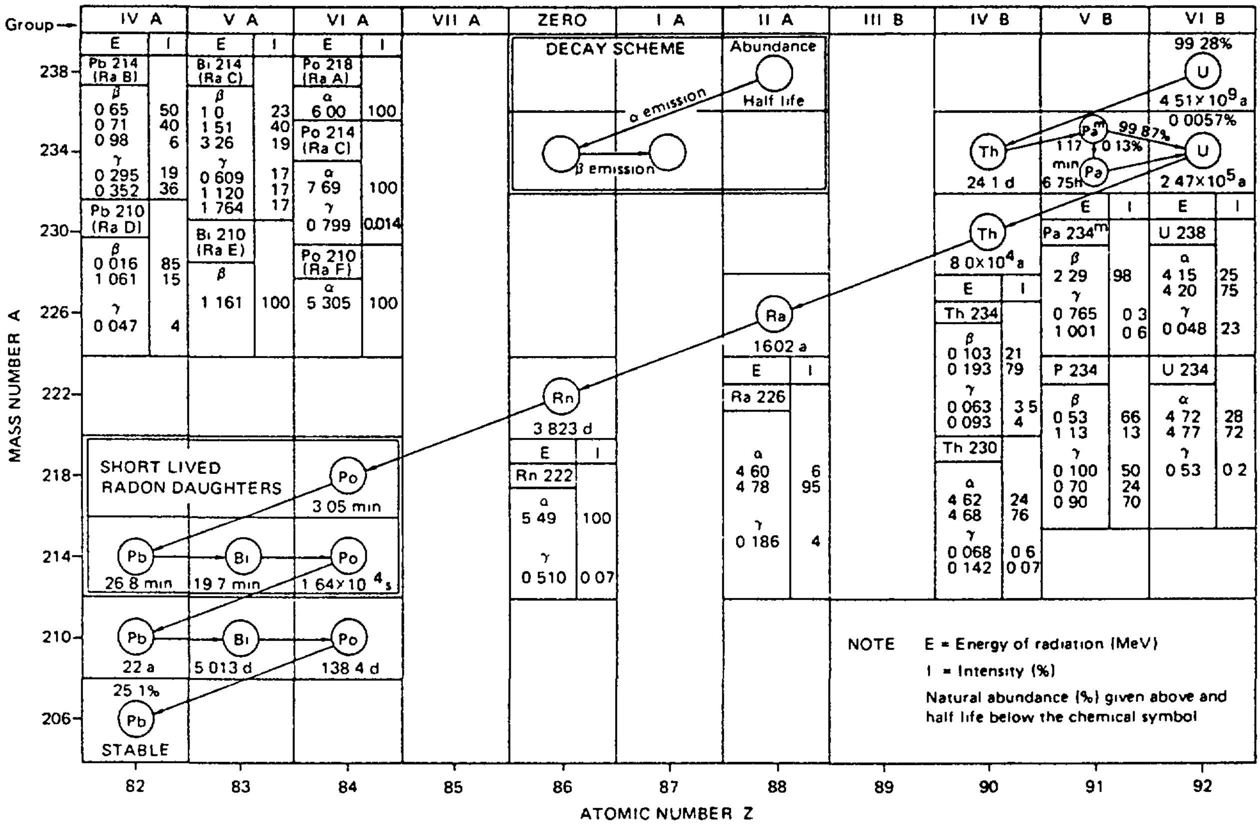

FIG. A.III-1. A simplified scheme for the ^{238}U decay series, with includes ^{226}Ra [2].

TABLE A.III-I.

CHARACTERISTICS OF FIVE RADIONUCLIDES OFTEN USED IN SEALED RADIATION SOURCES

Characteristics	Radionuclide Co-60	Cs-137	Ir-192	Ra-226	Am-241
Half life	5.26 y	30 y	74 d	1600 y	433 y
Principal					
- alpha energy [MeV]	-	-	-	1/	5.86
- max beta energy [MeV]	0.31	1.2	0.67	1/	-
- gamma energy [MeV]	1.17 1.32	0.66	0.32 0.47	1/	0.06
Gamma constant [μSv/h GBq at 1 m]	360	86	140	220	4
Dose rate at 1 cm from a 1 MBq source 2/ [mSv/h]	2.5	0.6	0.9	1.7	3/
Half value layer (HVL) of lead [mm]	12	6	5.5	14	0.2
ALI(oral) [Bq]	$7X10^6$	$4X10^6$	$4X10^7$	$7X10^4$	$5X10^4$
ALI(inhalation) [Bq]	$1X10^6$	$6X10^6$	$8X10^6$	$2X10^4$	$2X10^2$

1/ In the decay chain there are alpha energies up to 7.7 MeV, beta energies up to 2.8 MeV and main gamma energies up to 2.4 MeV.

2/ Dose rate calculated for a point source encapsulated in 0.8 mm stainless steel. An addition of 35-45% is made to take into account electron production in the encapsulation [2].

3/ Dose rate is very dependent on encapsulation, which may include a thin window. At short distances the dose rates can be very high from alpha and beta radiation, but not at larger distances.

Radium is an alkaline earth metal. It is very reactive and reacts even with nitrogen. In radiation sources radium is therefore always used in the form of salts, which may be bromides, chlorides, sulphates or carbonates. All are soluble in water in amounts which can give rise to radiological problems. These salts may easily be dispersed as powder if the source encapsulation is damaged. This is one reason why radium is not regarded as an ideal material for use in sealed sources.

In the body radium behaves like calcium, which means it concentrates in the bone where it has a very long biological half-life.

The decay of each atom of ^{226}Ra yields five helium atoms formed from the alpha particles emitted in the decay chain. This generates overpressure in a sealed radium source (about 0.2 atmospheres per year for one gram of radium and a free volume of 1 cm^3) and facilitates the spread of contamination if it starts leaking. If there is water of crystalization in the source the alpha particles emitted in the decay chain decompose it to oxygen and hydrogen, which further increases the overpressure. Leaking radium sources have always been a major radiation protection problem. In the early days there were explosions of large standard ^{226}Ra sources encapsulated in glass, and explosive ruptures of metal sealed sources have also been reported. This characteristic of ^{226}Ra is another reason why it is regarded as unsatisfactory from the point of view of radiation protection.

^{60}Co is produced by neutron bombardment of natural cobalt. If pure cobalt is used as target material ^{60}Co will be produced almost free of other radionuclides. It decays by emission of beta particles and two gamma quanta (1.17 and 1.33 MeV) to a stable nickel isotope. The half-life is 5.26 years. Important characteristics of ^{60}Co are shown in Table A.III-I.

In sealed radiation sources metallic cobalt is always used since this gives the highest specific activity to the source. Usually it is in the form of thin discs or small cylindrical pellets. The metal is stable in air, but a thin layer of oxide forms on its surface and this could cause contamination if unprotected cobalt is handled. For this reason the cobalt used in radiation sources is nickel plated before activation.

Cobalt metal is not soluble in water. If cobalt in a soluble form is taken up by the body it is evenly distributed, with the exception of the liver where four times higher concentration may be reached.

^{137}Cs is a fission product produced in reactor fuel. It must be purified chemically from other elements before it can be used in a radiation source. Its half-life is 30 years and the decay mode is beta and gamma. The gamma energy is low (0.66 MeV) in comparison to that of ^{60}Co, which implies that less shielding is required, but since the gamma output is also lower, higher activity is needed to achieve the same dose rate. The radiation output achievable from a sealed source is however limited by self absorption within the source. Important characteristics of ^{137}Cs are shown in Table A.III-I.

Caesium is an alkaline metal similar to potassium and sodium. It is very reactive and can only be used as a salt in sealed radiation sources. Caesium chloride has often been used. Today ^{137}Cs sources are also prepared in ceramic form, making the radionuclide virtually insoluble in water. This technique is used only for weak sources, however, because it results in a drastic reduction of specific activity. When taken up by the body the highest concentrations are reached in muscle.

^{192}Ir is produced by neutron irradiation of metallic iridium. It has a short half-life, only 74 days, which makes all iridium sources harmless within five years. It decays via emission of beta particles and gamma quanta to stable platinum and osmium isotopes. The decay scheme includes many different gamma quanta with energies up to about 0.5 MeV. Important characteristics of ^{192}Ir are shown in Table A.III-I. Iridium is a noble metal which is not oxidised in air or dissolved in water, which are excellent characteristics for a sealed radiation source.

^{241}Am is a transuranic element, produced in uranium by neutron bombardment. Like, ^{137}Cs, it is a by-product of nuclear power production. Its half-life is 433 y and it decays by alpha emission to a long-lived neptunium isotope with a half-life of 2 million years. Important characteristics of ^{241}Am are shown in Table A.III-I.

Americium has chemical characteristics similar to the rare earth metals, indicating that as metal it is not in a stable form. Normally oxides are used in sources. For neutron sources fine oxide powder is mixed with beryllium powder and sintered to a ceramic-like product which is stable in air and from which the americium is not leached by water. When used as a low energy gamma source the stainless steel capsule has a thin closure in one direction to allow the quanta to be emitted without undue attenuation. In the human body the element is concentrated in bone and liver, and small intakes give high committed dose.

Further details on the above and other radionuclides can be found in Refs.[1-3].

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Appendix IV

EFFECTS OF IONIZING RADIATION ON MAN AND THE ENVIRONMENT

By its very nature ionizing radiation can be harmful to man. At low doses it can cause cancer or genetic changes in a series of events which are not all fully understood, and at high doses it can kill cells, damage organs and even cause death to man. The temporal sequence of events, from the primary electrical interaction between a radiation quantum and a target material, which occurs within less than a picosecond, up to a manifested biological effect occurring hours, days or years later, is illustrated in Fig. A.IV-1.

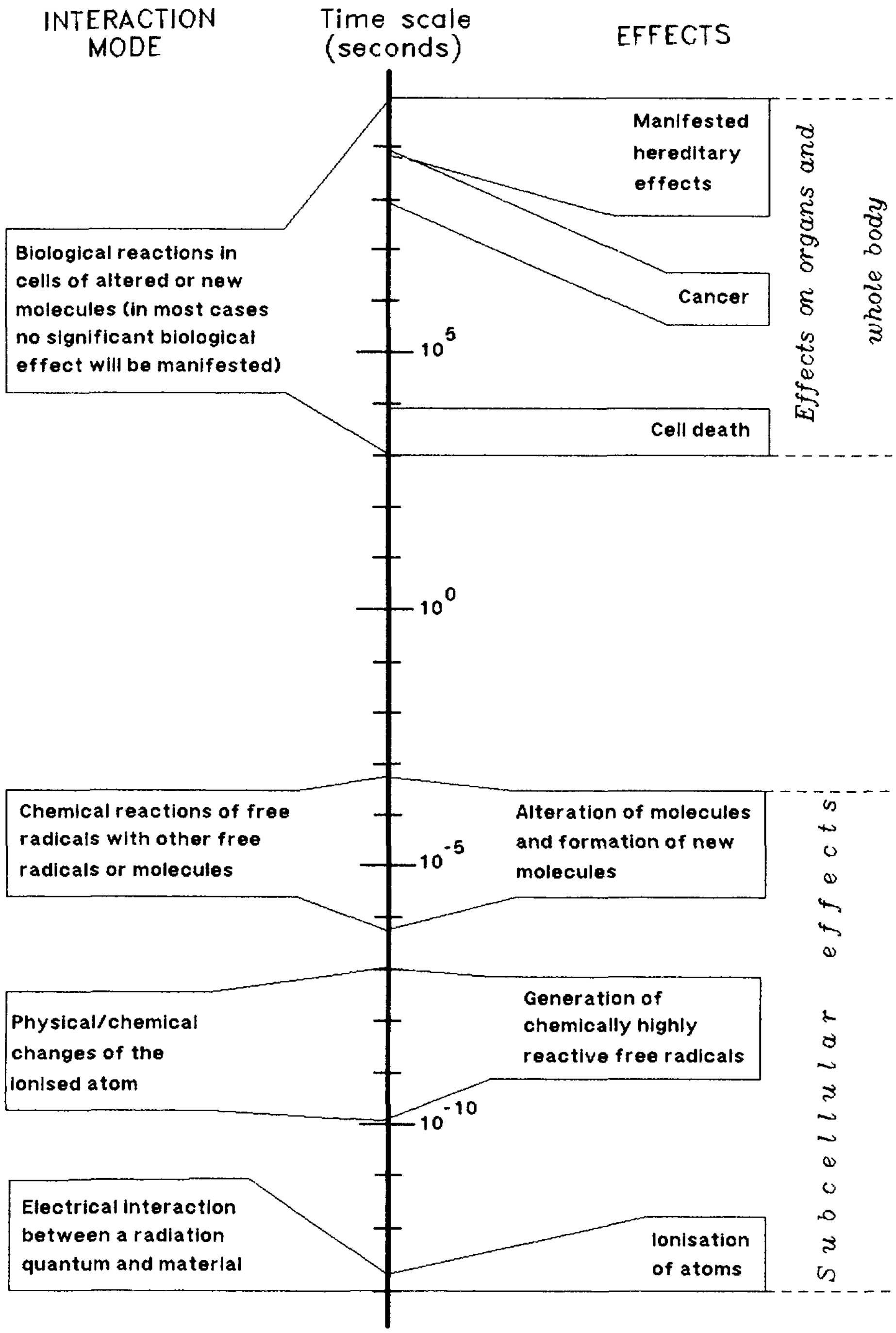

FIG. A.IV-1. Temporal sequence of events leading to radiation effects in man.

Damage caused by high doses to the exposed individual, known collectively as "deterministic effects", normally becomes evident within hours or days. "Stochastic effects" may be latent for a long time. Cancer takes years and even decades to appear, and by definition it takes at least one generation to manifest hereditary malfunctions and diseases caused by genetic damage. For this report it is the deterministic effects which are of main concern.

For deterministic effects there are thresholds below which the effect is not manifested. This is contrary to the situation for stochastic effects, for which it is believed that even the smallest dose can be effective, with a probability proportional to the dose.

The spatial distribution of the dose over the body is of great importance for the effect. A dose which could be lethal when given to the whole body would, if given to a small part of the body, only cause reddening of the skin a few days after the exposure, an effect which later will disappear. The distribution of dose in time is also important. If the same total dose is received over a period of weeks or longer there is more opportunity for the cellular repair mechanism to operate and there may not be any sign of deterministic effects, whereas they may appear if the same dose is given instantaneously.

Most of the existing information on the deterministic effects in man has been accumulated from the use of radiotherapy to treat cancer, but reports from radiation accidents have also given valuable knowledge.

If the dose is sufficiently high the exposed person will die. A whole body exposure of the order of 100 Sv will damage the central nervous system so badly that death may occur within hours. At doses of 10-50 Sv man may escape this fate only to die from gastrointestinal damage one to two weeks later. Lower doses still may avoid gastrointestinal injury - or permit recovery from it - but still cause death after a month or two. Death will then be caused by radiation damage to the red bone marrow. The white blood cells are formed in the red bone marrow, and when that is damaged, production of white blood cells ceases, resulting in loss of the normal immune defence system. The "LD_{50} dose", the whole body dose causing death in 50% of the cases, is in the range 3 to 5 Sv. Higher doses merely hasten the moment of death.

The red bone marrow and the rest of the blood-forming system are among the most sensitive parts of the body, and are affected by as little as 0.5 to 1 Sv. Fortunately they also have a remarkable capacity for regeneration and can recover completely. If only part of the body is irradiated enough bone marrow will normally survive to generate enough white bloodcells for immune defence and also to replace what has been damaged.

Reproductive organs are particularly sensitive. Single doses of as little as 0.1 Sv to the testes have made men temporarily sterile, and doses over 2 Sv can cause permanent sterility. The testes seem to be unique in that doses given in instalments cause more, not less, damage than the same exposure given all at once. Many years can pass after severely damaging doses before sperm is again produced normally. The ovary is rather less sensitive, at least in adult women, but single doses over 3 Sv will cause sterility, though higher doses can be given in instalments without impairing fertility.

The lens is the part of the eye most vulnerable to radiation. As its cells die they become opaque, and as the opacities grow they can lead to cataracts and eventually to total blindness. The higher the dose the greater the loss of vision. Single doses of 2 Sv or less can create opacities, and more serious progressive cataracts occur with doses of 5 Sv.

Most adult tissues are relatively robust in their response to radiation. The kidney will take more than 20 Sv over five weeks without significant signs of damage, the liver at least 40 Sv over a month, the bladder at least 55 Sv over four weeks. The lung, a particularly complex organ, is more sensitive, while subtle, but possibly important, changes can take place in blood vessels at quite low doses.

The threshold dose for skin erythema (reddening) is about 7 Sv, which gives a transient reaction. Higher doses will eventually give necrosis but this is very dependent on the total area of skin being exposed.

A summary of the deterministic effects is shown in Chapter 2, Fig. 2.2-1. A detailed discussion is given in the 1982 UNSCEAR report [1].

For stochastic effects there is no known threshold. The process which starts with radiation exposure and results in active cancer or a manifested hereditary effect is not yet fully understood. Risk figures for different stochastic effects have been derived from animal experiments and epidemiological studies with large groups of exposed people. Although these vary with the types of effects and population groups studied, a risk figure of $2 - 4 \times 10^{-2}$ per Sv for lethal cancer indicates the magnitude. The risk figure for induction of severe hereditary effects is smaller, about 10^{-2} per Sv [1,2]. A comprehensive discussion of these effects is given in the new radiation protection recommendations published by ICRP [3].

In most of the tragic cases of large exposures from spent radiation sources the exposure has been very unevenly distributed. In one case a spent radiography source was found and carried for 18 hours in the right and left hip pocket alternately, the local dose to parts of the thigh being as high as 17,000 Sv. The person survived, but both his legs had to be amputated.

Fingers will receive high dose rates if a source is handled manually, but the time during which it is handled is usually short compared to the time it may remain in a pocket.

Effects on the environment are conceptually not as well defined as effects on man and there are many reasons for this. Firstly, the environment is a very complex mixture of living and dead materials. According to an IAEA definition [4] the environment is "the sum of all conditions and influences that surround an organism, human or otherwise, that affects its life, survival and development". Secondly, there is no clear definition of a healthy environment against which effects on the environment can be evaluated, and thirdly, studies of environmental effects did not start to any significant extent until after global spread of radioactive material had occurred as a result of atmospheric nuclear bomb tests.

The main reason for studying the environmental effects of radiation has been that radioactive material in the environment can affect man. It is therefore of vital interest to get detailed knowledge of all environmental pathways of radionuclides to man, in order to establish correlations between radionuclide concentrations in the environment and dose to man. If contamination occurs there may also be important economic interests at stake. Buildings and areas may have to be decontaminated and even abandoned or dismantled if decontamination is impossible or unsuccessful. Farmers may not be able to use their fields and thus they suffer economic loss. Non-economic values can also be affected and destroyed. If land is contaminated there will be restrictions on the use of certain types of foodstuff and on access to recreation areas.

Radiation effects on animals were previously studied to evaluate effects on man, or to study effects on domestic or farm animals. Studies are now being made to evaluate effects on animals and plants for their own protection, both in short and long term perspectives.

Of relevance to spent radiation sources is the risk of contaminating buildings and living areas. This can result from handling leaking sources or by deliberate or unintended damage to the encapsulation. If the radioactive material inside the source is a fine powder, or a salt, large areas can be contaminated by material escaping from a leaking source while it is being moved, or when active material is spread by the wind. Further spread can result from men and animals moving from contaminated to uncontaminated areas and from moving contaminated goods. If the radioactive material in the source is soluble in water there is an additional route for contamination, namely all water systems. When there is outdoor contamination, rain water may contaminate wells and other sources of drinking water. Only when contamination has been recognised and monitored will efforts be made to stop its further spread.

Most sealed radiation sources contain radioactive materials with high specific activity. This means that spread of even a small fraction of the material in a source can create environmental contamination sufficient to cause acute effects in man. Theoretical values of the maximum specific activity of ^{60}Co, ^{137}Cs, ^{226}Ra and ^{241}Am are 42, 3.2, 0.04 and 0.13 MBq per μg, respectively. The specific activity of a real source is of course lower, but for example the ^{60}Co source which was lost in Mexico in 1983 had a specific activity of 0.4 MBq/μg at the time of the accident and the ^{137}Cs source which caused the Goiânia accident in 1987 had a specific activity of 0.5 MBq/μg [5].

There is as yet no internationally agreed level of protection of the environment which is considered necessary and sufficient, but a number of levels have been set in various countries for specific purposes. For example ground contamination levels have been set above which cattle should not be sent out for pasture, contamination levels below which buildings may be used without any radiological constraint, etc.

Although most accidents with spent sources have had no, or very little, effect on the environment, there are exceptions, the 1987 accident in Goiânia and the 1983 accident in Mexico. In addition to the tragic deaths of 4 people and acute effects to additional individuals, the accident in Goiânia caused extensive contamination over an area of about 1 km^2. Animals in the area became so contaminated that they had to be decontaminated or killed and some buildings had to be demolished.

In the accident in Mexico a ^{60}Co source containing 6000 small cobalt pellets (cylinders with diameter 1 mm and length 1 mm) caused environmental contamination in three ways. First a truck transporting the obsolete equipment containing the sources was heavily contaminated (the source capsule having already been deliberately cut open), secondly cobalt pellets were scattered along a road and in a junk yard, and thirdly, contaminated steel was produced from a melt containing the obsolete equipment and some of the pellets.

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Appendix V

EARLIER REVIEWS OF THE LOSS OF RADIUM SOURCES

As soon as radium sources came into use they were involved in accidents. Some large sources were broken or exploded during use. Radium was spread around in laboratories and onto people working in them. When the number of sources increased some were lost, mainly during medical use, but also during transport and storage, and some were stolen. It must be remembered that at that time, before the 1940s, there were no convenient instruments for detecting ionizing radiation. When searching for lost sources electroscopes had to be used, which made the task so difficult and tedious that it was tempting to cut it short. Lost sources were not considered a serious danger to health; the problem was loss of an economically valuable item.

There were many accidents and overexposures during the first decades of the use of sealed radiation sources. The deaths of more than 100 of the pioneers in the field were attributed to high exposure to ionizing radiation [1]. Almost no sources were deliberately thrown away because of age and obsolescence, since at that time radium was so expensive that it was always reused. It is therefore more interesting to look at the theft or accidental loss of sources during the early period.

The first comprehensive review of lost radium sources was made by Dr R.B. Taft and reflected the situation in the USA in 1937 [2]. He searched for national information on the subject, but since there were no national radium registers he had to use personal contacts as his main source of information. He identified 105 cases of lost sources. Four sources were stolen, 22 were lost in sewer systems, 41 in trash waste systems including incinerators, and in 38 cases the sources were lost in other places, mainly laboratories. In total more than 3.5 grams of radium were lost. Although 75% of the activity was found and retrieved, about 1 gram remained lost. Table A.V-I gives a summary of Dr Taft's finding. The high percentage of sources retrieved may be explained by the fact that the events brought to his attention were cases where great effort was made to locate the sources.

In 1963 the US Public Health Service began collecting information on radium accidents in the USA, including the loss and theft of sources. The Service also tried to collect information about old accidents. Up to 1968 it recorded 299 cases of sources lost or stolen since 1905 [3]. Of those lost 33% were recovered, a much lower figure than in the Taft report. Table A.V-II gives figures for the lost and recovered sources and Fig. A.V-1 gives the time distribution of the losses.

There are a few other accounts of early losses but none is as comprehensive as the above USA reports.

The true number of sources lost during the early period is of course much greater than is suggested by the figures given above. They represent the situation in only one country (although a major radium user) and they refer to a period when there was no nationally organised radiation protection service.

TABLE A.V-I. LOST AND FOUND RADIUM SOURCES IN THE USA BEFORE 1937

Means of disappearance	No. of sources	Quantity of radium [mg] 1/ Total lost	Found	Not found	Percent not retrieved
Theft	4	200	75	125	62
Sewage system	22	840	460	380	45
Trash waste system	41	2070	1830	240	12
Miscellaneous	38	445	280	165	37
Total	105	3555	2645	910	26

1/ In 25 cases no quantities are given. The figures in the Table are therefore underestimates.

TABLE A.V-II. SUMMARY OF DATA ON THE LOSS OF RADIUM SOURCES IN THE USA AS AT END 1968 1/

Means of disappearance	Number of sources	Number of radium sources: Completely recovered	Partly recovered	Not recovered
Theft	28	11 (39%)	4 (14%)	13 (47%)
Loss	271	175 (65%)	9 (3%)	87 (32%)
Total	299	186 (58%)	13 (4%)	100 (33%)

1/ Data from a US Public Health Service Report

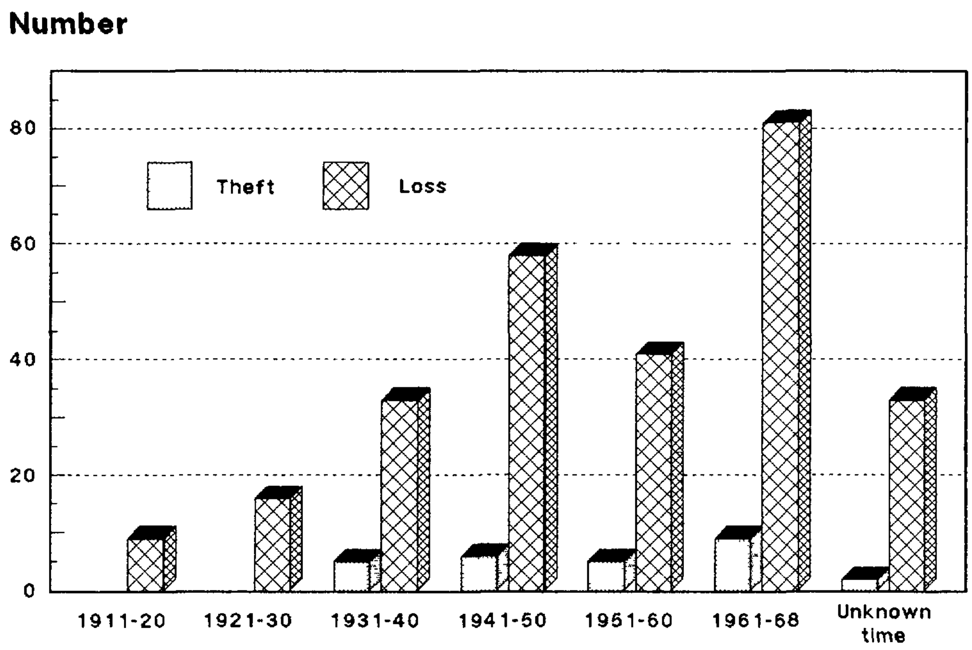

FIG. A.V-1. Radium sources reported lost in the USA up to 1968.

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Appendix VI

EXISTING PRACTICES FOR THE MANAGEMENT OF SPENT RADIATION SOURCES

A.VI.1 Identification

In the ideal case information about all sealed radiation sources produced in a country or imported into it would be entered into a national data base. The information should comprise type of source, identification number, radionuclide, activity, date, user, place of use, where stored, how disposed of, etc. All changes in status of the source should be noted, including transfer from one user to another and from in-use to in-storage. When it is decided not to use the source any more the data base can be interrogated for information to facilitate decision on measures to ensure safe management of the source. Such a data base also helps to identify sources which have been stored for a long time without being used and so should be reclassified as spent sources.

A data base which aims to improve radiation safety need not include sources of such low activity that they do not represent any radiation hazard. By excluding such sources the number of items in the data base is significantly reduced, making it easier to use and keep up to date.

This type of data base is needed not only in developed but even more in developing countries which are in the process of establishing a radiation protection and waste management infrastructure. WAMAP missions have helped to make these countries aware of this.

In countries where there are very many sealed sources the effort needed to establish and maintain such a data base has often been considered excessive. Countries with existing waste management infrastructures may also consider themselves capable of managing spent sources without use of a central data base. However, the increasing number of spent sources and general increase in the standards of safety all over the world will sooner or later make it necessary to take this additional step.

Among the most comprehensive, if not most sophisticated, national data bases for spent sources are some in the developing countries, notably in Latin America. There the number of sources is still quite small and the Competent Authority has rightly considered it essential to have this type of central information system in order to fulfil its responsibilities regarding spent radiation sources.

The spent sources which are hardest to identify are those which are outside the system of radiation control. They may have entered a country without any licence, not be individually identifiable, or old sources no one knows about. There is no easy way to find and identify such sources. It is not possible to search a whole country, region or even small town for unknown sources. They may be in unmarked containers with excellent shielding but which are recognizable only by someone with expert knowledge.

It is however possible to search successfully for spent sources in areas and buildings where there is good reason to suppose that sources may be found. Examples of such places are hospitals, process industries, and research institutes which have used sealed sources. In such cases there is information about what types of equipment have been used, making it easier to identify apparatus containing a source. Searches for sources have been made when closing down factories, hospitals or medical practices. It has been part of the "cleaning up" operation.

General information to the public, and advertisments in newspapers, have been used by national authorities to seek information about sealed radiation sources, but without much success. In one case this method was used to ask for information about lightning rods containing radium sources. Although the information required was limited to this one subject there was little response from the public. This may have been because there was no benefit to individuals giving such information. If a source is lost or stolen the information requested can be even more specific and a reward may be offered. The method is evidently not useful for a general search for spent sources.

Many sources have been found, and subsequently identified, by chance. Someone with basic knowledge in radiation protection has been curious or suspicious, and either asked questions or made his own investigations. Even journalists can initiate actions leading to the identification of spent sources. Unfortunately there are also examples of equipment containing sealed radiation sources, or naked sources, being found without anyone identifying the risks until it was too late.

A.VI.2 Collection and transport

The first step to secure a spent source, once it has been located and identified, is to have it collected and transported to an interim store to await further treatment. Alternatively, mobile conditioning equipment (see A.VI.4 below) can be taken to the source, and the conditioned source then taken to the interim store. The latter would normally be done only if the spent source is damaged to such an extent that it cannot be transported safely without conditioning.

If a country has an organization responsible for managing radioactive wastes this may provide collection and transport services for spent sources. In developed countries such organizations are often governmental or privately owned bodies which do the work on strictly economic terms. There may however be a national nuclear research organization or other national laboratory which will provide this service on a cost-free, or near cost-free, basis.

Most developing countries do not have any formally established organization with overall national responsibility for waste management. Some developed countries also lack that function or have delegated it to those who produce the waste.

Large firms producing or distributing sealed radiation sources also provide collection and transport services for spent sources. This service is worldwide, but usually applies only to sources which the firm has supplied. It is widely used, especially when old sources are replaced with new ones. When replacing a source the supplier accepts the old source back in the transport package used to deliver the new source.

Safe collection and transport require skilled and experienced personnel, as well as proper equipment, notably transport packages. The IAEA's Transport Regulations [1] give detailed requirements for transporting radioactive materials, and are used as a basis for international as well as national transport regulations. These give detailed requirements for documentation, administrative control, and packaging for each individual transport problem. Special transport packages, known as Type A or Type B packages, are often required for sealed radiation sources. These packages are tested according to specifications given in the transport regulations. For Type B packages a certificate issued by the national Competent Authority is also required as evidence that the design requirements have been met. Specifications on leak tightness for Type B packages ensure that no significant release of radioactive material can occur when a leaking source is transported. Special transport packages have been developed for leaking radium sources. Examples of packages which can be used to transport spent sources are shown in Fig. A.VI-1.

In countries which use many sealed radiation sources there are experienced people and proper equipment for collecting and transporting spent sources. This is not so in most developing countries. Some individuals may have received basic training on the Transport Regulations in courses arranged by the Agency, but they have little chance to gain practical experience. They may have no proper transport package for collecting a spent source. The Agency can help in such cases.

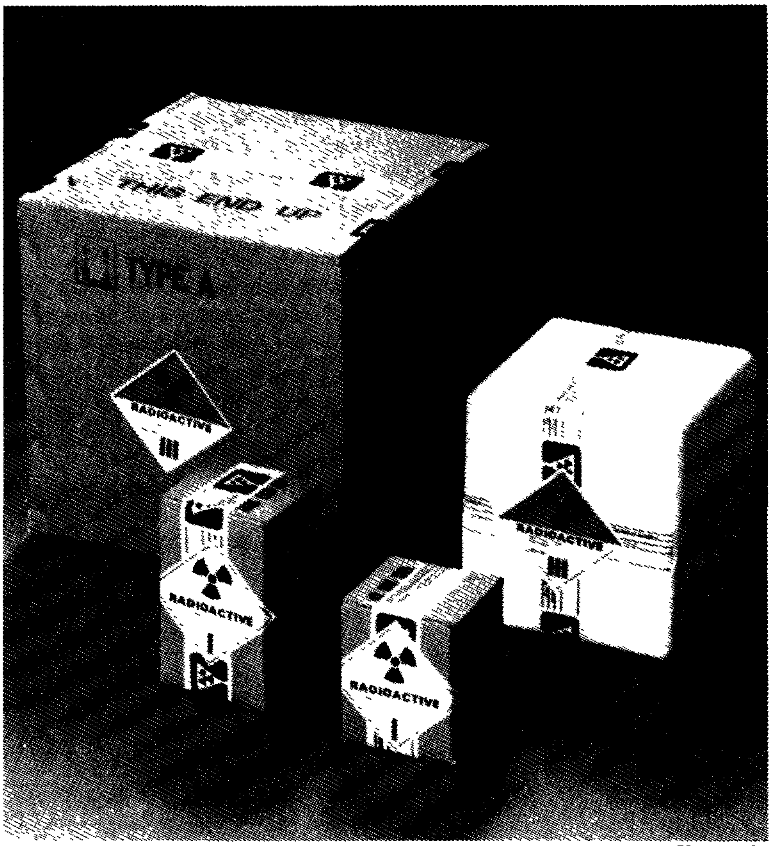
Some countries have systematically identified spent radium sources in their hospitals and then collected them in a central store. Sometimes there have been difficulties. Problems which have complicated or halted such programmes are:

- lack of legislation giving the Competent Authority the right to require sources to be sent to the central store
- lack of suitable transport packages
- lack of facilities for conditioning damaged sources
- lack of a proper storage or disposal facility
- shortage of funds
- shortage of manpower

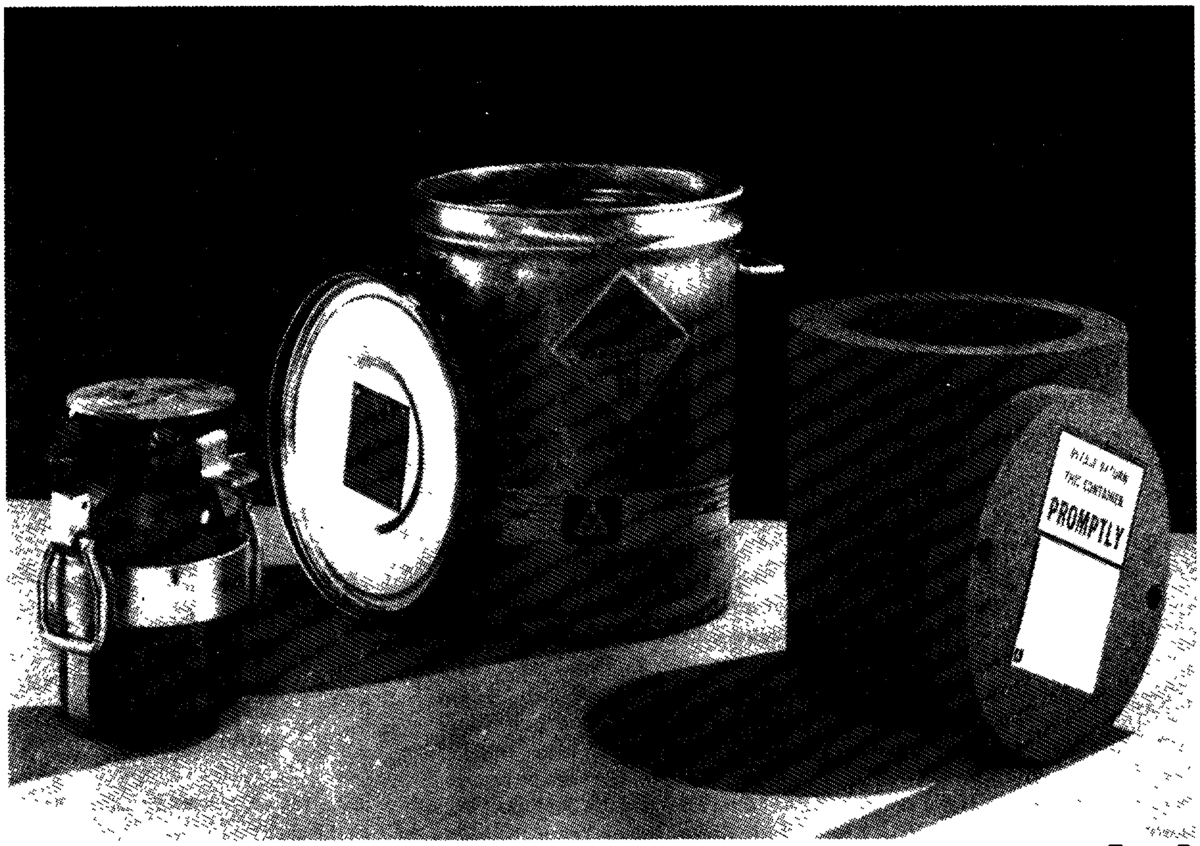
The Agency can assist with most of these problems.

A.VI.3 Return to supplier

The large firms which supply sealed radiation sources to the international market have all the technical and personnel resources necessary for their safe management, sometimes even including means for the disposal of spent sources. These firms regularly handle large numbers of sources in the course of their normal commercial activities and for that reason maintain sophisticated equipment for handling and transport. Their personnel are trained and experienced in handling radiation sources. The return of spent sources to a supplier is thus the best option for all countries not having sufficiently developed waste management infrastructures, at least when the sources are too long-lived to become safe by natural radioactive decay within a few years.



Type A



Type B

FIG. A.VI-1. Type A and Type B transport packages.

Most countries now make it a general principle not to accept radioactive wastes from other countries either for storage or for disposal. This principle was intended to prevent the entry of large quantities of radioactive waste from the nuclear fuel cycle, but in response to the activities of anti-nuclear pressure groups it is sometimes being applied to all radioactive materials, including even the relatively low levels of activity in spent radiation sources. In spite of this it has not been any problem for the source suppliers to take back sources which they previously delivered. Also, a few developed countries have assisted developing countries by accepting their spent sources for disposal. To meet international requirements for better control of transbounday movements of radioactive wastes, the IAEA has worked out a Code of Practice on the subject. The Code, which is applicable to transport of spent radiation sources, does not forbid transboundary movements, but stipulates certain requirements to be met.

For several years the Agency has strongly recommended that developing countries should include a clause in purchasing contracts stipulating the right to return a source to the supplier when it is spent. This recommendation is widely followed. The Agency also recommends that suppliers give technical assistance in case of an accident with the source. Suppliers will in general do this.

Since companies work on commercial terms one must expect that their assistance will be expensive for the user of a source. Especially if equipment is damaged, and the collection and transport of the source require special arrangements, the costs can be high and it is not normally possible to cover such situations when agreeing on a contract to purchase a source. As an example there is an apparatus containing a large spent gamma source known to be lying unprotected in a field in a developing country even though a method to collect and transport it exists and there is a company willing to take responsibility for the source. Lack of money is the problem, although, the amount required is not more than might be paid for a new source.

The option to return spent sources to the supplier is available in most developed countries. One country even requires that imported sources should be exported (returned to the supplier) within a certain time after import. This regulation is however so new that there is as yet no experience of its implementation.

Even if all new orders for sealed sources were to include a return clause there would still be many old sources in use for which the supplier is unknown, or has ceased to exist. Also a return clause cannot prevent a source being lost or stolen, nor does it give funding to cover transport costs. Thus it must be accepted that return to the supplier can only be a partial solution to the spent source problem.

A.VI.4 Conditioning

"Conditioning" means all those operations needed to transform radioactive waste into a form suitable for transport, storage and disposal. The operations may include conversion to another form, enclosure in a special container, or providing additional packaging.

Most accidents with spent sources happen because of their small dimensions, their resemblance to an ordinary piece of metal, or because they are included in some larger item which has been stolen or sent for scrap. Safety can therefore be gained by enclosing the source in a substantial package made up of inexpensive material of low scrap value. This should be done in such a way that the source cannot be retrieved without destroying the package. Finally, the package should be given an unambiguous marking. Conditioning should be done as soon as practicable after the source is recognised as being of no further use.

Some large sources used for sterilization or radiation processing, with activities of the order of 10 TBq or more, cannot readily be conditioned into a normal waste package due to their high activity. Those sources should always be returned to a source production facility where they can often be refurbished and reused.

The conditioning operation requires trained personnel with special equipment for handling the spent sources and doing the conditioning. In countries having nuclear power, and in many countries with research reactors, there is equipment of this type for managing the radioactive waste generated at the reactors. It can also be used for conditioning spent radiation sources. Methods used for managing reactor waste are described in many IAEA reports, see for example Refs. [2-4].

If the majority of radioactive waste in a country comes from the use of radionuclides in medicine, research and industry, the volume will be small, often only a few cubic metres per year. The country may not have sophisticated equipment for conditioning radioactive wastes, but spent sources can still be conditioned by simple but quite adequate methods [5].

One such method is as follows (Fig. A.VI-2). A number of 200 litre drums are prepared with concrete filling having a hole in the centre (a steel tube with a closed end is often used). Spent sources, with or without extra radiation shielding, are successively placed in the hole until it is full or until a limit of activity has been reached. Cement mortar is then poured over the sources. It may be necessary to prevent them floating up due to their density being lower than that of the mortar used.

It is good practice to have two or more drums in use simultaneously so that radionuclides with different half-lives may be segregated. Thus ^{60}Co and radium sources may be conditioned separately so that the ^{60}Co does not have to be disposed of according to the more strict rules applicable to radium.

The volumes of spent sources to be conditioned are always small, particularly in developing countries. It can therefore be appropriate to have only one place in the country where the sources are conditioned. This would preferably be a nuclear research centre but could be a major hospital or other location at which radionuclides are used.

If the spent source is part of a piece of equipment the whole assembly including the source is conditioned in a 200 litre drum (items such as electric cables having been removed). Some old industrial equipment containing sources to be conditioned is shown in Fig. A.VI-3. For larger items prefabricated concrete cubes (Fig. A.VI-4) or larger drums are used. In some cases the sources are taken out of their shielding before conditioning in order to reduce the volume of waste to be conditioned. Such operations require very experienced personnel with access to special equipment, including hot cells, and should be avoided if these requirements cannot be met.

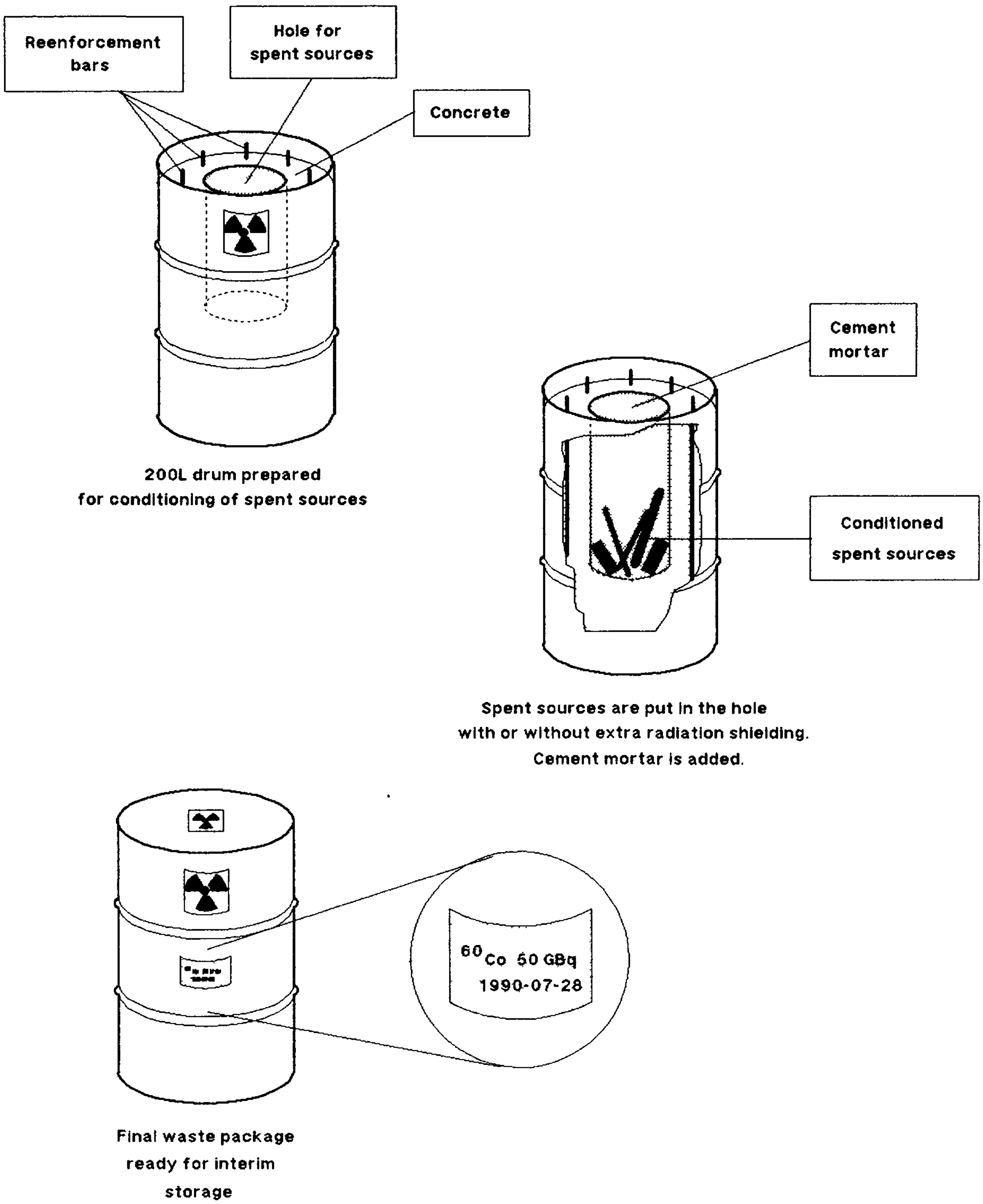


FIG. A.VI-2. Simple method for conditioning spent radiation sources in 200 litre drums.

FIG. A.VI-3. A collection of old shielded containers holding industrial sources.

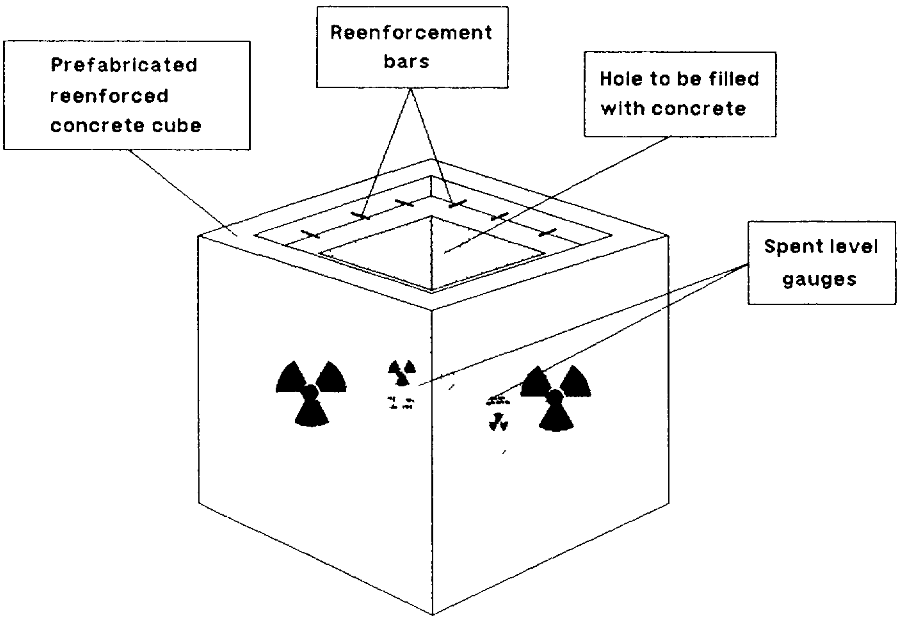
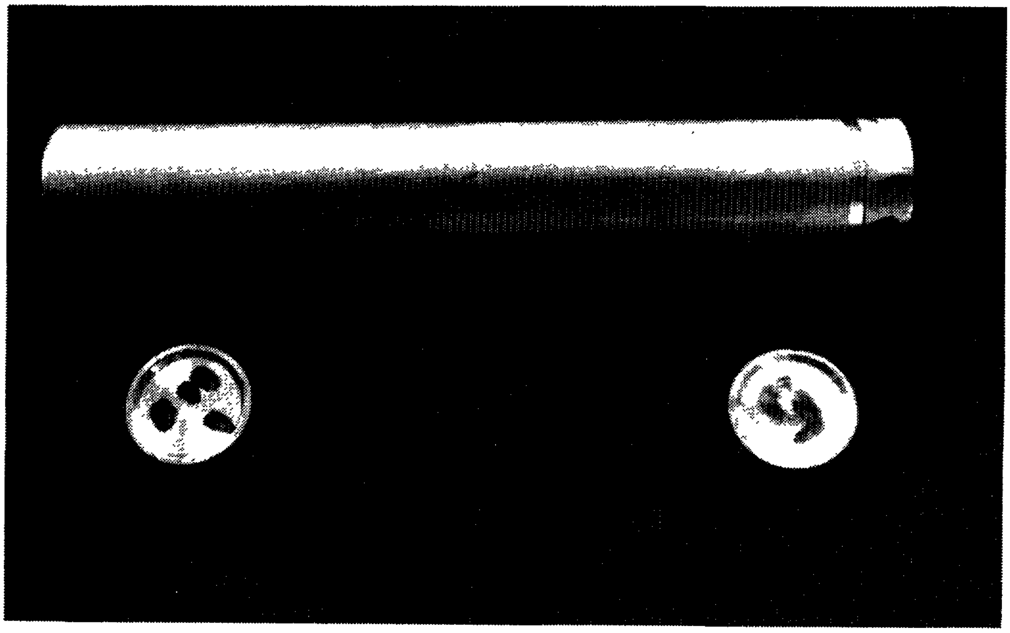
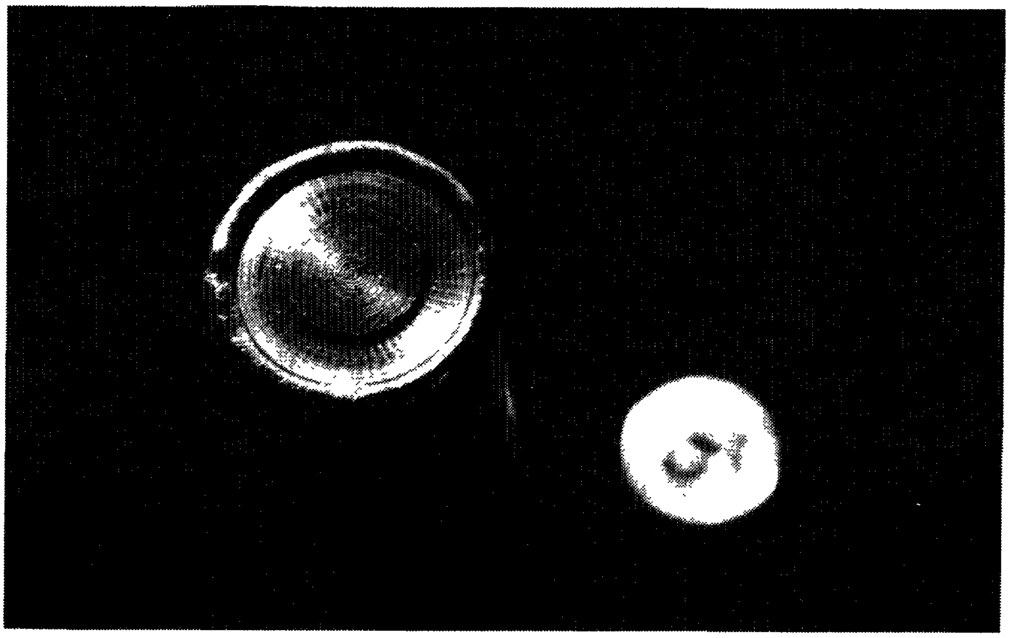


FIG. A.VI-4. Prefabricated concrete cube for conditioning obsolete equipment holding spent sources.

Spent radium sources pose a special problem because of their continuous generation of radon gas. Old radium sources may be leaking when they are presented for conditioning, and the long-term integrity of apparently sound sources cannot be assumed. To manage this problem two different approaches may be used. If the necessary equipment is available the sources may be enclosed in a stainless steel capsule and the lid welded on to ensure an air-tight seal (Fig. A.VI-5), the free volume inside the new capsule being large enough to avoid unacceptable pressure build-up. The sealed capsule is then embedded in concrete in a 200 litre drum.



a)



b)

FIG. A.VI-5. Stainless steel capsule used for conditioning radium sources: a) before welding; b) after welding.

The other approach is to surround the radium sources with activated charcoal which will adsorb any radon leaking out. In this case air-tight sealing is not critical, although this extra barrier is desirable. Ordinary tin cans have been used to hold the sources and activated charcoal and the lid is sealed on with araldite or by soldering. The cans are then conditioned in cement.

Experience of conditioning spent sources is very limited in the developing countries. According to information available to the Agency, not more than a handfull of these countries have extensive experience and two thirds have no experience at all.

A.VI.5 Interim storage

The aim of interim storage is to ensure that the spent radiation sources do not give unnecessary exposure when decaying to exemption levels or awaiting disposal. This is achieved by storing active waste in a place where isolation, monitoring, environmental protection and human control are provided.

Spent radiation sources may have to be stored in different forms, in unconditioned form while awaiting conditioning or decay to a safe level, or as conditioned waste packages. The two forms should be stored separately. Stores for radioactive waste should not be used for radioactive material which is still in use, or for non-radioactive waste. If waste, which can generate radioactive gases, is to be stored, the store must have a proper ventilation system. Ventilation may also be required to maintain good atmospheric conditions, to avoid degradation of the waste packages or of text written on labels.

At each site where radioactive sources are used there must be a specified location for the interim storage of unconditioned waste. If the quantities of waste are small a strong cupboard or safe should be adequate. Of course all users of radiation sources already have interim storage in the sense that there is a place where the sources are stored, but in the developing countries this place is often not really appropriate and in some cases not even acceptable. Old equipment containing radiation sources has been left lying out of doors without any protection against the weather, so that damage and corrosion make it more and more difficult to make the sources safe.

In many developed countries there is adequate storage of acceptable quality which can be used for the long-term interim storage of spent radiation sources. The situation in the developing countries is in general much worse. According to a summary based on the reports of WAMAP missions, only 4 countries had adequate interim storage while 12 had inadequate and deficient storage. For six countries no comments were made. Examples of the deficiences described are:

- Radioactive wastes are stored together with large quantities of non-radioactive wastes.

- Radioactive wastes are stored together with radioactive material still in use.

- The store is not safe. Unauthorized people can enter without realizing they are entering a radioactive waste storage area.

- The waste is not protected from deterioration by rain, wind and sun.

- The store is too small.

- The store is not ventilated, giving conditions which cause corrosion and destroy written documents.

- The store is not safe against flooding.

Spent sources containing radionuclides with long half-lives will eventually have to be disposed of in deep geological repositories. At present no such repository is in operation, so the sources must be kept in interim storage. In many developing countries it cannot be assumed that interim storage will be constructed which is good enough to guarantee safe storage for several decades. It will therefore be necessary to establish a number of regional interim storage facilities for long-lived spent radiation sources, or an international facility operated by an organization such as the IAEA, to ensure safe interim storage of long-lived spent sources. This is especially necessary for sources containing radium.

A.VI.6 Disposal

According to one definition [6] disposal is : "the emplacement of waste in a repository, or at a given location, without the intention of retrieval". It is thus the last step in the chain of actions necessary for the safe management of radioactive waste. Provided disposal is done properly in a suitable repository, the waste should from then on represent no further risk.

For spent radiation sources of moderate half-life there are two options: to dispose of them as radioactive waste in a licensed repository, or to hold them in licensed interim storage until they can be exempted.

Up to now only a few countries have established exemption criteria for spent sources, but many are in the process of doing so. The basis for this work is the recently published IAEA Safety Series No 89 [7]. However, many countries already practise some form of exemption. Lack of established levels has not resulted in a thoughtless exemption at too high levels; on the contrary, in most cases the levels currently in use may be raised as a result of the recent work. Exemption is not a significant problem for the safety of spent radiation sources.

Disposal of spent radiation sources other than as exempted waste includes the following options:

- Dilution of radium in mill tailings

- Sea disposal

- Shallow land repositories, with or without engineered barriers

- Deep geological repositories

Tailings from uranium mining and milling contain up to a milligram of radium per tonne. At each major uranium mine there are huge quantities of tailings, 100,000 tonnes or more. In one such pile there may be more than 100 grams of radium, which is comparable to the total quantity of radium sources in all the developing countries. Since radium was originally extracted from uranium ores it has been suggested that spent radium sources could be disposed of by opening them and adding the radium to the milling process. The additions should not significantly increase the radium concentration in the tailings.

Sea disposal has been used since the 1940s for low-level radioactive wastes. In the beginning it was done under national responsibility, but since 1972 has been under international control, following the conditions specified in the London Dumping Convention (LDC). After some international debate, and at the request of the LDC contracting parties, there has been a moratorium on dumping since 1983, pending international evaluation of the safety of sea disposal.

It may be doubted whether the method will ever be internationally acceptable again, even though it may be demonstrated to be safe. It has however, been argued that the oceans already contain about 10^{-13} grams of radium per litre of sea water. The volume of an ocean basin used by the LDC for deriving activity limits for sea disposal is 10^{17} m^3, and such a basin contains 10 tonnes of radium. The total inventory in all oceans is 140 tonnes. The addition of at most a few kilograms would be entirely negligible, rendering sea disposal an excellent option for spent radium sources, if it were not blocked by public opposition.

Before the moratorium was imposed some 5×10^{17} Bq of radioactive waste had been disposed of at sea in accordance with the LDC regulations. An unspecified number of spent sources was included, and unspecified quantities of radium.

Many shallow land repositories for radioactive wastes are in operation around the world, most of them in the developed countries, but only a few are sited, constructed, and operated so that they meet present IAEA safety recommendations [8-10]. These repositories are on or near the surface of the ground, some with and some without engineered barriers. Examples of different types of repository are shown in Fig. A.VI-6.

For each licensed site there are waste acceptance criteria defining what waste can be disposed of in the repository. These specify the requirements to be met by the waste packages, including activity levels. Usually the acceptable activity is given both as a concentration limit for the different radionuclides or groups of radionuclides in a waste package and total activity. No special limitations are given for sealed sources containing long-lived radionuclides. Due to the waste always being transported to the repository, the requirements in the transport regulations have also to be met. This can often give additional constraints.

In the case where there are specific limits for concentrations of long-lived alpha emitting radionuclides like in France and the USA, these give about 20 mg of radium in a 200 litre drum as the upper level for radium content. For ^{60}Co and ^{137}Cs the limitation is often set by the transport regulations. Although spent sealed sources have been and still are disposed of in some shallow land repositories, in conformity with their operating licences, there are now operators who advise their customers to send spent sources to interim storage rather than to disposal.

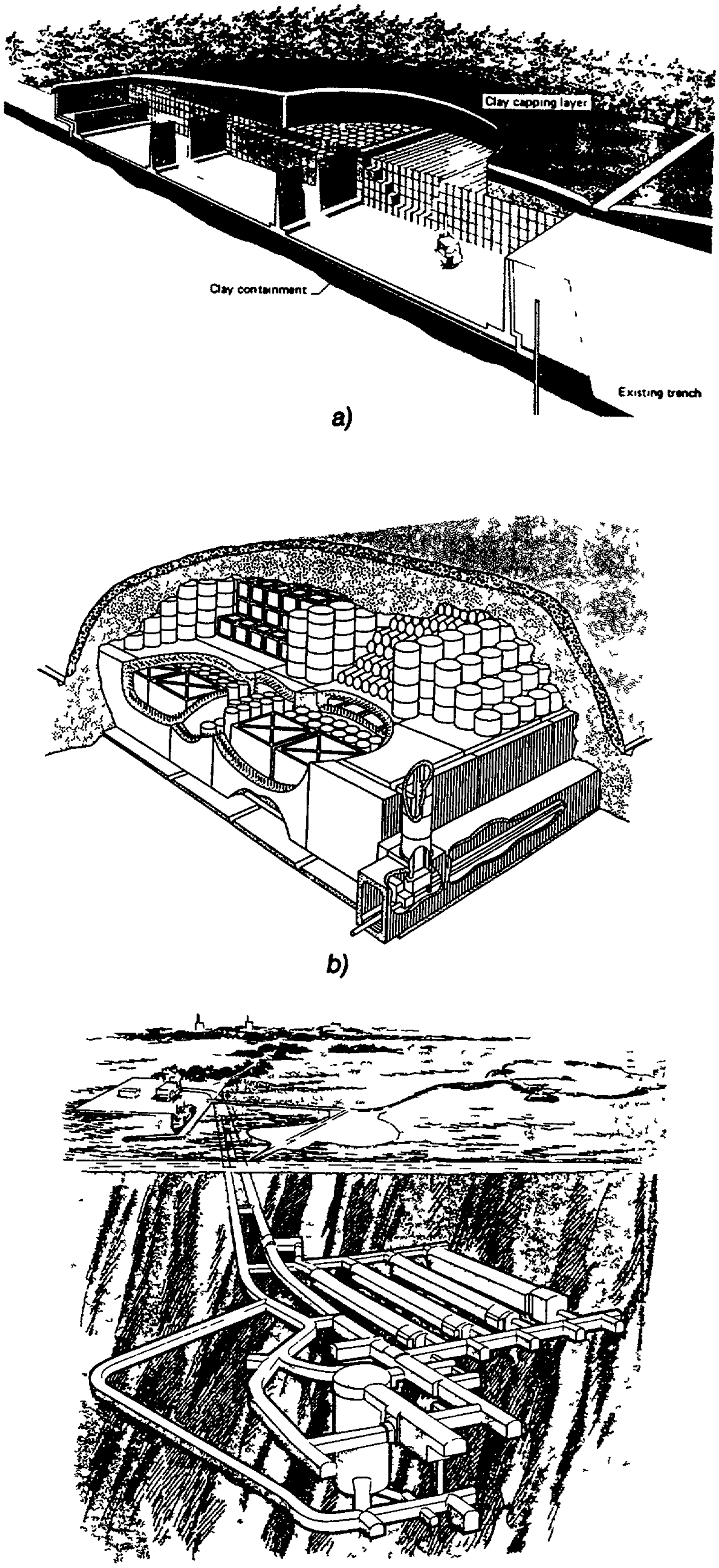


FIG. A.VI-6. Three different disposal options: a) trench (Drigg, UK); b) mould (Centre de la Manche, France); c) rock cavities (SFR-1, Sweden).

Spent sources have not always been disposed of in the best way. In one developing country 27 industrial sources were dumped in a shallow pit with no engineered barriers. The sources were still in their original equipment, mainly level gauges, without any conditioning. The inventory of sources in the pit is:

Co-60	1.5 GBq	(4 sources)
Cs-137	160 GBq	(21 sources)
Am-241(Be)	50 GBq	(2 sources)

Those activities, especially for the ^{241}Am(Be) sources, are much higher than is acceptable for a shallow land repository of this type. The Agency has strongly advised the country in question to retrieve at least the larger of the two ^{241}Am(Be) sources. Due to financial and other problems this has not yet been done.

In another place a number of spent radium sources has been embedded in concrete and buried under the floor of a laboratory building. No specific explanation is given for this choice of disposal site.

Provided a shallow land repository is properly sited, constructed and operated, it may safely be used for the disposal of most spent sources. The main exceptions are ^{226}Ra and ^{241}Am sources and the large sources used in teletherapy or irradiation facilities.

It would be possible to establish safe shallow land repositories, suitable for most spent sources, in most countries. However, many countries generate only small quantities of radioactive waste, up to a few cubic metres per year. The cost of disposal per unit of waste would be very high if they have to establish their own repositories. Thus combined efforts should be made, between several countries in a region, to set up a regional repository. In this way a better site may be selected, and also additional engineered barriers could be constructed and more efficient control measures put into effect.

There are sealed sources which cannot be disposed of in near-surface repositories for reasons of radiation safety, but there is no deep geological repository in operation anywhere in the world, nor will there be for at least the next 20 years. Spent sources requiring such repositories will thus have to be stored near the surface for at least that period of time.

The cost of construction of a deep geological repository will be extremely high, of the order of billions of US dollars. It will be out of the question to construct such repositories in all countries having a few long-lived spent radiation sources. The amounts of radioactive material in these sources are however negligible compared to the activities in the high-level wastes from nuclear power programmes, for which high-level waste repositories will have to be built. The addition of spent sources to the nuclear energy waste going into a high-level repository will not endanger it. There is a strong need for agreement, on a multinational or bilateral basis, that will eventually make this type of co-disposal possible.

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LIST OF ABBREVIATIONS

Afr	Africa
A&P	Asia and Pacific
IAEA or Agency	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LA	Latin America
LDC	London Dumping Convention
ME&E	Middle East and Europe
NDT	Nondestructive testing
RAPAT	Radiation Protection Advisory Team
REAC/TS	Radiation Emergency Assistance Centre/Training Site
SRS	Spent Radiation Source
WAMAP	Radioactive Waste Management Advisory Programme

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