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MANAGEMENT OF DISUSED SEALED RADIOACTIVE SOURCES

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6, of the IAEA's Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

Sealed radioactive sources have been used widely in industry, medicine and research in Member States for many decades. Although most Member States have laid down a regulatory framework to control sealed sources and have adequate technical abilities to handle them properly, there are still a number of uncertainties concerning the management of these sources during their life cycle. Management schemes and practices currently implemented in Member States may be somewhat conflicting and create problems for storage, particularly the disposal of disused sources. For instance, there is no consensus on the appropriate methods of conditioning of sources held in central interim storage. In most cases, the methods used are determined to a large extent by the available facilities, which may have been built to deal principally with other types of waste. The IAEA's experience in working with Member States has revealed that the modest infrastructure and limited budgets in many Member States require simple solutions that are low cost and straightforward, without compromising safety or security.

Recognizing the need to assist Member States in the safe and effective and management of disused sources, the IAEA developed an 'Action Plan on the Safety of Radiation Sources and Security of Radioactive Material', which focused on the development of a series of publications dealing with the handling, conditioning, storage and disposal of such sources. Titles in this series, for example entitled 'Technical Manuals for the Management of Low and Intermediate Level Wastes Generated at Small Nuclear Research Centres and by Radioisotope Users in Medicine, Research and Industry', have been published since the 1990s with the objective of addressing the needs of developing Member States by suggesting technological solutions that can fulfil requirements, implement solutions and meet criteria set in IAEA publications, and can also be easily integrated into an overall national programme.

Although Member States have benefited from these publications issued over the last two decades, it was felt they needed to be revised and upgraded to take advantage of new developments and to ensure compliance with modern standards. Since previously published reports addressed specific areas of the management of disused sealed sources for different categories of sources, this publication could provide a good opportunity to merge the contents into one single report.

Until recently, the emphasis was primarily on the safety of radioactive sources, with source security as one aspect of safety. However, given the potential for the use of radioactive sources in malevolent acts, source security has taken on a new urgency. The new approach of cradle to grave control of radioactive sources can provide protection against malevolent uses. This means consideration of security during the entire life cycle of radioactive sources, covering all phases, including manufacture, distribution, installation, commission, use, storage and disposal, is of paramount importance.

The present report summarizes the information contained in the earlier IAEA publications and provides up to date guidance on the management of disused sealed radioactive sources. Problems encountered and lessons learned are included in this report to help avoid the mistakes made in the past in managing disused sources.

The IAEA officers responsible for this publication were J. Balla and J.C. Benitez-Navarro of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

Sealed radioactive sources (SRSs) are used extensively in agriculture, industry, medicine and various research areas in both developed and developing Member States. Virtually, all countries utilize radioactive SRSs for one purpose or another. The total inventory of SRSs worldwide is estimated to be in the millions. Despite their predominantly small physical size, many sources contain very high concentrations of radionuclides (industrial and medical sources are typically in the GBq to PBq range). The radiation emitted from these sources is quite intense, requiring heavily shielded containers for their safe use, transportation and storage.

A radioactive source that is no longer in use or not intended to be used, for the practice for which an authorization has been granted, is termed as *disused* [1]. If a source is no longer suitable for its intended purpose as a result of radioactive decay, it is considered as *spent*. It is important to emphasize that a source declared by one user as disused may still be used by a different user, supplier or manufacturer. A disused or spent SRS may still be highly radioactive and potentially hazardous to human health and the environment. The nature and magnitude of the various problems associated with disused SRSs are addressed in Ref. [2].

Although the vast majority of radioactive sources used around the world are managed safely and securely, bringing many benefits to humankind, a number of accidents involving radioactive sources have occurred [3–10]. Where the amount of radioactive material is substantial, as in the case of radiotherapy sources or industrial radiography sources, the accidents have resulted in severe or even fatal consequences [3, 5]. The majority of accidents were related to SRSs in use, which were still under regulatory control, but several accidents have occurred with disused sources when regulatory control was weak or totally absent. Some of these accidents have resulted in contamination of large areas that required costly clean-up operations for mitigation of the consequences of such accidents [3].

In order to reduce the risks associated with disused sealed radioactive sources (DSRSs), it is important to have a well-developed national strategy, legal framework and infrastructure for their safe management both at the user's site and in the entire country. It is essential that sources that either are in use, or declared disused, do not pose any potential hazard to the workers, the general public or the environment. Ideally, all requirements for the safe management of DSRSs need to be enforced and implemented, prior to initiating any particular application of SRSs in a Member State.

Countries lacking comprehensive infrastructure for radiation protection and waste management systems may not be cognizant of the risks associated with disused radioactive sources. Even some developed countries that use SRSs extensively may underestimate the risks involved and, thus, may not have fully effective control of their radioactive sources, even though they have adequate legislation, radiation protection and a waste management system in place [9]. Other countries do not give high enough priority to DSRS management programmes because there are more urgent issues demanding their available resources. Even if the risks associated with using SRSs are recognized, there are still significant potential risks associated with disused SRSs.

The number of disused radioactive sources in a given Member State does not influence the consequences of an individual accident, but increases the likelihood that an accident will occur. The degree of regulatory control and its effectiveness also influence the probability of an accident. The consequences of such accidents are governed by the characteristics of the source (source design, activity, chemical form etc.), nature of the accident, people involved, countermeasures taken, etc.

In the 1990s, there was growing international concern about radioactive sources, which for one reason or another, were not subject to regulatory control or over which regulatory control had been inadequate. The IAEA programme on DSRS was established in 1991 with the specific purpose to assist Member States in their effort to avoid situations that might result in unnecessary radiation exposure or accidents. The programme includes provision of technical assistance to Member States in the form of IAEA's technical reports, training of experts and development or improvement of the required infrastructure by provision of tools, equipment and transfer of technology through the IAEA's appraisal service for evaluating a Member State's radiation safety regulatory framework.

In 2011, the IAEA published the General Safety Requirements publication, IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, Interim Edition (hereafter BSS) [11]. This publication supersedes the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, which was issued in 1996 [12]. A binding international legal instrument for radioactive waste management has been established through the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (hereafter the Joint Convention) [13]. Under Article 28 of the Joint Convention, Contracting Parties are required to ensure that the possession, remanufacturing or disposal of disused sealed sources takes place in a safe manner, and Contracting Parties allow for re-entry into its territory of DSRS (if accepted in the framework of its national law). The IAEA has also published the Code of Conduct on the Safety and Security of Radiation Sources (thereafter Code of Conduct) [14]. The objectives of the Code of Conduct are, through the development, harmonization and implementation of national policies, laws and regulations, and through the fostering of international cooperation, to:

- Achieve and maintain a high level of safety and security of radioactive sources;
- Prevent unauthorized access or damage to, and loss, theft or unauthorized transfer of, radioactive sources, so as to reduce the likelihood of accidental harmful exposure to such sources or the malicious use of such sources to cause harm to individuals, society or the environment;
- Mitigate or minimize the radiological consequences of any accident or malicious act involving a radioactive source.

The IAEA continues to explore ways to improve its radioactive waste management programme to support various Member States. One new initiative is specifically related to the end of life management of DSRSs; including when disused sources are managed as radioactive waste. Until recently, the emphasis was primarily on the safety of radioactive sources, with source security as one aspect of safety. However, given the potential for the use of radioactive sources in malevolent acts, source security has taken on a new urgency. The new approach of cradle-to-grave control of radioactive sources can provide protection against malevolent uses. This includes consideration of security during the entire life cycle of radioactive sources, covering all phases, including manufacture, distribution, installation, commission, usage, storage and disposal, is of paramount importance.

1.2. OBJECTIVE

The main objective of this report is to provide reference material and technical guidance on the safe management of DSRSs, covering all aspects, including handling, conditioning, transportation, storage and disposal. It is anticipated that this report will be useful and of direct relevance to various stakeholders, including policy makers, users of SRSs, operators of waste management facilities and regulatory bodies, particularly in Member States that are exploring options or developing strategies for the safe management of DSRSs. It is intended to respond to the needs of various Member States in the management of disused sources, ranging from countries that have a relatively well developed radioactive source management infrastructure and regulatory framework to countries that are in a very early stage of conceptual planning for the management of disused radioactive sources.

1.3. SCOPE

This report presents information on the management of DSRSs, based on the information compiled in a series of earlier IAEA technical publications issued between 1990 and 2003 [2, 15–19]. However, the information in those publications has been reviewed and has been improved with the inclusion of new management techniques acquired in recent years.

The scope of this report covers all types of DSRSs, except those exempted from regulatory control, e.g. watches or instrumentation dials. However, the report does include smoke detectors and other low activity sources, which have been exempted from regulatory control as individual sources but after collection can represent a significant risk and thus require safe management. It discusses, in some detail, various approaches, options and procedures for the handling, conditioning, transportation, storage and disposal of DSRSs, and the associated management system requirements. Some problems encountered and lessons learned are included for every waste management step.

1.4. STRUCTURE

This report comprises 14 sections and one annex. Sections 2–6 deal with the general issues of DSRS management, while Sections 7–12 review the main steps of DSRS management in consecutive order. The consecutive order refers to an ideal DSRS management scenario, when all the institutions, facilities and personnel are in place. Of course, this situation rarely exists in most of the Member States; however, this approach provides the benefit of showing the ideal DSRS management scenario. At the end of each section dealing with a separate DSRS management step, some examples are provided together with appropriate lessons learned.

Section 2 outlines the key radiological, physical and chemical characteristics of sealed radioactive sources, which are important in the selection of appropriate management options for the sources.

Section 3 provides general information on the current international approaches to categorization and classification of SRSs.

Section 4 describes the devices together with associated sources that are used in various applications, keeping in mind that a good understanding of the specific application of the source and used equipment are an important consideration in developing a strategy for the management of disused sources.

Section 5 presents the basic elements of a national system for the safe management of disused radioactive sources, including legal, regulatory and licensing aspects, technical capabilities, and financing mechanisms and describes the elements of a modern management system applied in all activities. This section also describes the main reasons and rationale for declaring an SRS ‘disused’ or ‘spent’.

Section 6 discusses an approach for selecting a strategy for the management of disused radioactive sources and describes various key management options.

Section 7 deals with the characterization of sealed radioactive sources by various non-destructive and destructive methods and emphasize the role of characterization in the selection of a safe and secure management option.

Section 8 addresses the handling procedures, equipment and tools used at different stages of DSRS management.

Section 9 addresses the storage of unconditioned disused sources at user’s premises as well as the storage of conditioned DSRS at central stores, with particular emphasis on the design features of a waste package accepted for storage and design requirements for a storage facility, emphasizing the importance of safety assessment for such facilities. It also provides a summary of the approaches used, including a description of specific processes, for the storage of high activity sources.

Section 10 deals with conditioning of different types of disused sources. It begins with the conditioning requirements, including design, operation and records keeping. It also discusses recommendations for the selection of an appropriate conditioning methodology, including a description of various conditioning methods.

Section 11 examines the transportation of disused radioactive sources, introducing the IAEA transport regulations, and addresses transportation problems that are unique to high activity radioactive sources. Some transportation options are also discussed.

Section 12 deals with the disposal options for disused radioactive sources, including a discussion of the specific characteristics of radioactive sources that present a problem for their disposal. It also presents a review of problems encountered and lessons learned, and discusses the borehole disposal concept as a potentially promising option.

Section 13 describes the role of safety assessments throughout the lifetime of the facility or activity whenever the designers, constructors, manufacturers, operating organization or regulatory body should make decisions on the management options and related safety issues. It also represents briefly the process for the development of safety assessments.

Section 14 summarizes the achievements in the management of disused radioactive sources, emphasizing some activities that are important in addressing the problematic issues.

The Annex addresses the radiological risks associated with disused sources, in particular where control was inadequate or completely lost. Some accidents with disused sources are briefly discussed.

2. CHARACTERISTICS OF SEALED RADIOACTIVE SOURCES

A radiation source is any source capable of emitting ionizing radiation. The sources considered in this publication are SRSs, which contain radioactive material as their primary source of ionizing radiation (other sources can be X ray, nuclear reactors or particle accelerators). According to the IAEA Safety Glossary [1], a sealed source is “radioactive material that is permanently sealed in a capsule, or closely bonded, and in a solid form”. The capsule or material of a sealed source is durable and strong enough to maintain leaktightness under the conditions of use and wear for which the source is designed, as well as also under foreseeable mishaps [10]. In many cases, double encapsulation is used.

Radioactive sources are used in a wide range of practices in industry, medicine, agriculture, research and education, as well as in military and defense applications. The sources, used in these applications, contain a variety of radionuclides, forms and quantities of radioactive material and exhibit a wide range of physical, chemical and radiological properties.

When a sealed source becomes disused, a suitable management option for it needs to be selected. For the selection of a management option it is important to get all necessary information on the parameters of the source. The following sections describe in brief the parameters and features of sealed sources that are most important for selecting and implementing an appropriate management option.

The most important parameters are as follows:

- Physical form: Mostly solid; liquid or gaseous (in very few cases).
- Radiological characteristics: Radionuclide, type of radiation (α, β, γ, neutron), activity, half-life, energy and dose conversion factors.
- Neutron emission (for neutron sources).
- Chemical characteristics: Compounds or alloys used, solubility, etc.
- Structure and design (including the dimensions of the active filling and the capsule).
- Physical condition: Intact, damaged or leaking.
- Further characteristics related to the particular mode of application of a source (corrosion resistance, thermal properties, stability, etc.).

The radionuclide half-life of a source, as well as its activity, is particularly important for selecting a disposal option for disused sources.

2.1. RADIOLOGICAL, PHYSICAL AND CHEMICAL CHARACTERISTICS

2.1.1. Physical forms

The radioactive material in SRSs can be grouped as follows, based on its physical properties:

- Solid: Mostly metallic, ceramic, sometimes compressed powder and seldom soluble salts.
- Gas: Mainly ^{85}Kr and ^{3}H.
- Liquid: Not common.

Powder or soluble materials may give rise to radioactive contamination if the encapsulation leaks.

2.1.2. Radiation type

In general, radionuclides can emit different types of radiation simultaneously. Particle emission, as α and β radiation, is usually accompanied by γ emission. Even in the case of pure β emitters, Bremsstrahlung[1] needs to be taken into account.

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[1] **Bremsstrahlung:** Radiation emitted by the slowing down of light charged particles, such as the X rays produced when electrons from an accelerator are stopped in a metal target.

For radionuclides whose decay products are also radioactive, one must also consider the same characteristics of the decay product. For this report, the chemical form and structure of the bulk that incorporates the radionuclide (e.g. caesium chloride in granular salt form) is also important.

2.1.3. Physical and chemical characteristics of radionuclides

The principal characteristics of some selected radionuclides in sealed sources are detailed below.

Radium

Radium-226 is part of the radioactive decay series of ^{238}U; it has a very long half-life (1600 years) and is a strong alpha emitter with a low level of gamma energy. Radium-226 decays by alpha emission to ^{222}Rn, a noble gas with a half-life of 3.6 days. Before the radioactive decay chain ends in the stable isotope ^{206}Pb, eight decay products, of which four are alpha emitters, are generated. Each decaying ^{226}Ra atom thus gives rise to five alpha particles. During decay, many high as well as low energy gamma photons and beta particles are also emitted. In a radium source, the daughter products are always present, besides the parent ^{226}Ra. Therefore, it has a rather high gamma constant [11].

Old medical sources of radium represent the problem in their management as they often leak due to internal over-pressure created by the ^{226}Ra decay which forms radon and helium gas. The small sizes of the sources prevent marking and this gives SRSs the deceptively harmless appearance of a small, smooth piece of metal. The high apparent value of these small sources, often in a platinum capsule, increases the risk of theft.

Radium is an alkaline earth metal. It is very reactive and even reacts with nitrogen. In radioactive 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. In the body, radium behaves like calcium, which means it concentrates in bones. For all these reasons, the radium is no longer regarded as an ideal radionuclide for use in sealed sources.

Cobalt

Cobalt is a metal element with only one stable isotope: ^{59}Co. When natural cobalt slugs are placed in a nuclear reactor, the nuclei absorb thermal neutrons to make ^{60}Co, a radionuclide with a 5.27 year half-life. Cobalt-60 undergoes beta decay (emits an electron and a neutrino) and emits two gamma rays with each decay: one at 1.173 MeV and one at 1.333 MeV, and finally decays to the stable isotope ^{60}Ni. Cobalt-60 sources are produced as high specific activity sources for teletherapy and industrial radiography and industrial sources for irradiators and other applications. High specific activity sources are small pellets (typically cylinders 1 mm in diameter and height) of metal produced in specialized high flux nuclear reactors.

In SRSs, metallic cobalt is commonly used because it results in the highest specific activity for the source. Usually, ^{60}Co is in the form of thin discs or small cylindrical pellets or slugs welded into stainless steel capsules. Metallic cobalt is not soluble in water and 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 radioactive sources is nickel plated before activation [20].

Caesium

Caesium-137 is produced by fissioning uranium nuclei and then chemically separating the cesium from the irradiated nuclear fuel or targets. Most facilities that chemically process (reprocess) spent nuclear fuel to recover uranium and plutonium leave caesium in the waste stream. The caesium actually is made up of four isotopes: ^{133}Cs (stable), ^{134}Cs (half-life: 2 years), ^{135}Cs (half-life: 2.3 million years), and ^{137}Cs (half-life: 30 years). Caesium-137 is commonly regarded as a gamma emitter of medium energy, although the 662 keV energy gamma photons are produced by $^{137}Ba^{m}$ formed from ^{137}Cs by beta decay.

Caesium is a highly reactive alkali metal element, similar to potassium and sodium. Due to its high reactivity it can only be used as a chemical compound in a SRS. Usually, ^{137}Cs is supplied as caesium chloride, a crystalline salt (it is chemically and structurally related to table salt, sodium chloride) that can be made in a range of particle sizes, from centimetre scale blocks to powder, as is used in the manufacture of radioactive caesium chloride sources. After cold-pressing to form a pellet inside a stainless steel, thimble shaped receptacle, the receptacle is loaded in a protective stainless steel capsule that is welded to form the inner containment, and a second stainless steel jacket is welded over the first to form the actual sealed radioactive caesium chloride source. The production of radioactive caesium chloride sources is carried out at around 200°C because caesium chloride is hygroscopic.

Caesium chloride is soluble in water at room temperature and so, if it is intentionally or accidentally removed from its container, it can readily be dispersed. If a leak in the stainless steel container were to occur, it could dissolve in water and contaminate the nearby environment. It is highly reactive in the environment; binding to surfaces and even migrating into concrete. If it enters the body, it disperses wherever water goes and delivers a whole-body dose.

One approach to reducing the problems posed by the very high solubility of caesium chloride in water is to use another compound containing ^{137}Cs as a direct replacement for the caesium chloride powder. A suitable process includes evaporation and enameling in sintered alumina cups, in sintered 'pollucite' pellets (caesium silica-aluminate $Cs_20\ Al_20_3\ 4SiO_2$) or in ceramic pellets and rods. These forms render the radionuclide virtually insoluble in water, but in this case a drastic reduction of the specific activity results.

An alternative approach to reducing solubility and dispersibility is to make cement incorporating the ^{137}Cs by the addition of cement paste and fillers. This approach has the advantage of low temperature processing and, with judicious choice of the cement phase, low aqueous solubility. However, the dilution associated with making cement limits the attainable specific activity. Also, the product remains a brittle solid that could degrade due to radiation effects, so it does not lower the cesium's potential dispersibility in an explosion. The cementitious approach has advantages for large-scale immobilization of waste containing ^{137}Cs.

Strontium

Strontium is a reactive metal typically found as a chloride, nitrate, oxide or titanate in sources. It has four stable isotopes, Strontium-84, -86, -87, and -88, the last of which is the most naturally abundant (82.6%). The radionuclide ^{90}Sr is a fission product produced in 5.8% of thermal fissions in ^{235}U and 2% of thermal fissions in ^{239}Pu. Strontium-90 decays by beta decay (0.546 MeV) with a half-life of 28.78 years to ^{90}Y, which itself decays by fairly high energy (2.28 MeV) beta decay with a 2.67 day half-life.

Typically, ^{90}Sr is used as a titanate in ceramic form. For some medical applications, the strontium compound is contained in a silver plate and screened with 0.1 mm palladium coated silver. For other applications the strontium compound may be incorporated in a ceramic, glass bead or rolled silver foil.

Strontium-90 is generated in nuclear power or isotope production reactors. Strontium-90 does not emit penetrating gamma rays, so when it is a contaminant it is only a concern for external exposure if it is deposited on the skin. The major concerns are internal exposures because of the high energy beta emissions and because strontium is in the same chemical group as calcium, so the human body concentrates ingested strontium in the bones where it resides essentially permanently rather than being eliminated through common bodily functions. High activity ^{90}Sr sources, however, produce significant bremsstrahlung radiation from stopping of the high energy electrons emitted by nuclear decay. This bremsstrahlung radiation can even cause deterministic health effects if a very high activity source is involved (such an incident occurred with a radioisotope thermoelectric generator (RTG) in Georgia in 2002).

Iridium

Iridium, one of the two densest metals (22.42 g/cm^3, same as osmium), is very hard and brittle, and is difficult to machine. It is also very resistant to chemical reaction and has a high melting point (over 2400°C) [20]. Natural iridium, which is found alloyed with platinum and in nickel ores, is 37% ^{191}Ir and 63% ^{193}Ir. Iridium-192 radiation sources are used in gamma radiography (e.g. non-destructive inspection of pipes) and in brachytherapy.

Iridium-192 radiation sources are made by irradiating natural iridium in a nuclear reactor. The iridium-191 can capture a neutron to create ^{192}Ir which has a 73.83 day half-life and has a 95% probability of decaying by beta decay to ^{192}Pt and emitting gamma rays and a 5% probability of decaying by electron capture to form ^{192}Os. In the decay to ^{192}Pt, on average 2.33 gamma rays are emitted with energies ranging from 135 keV to 1.378 MeV, with an average energy of 380 keV.

Iridium sources are usually in the form of wires or stacks of thin foil discs rather than bulk material pellets, slugs, or powders. Used ^{192}Ir sources typically can be shipped back to their manufacturer and distributor or stored for decay because of their relatively short half-life. So, although disposal of ^{192}Ir is not a problem, the short half-life forces users to replace the sources frequently, meaning that many sources are in transport and storage at any given time.

Americium

Americium is an actinide or transuranium element with no stable isotopes. Like the other actinides, americium oxidizes fairly readily. Americium is produced by successive neutron captures in ^{238}U, its activation products and decay products, to produce ^{241}Pu, which decays to ^{241}Am with a 14.4 year half-life. Americium is recovered from ageing plutonium stocks in which it builds up through radioactive decay. Americium-241 decays with a half-life of 432.7 years by emitting an alpha particle. The alpha particle has an average energy of 5.465 MeV and is accompanied by a 13.9 keV X ray in 43% of decays and a 59.5 keV X ray in 36% of decays, and no X rays in the other decays. The decay product, ^{237}Np, is also radioactive, with a 2 million year half-life. Americium-241 is used both as an alpha source and with beryllium as a neutron source (called an americium–beryllium or Am–Be source). In an Am–Be source, some of the alpha particles from decay of the americium are absorbed in the beryllium, which then emits a neutron with energy ranging from 0 to about 11 MeV, with the average energy at about 6 MeV. Am–Be produces about 1 neutron for 20 000 alpha decays.

The 'recommended working life' of an Am–Be source is 15 years, after which the source manufacturers recommend that the sources be recertified (if it is in good condition), re-encapsulated (if the capsule is slightly damaged, but the design is still in use), or recycled (if the design is no longer in use or the damage to the capsule is severe, then the raw Am–Be can be removed and manufactured into a new source).

Americium has chemical characteristics similar to the rare earth metals. Normally, ^{241}Am is used in oxide form in sealed 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 readily soluble in water. When used as a low energy, gamma source, the stainless steel capsule contains a thin window to allow the gamma photons to be emitted without undue attenuation [20].

For smoke detectors and lightning protectors, it can be presented sealed in a single envelope (metal foil) or be deposited on a ceramic support and vitrified.

Californium

Californium is an actinide element with no stable isotopes. It is produced by successive neutron captures in actinide targets. Californium-252 has a 2.645 year half-life and decays by spontaneous fission 3.1% of the time and by alpha decay in the other 96.9%. The fissions release neutrons, and thus ^{252}Cf is a very intense neutron source (2.3×10^{12} neutrons per second per gram). Because a ^{238}U nucleus must absorb 14 neutrons without undergoing other reactions that reduce the number of nucleons to yield a ^{252}Cf nucleus, californium is produced in very small quantities.

Selenium

Selenium is a volatile, reactive, and corrosive element chemically resembling sulfur and forming extremely toxic compounds. It has moderate density (4.3 g/cm^3 to 4.8 g/cm^3) and melts at 217°C. Selenium has several natural isotopes: ^{74}Se (0.89%), ^{76}Se (9.36%), ^{77}Se (7.63%), ^{78}Se (23.78%), ^{80}Se (49.61%), and ^{82}Se (8.73%). Selenium-75 decays by electron capture with a half-life of 119.8 days to stable ^{75}As, emitting an average of 1.75 gamma rays with an average energy of 215 keV each, and a peak energy of 800 keV. It is used in radiography cameras for thin walled structures. Selenium-75 is obtained by the irradiation of the natural isotope ^{74}Se in a nuclear reactor. Easily oxidizable, selenium dioxide is highly soluble in water. Selenium's chemical toxicity is very high. It has a medium radiotoxicity level.

The ^{75}Se radioactive powder is pressed into pellet form and is placed in a welded titanium (or titanium alloy) inner capsule. The titanium capsule is placed in a welded stainless steel outer capsule.

Iodine

Iodine-125 is normally produced as the result of alpha irradiation of antimony according to the reaction ^{123}S (α, 2n)125I. It has a short half-life of 60 days. It decays by electron capture resulting in the emission of low energy X rays of 27 and 35 keV.

Iodine sources used for brachytherapy would typically consist of ^{125}I absorbed onto a silver rod or an ion exchange resin bead, welded into a thin titanium capsule. When used for industrial purposes, the sources would typically take form of an active resin bead enclosed in a stainless steel capsule with a thin titanium window.

Because the source is constructed of active material absorbed onto a substrate, should the encapsulation become damaged some of the radioiodine may become volatilized.

Plutonium

Plutonium is an actinide or transuranium element with no stable isotopes. It is a silvery white reactive metal that turns a dull, darker hue when it oxidizes, which it does readily. It has low solubility in pure water, but saltwater and halide acids attack it vigorously. Plutonium-238 is produced by neutron absorption in ^{237}Np, which itself is produced by irradiation of uranium in a reactor followed by chemical separations. Plutonium-238 has a half-life of 87.7 years, decaying by alpha decay with an average energy of 5.486 MeV. The decay product, ^{234}U, is a naturally occurring radionuclide. The heat generated by decay in relatively pure ^{238}Pu is such that a solid sphere of the material the size of a golf ball will glow red from thermal radiation if it is not actively cooled.

Table 1 [19] summarizes the main radiological characteristics of the selected radionuclides emitting alpha/beta/gamma radiation.

TABLE 1. CHARACTERISTICS OF SELECTED ALPHA/BETA/GAMMA EMITTING RADIONUCLIDES OFTEN USED IN SRSs [19]

Characteristics	^{60}Co	^{137}Cs	^{192}Ir	^{226}Ra	^{241}Am	^{90}Sr (^{90}Y)	^{75}Se	^{125}I
Half-life	5.27 a	30 a	74 d	1600 a	433 a	29 a	120 d	60 d
Alpha energy (MeV)	—	—	—	7.7	5.86	—	—	—
Max beta energy (MeV)	0.31	1.2	0.67	2.8	—	0.55 (2.3)	—	—
Gamma energy (MeV)	1.17 1.33	0.66	0.32 0.47	Up to 2.4	0.06	—	Medium level	0.03
Gamma constant (µSv/h × GBq at 1 m)	360	86	140	220	4	3.5 (Bremss.)	39	39

Neutron sources

Neutron sources contain mostly alpha emitting radionuclides (^{241}Am, ^{238}Pu, ^{239}Pu and ^{226}Ra) to induce (α, n) reactions with light elements, e.g. beryllium, boron, lithium or fluorine. A beryllium or boron nucleus will absorb an alpha particle and emit a neutron with energy ranging from 0 to about 11 MeV, with the average energy at about 4 MeV. The most commonly used radionuclide neutron sources are Am–Be sources, although some plutonium–beryllium (Pu–Be) sources have been used in the past. Am–Be sources, such as those used in oil well logging, are typically formed by cold pressing mixtures of americium oxide (AmO_2) and beryllium powders to form a pellet which is then either diffusion bonded to a metal strip (for small sources) or sealed in a welded stainless steel container.

A spontaneous fission source using ^{252}Cf has been demonstrated as a replacement for Am–Be sources. Plutonium-238 is used to induce the emission of fast neutrons, while ^{241}Am is used extensively for other applications. Radium-226 is also used in neutron sources; however, it presents problems due to the associated gamma radiation.

The radiological characteristics of the most important neutron sources are presented in Table 2 [17].

TABLE 2. THE MOST IMPORTANT NEUTRON SOURCES [17]

Source	Nuclear reaction	Half-life	Yield of neutrons 1/(TBq.s)	Mean energy (MeV)
^{226}Ra–Be	^{9}Be(α, n) ^{12}C	1602 a	4.6×10^{8}	5
^{239}Pu–Be	^{9}Be(α, n) ^{12}C	2.44×10^{4} a	4.8×10^{7}	4
^{241}Am–Be	^{9}Be(α, n) ^{12}C	458 a	5.7×10^{7}	4
^{252}Cf	Spontaneous fission	2.64 a	1.2×10^{11}	1

2.2. STRUCTURE AND DESIGN

Depending on the applications and activity content, SRSs can be found in a variety of shapes, forms and dimensions. Geometrical parameters are important in the selection of suitable methods for the conditioning, transport, storage and disposal of disused sources.

2.2.1. Gamma sources

The active part of the radioactive source may have various forms. For beta–gamma radiation the active parts may be in the form of cylinders, disks, granules, plates and wires. The radioactive material in the gamma sources is usually in a solid, low solubility form. One exception is ^{137}Cs chloride in high activity sources, which is readily soluble. Generally, stainless steel, or, to a lesser extent, aluminium and titanium, are used for encapsulation of gamma sources. The protective envelope of the sealed radioactive source can be constituted by one or several capsules (see Fig. 1). Most of the highenergy sources are doubly encapsulated; the low energy sources are encapsulated in a strong metallic capsule with a thin window. In low energy gamma sources the radioactive material is fixed as a thin layer on the surface of the plate (see Fig. 2).

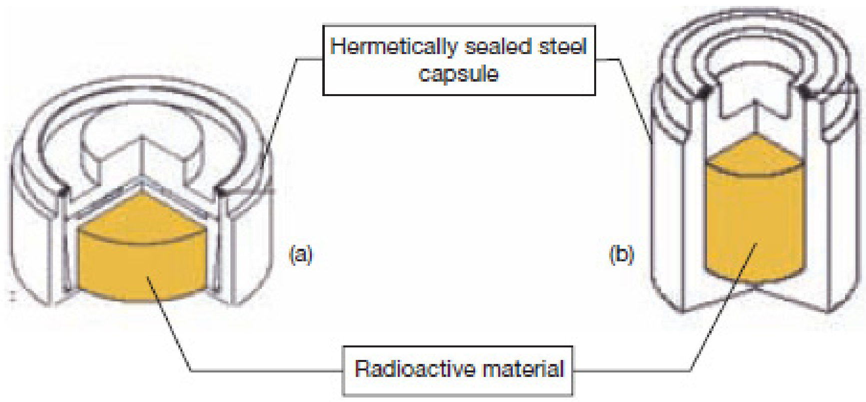


FIG. 1. Examples of double and single encapsulated sources: (a) a typical ^{241}Am disc source and (b) a typical ^{137}Cs cylindrical source.

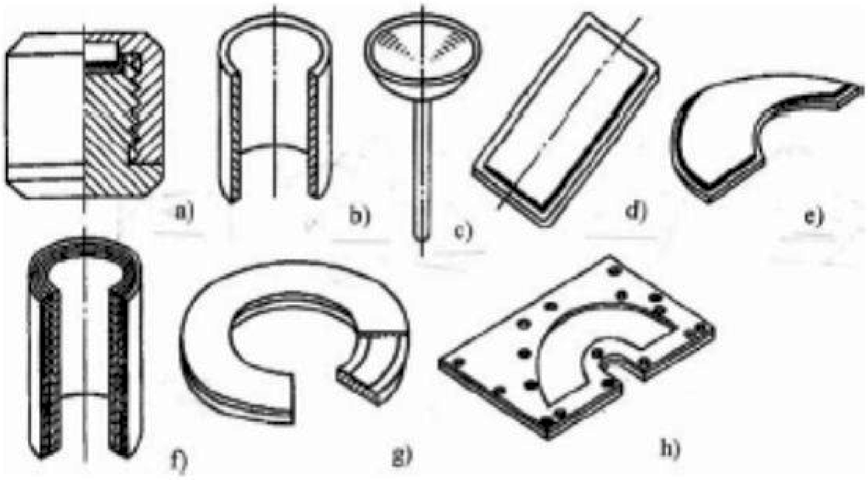


FIG. 2. Surface radioactive sources: (a) beta sources with $^{90}Sr + ^{90}Y$, $^{144}Ce + ^{144}Pr$, $^{106}Ru + ^{106}Rh$;(b) α source with Pu; (c) beta source with $^{90}Sr + ^{90}Y$; (d) α source with Pu; (e) beta source with ^{147}Pm; (f) beta source with $^{90}Sr + ^{90}Y$; (g) X ray source with ^{55}Fe; (h) beta sources with $^{90}Sr + ^{90}Y$, $^{144}Ce + ^{144}Pr$.

2.2.2. Alpha sources

As a rule, alpha sources comprise a ceramic or metal support containing radionuclides, such as ^{238}Pu, ^{239}Pu, ^{241}Am, ^{210}Po, ^{237}Np or ^{226}Ra. The dimensions of these sources can vary significantly. A typical ^{241}Am radioactive foil type source is shown in Fig. 3.

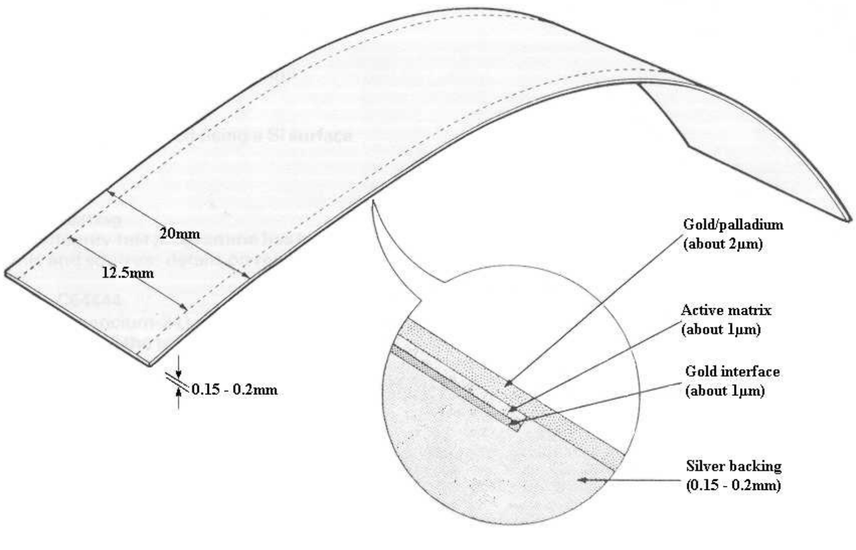


FIG. 3. A typical alpha emitting radioactive source with ^{241}Am in a strip.

Some alpha sealed sources contain radioactive material in powder or liquid form inside glass or plastic vials and ampoules. These sources require special precautions during handling, transportation, conditioning and storage. Early radium liquid sources were sealed in glass vials (Fig. 4), but this practice was abandoned many years ago. Nevertheless, these sources are still encountered.

FIG. 4. ^{226}Ra liquid sources in glass vials.

2.2.3. Beta sources

The design of beta sources comprises a strong metallic capsule with a thin window or a surface of inactive substrate where active material is deposited, often coated with a very thin, inactive layer.

Nickel-63 sources are prepared on a substrate of metallic tubing or wire, with an electrochemically deposited layer of radioactive material. The length of these sources does not typically exceed 40 mm.

Carbon-14 sources consist of polymeric (polymethylmethacrylate — PMMA) films glued to an aluminium film. Usually these films do not exceed 70 mm in length and 1 mm in thickness.

Strontium-90 sources are usually made of a ceramic matrix encapsulated in steel. But ^{90}Sr eye applicators are based on silver foil technology.

For ^{85}Kr sources, the radioactive content is a rare noble gas.

2.2.4. Neutron sources

Almost all neutron sources contain an alpha emitting radionuclide mixed with beryllium or other light metal powder that is pressed and doubly encased in stainless steel. The length of sources can vary from 3 to 40 mm.

2.3. DIMENSIONS

Some examples of the dimensions of SRSs are given in Table 3 [21].

TABLE 3. TYPICAL DIMENSIONS OF SOME SEALED SOURCES [21]

Sealed sources	Category	Dimensions
Co-60 teletherapy source	1	20 mm diameter × 30 mm length cylinder
Co-60 gamma sterilization source	1	11 mm diameter × 450 mm length
Sr-90 RTG source	1	Up to 100 mm diameter × 200 mm length
Industrial gamma radiography sources	2	Up to 7 mm diameter × 15 mm length; flexible tail up to 200 mm length
High dose rate (HDR) remote afterloading brachytherapy sources	2	*Modern sources:* Up to 3 mm diameter × 15 mm length; flexible tail up to 300 mm length *Older sources*: Spherical: approx. 3 mm diameter; activity: Cs-137

TABLE 3. TYPICAL DIMENSIONS OF SOME SEALED SOURCES [21] (cont.)

Sealed sources	Category	Dimensions
High energy gamma industrial gauging sources	3 or 4	Typically cylindrical capsules: 3–12 mm diameter × 5–15 mm length
Neutron industrial gauging sources	3 or 4	3 or 4–6 mm diameter × 12 mm length or 8–20 mm × 12–30 mm length
Gamma and neutron oil well logging sources	2 or 3	*Gamma sources:* 8–20 mm diameter × 15–40 mm length *Neutron sources:* 15–25 mm diameter × 25–60 mm length
Low energy fixed industrial gauging sources	4	10–50 mm diameter × 7–15 mm height
Permanent implant and low dose rate (LDR) brachytherapy seed sources	5	Less than 1 mm diameter × less than 5 mm length
Eye plaques	5	Less than 1 mm diameter × less than 5 mm length
Low energy gamma analytical sources	5	3–15 mm diameter × 7–10 mm height
Calibration and reference sources	5	Various sizes and shapes

There are specific applications where the sources are very large in size, for example, the static electricity eliminators which are more than 1 m in length. The geometrical configuration of some of these devices is rather complicated in the sense that the radioactive source material is distributed on the surface of the structure.

2.4. PHYSICAL CONDITION

Some SRSs may leak and need to be tested at regular intervals recommended by the manufacturer and/or as required by the national regulatory authority. This testing needs to be carried out by adequately trained personnel. Guidance on leak test methods is given in the reference on the ISO international standard [22].

Leaking sources are considered as disused, and immediately taken out of service for safe management. For instance, old radium sources, encapsulated in platinum or glass ampoules, may leak. An increase in internal pressure, resulting from the build-up of ^{226}Ra decay products, is a common safety concern. Leaked or damaged sources require particular attention during conditioning and storage.

3. CATEGORIZATION AND CLASSIFICATION

Categorization, or classification, is an approach used, mainly when the quantity of elements considered (objects or ideas) is large, to facilitate management of the elements by reducing their number. Categorization is realized by selecting the main features (criteria) and by structuring these criteria. SRSs are used for a variety of purposes and they incorporate a wide range of radionuclides and amounts of radioactive material. In this particular case, the categorization is based mainly on the features of the radiation and the risk represented by the source for human beings and the environment. Some risks associated with radioactive sources are described briefly in the Annex.

3.1. RATIONALE FOR RADIOACTIVE SOURCE CATEGORIZATION

Categorization or classification of radioactive sources may be helpful at any stage of the life cycle of a radioactive source, from its initial production and usage phase to final disposal. A source categorization system is also needed to provide a risk informed ranking and grouping of the sources and their applications, which in turn is of direct relevance to the following issues:

— *Regulatory measures.* To provide a logical and transparent basis for a risk informed system of notification, registration, licensing and inspections. The categorization also provides a basis for ensuring that the allocation of human and financial resources is commensurate with the risks associated with the use of the source.
— *Safety measures*. To provide a risk informed basis for the determination of safety measures to be applied during the life cycle of the sealed source (from in-use status until disposal as disused). To assess potential hazards associated with the various types of sources.
— *Management options*. To assist in planning and designing the conditioning and storage facilities and making a decision on a possible disposal route for a source.
— *Security measures.* To provide a risk informed basis for assisting in the determination of security measures, recognizing that other factors are important (e.g. threats against specific facilities/sources).
— *National registry of sources.* To optimize decisions on the categories of sources and the level of detail to be included in national reporting.
— *Import/export controls.* To optimize decisions regarding sources that may be subject to import and export controls.
— *Labelling of sources.* To optimize decisions regarding sources that may be marked with an appropriate label (in addition to the trefoil) to warn persons of the radiation hazard.
— *Emergency preparedness and response.* To ensure that emergency preparedness plans and response to accidents are commensurate with the category of the source.
— *Prioritization for regaining control over orphan sources.* To optimize decisions relating to where efforts need to be focused to regain control over orphan sources.
— *Communication with the public.* To provide a basis for explaining the relative hazard of events involving radioactive sources.

The purpose of categorizing radioactive sources is to provide a fundamental and internationally harmonized basis for risk informed decision making. Various source categorization systems have been developed by international organizations, but these systems have been developed for different decision making purposes. The three main international categorization systems developed for informing management strategies for disused radioactive sources are described below. Additionally, for those Member States considering disposal options, the IAEA waste classification system is described in Section 12.

Member States that have no source classification (categorization) system can develop their own system based on relevant international guidance or can adopt existing international source categorization systems to meet specific national requirements.

3.2. THE IAEA SOURCE CATEGORIZATION SYSTEM

Recognizing the need for a risk based approach to the regulatory control of radioactive sources, the IAEA provides a categorization scheme for radioactive sources and practices in the BSS [11] and in Safety Guide RS-G.1.9 [23], based on IAEA-TECDOC-1344 [24] .

Table 2 in Appendix I of Ref [23] shows examples of the wide range of radionuclides and activities in radioactive sources used for beneficial purposes around the world. In recognition of the fact that human health is of paramount importance, the categorization system is based primarily on the potential for radioactive sources to cause deterministic health effects, considering both the physical properties and the specific application of the source. The categorization system is therefore based on the concept of 'dangerous sources' — which are quantified in terms of 'D values'[2]. The D value is the radionuclide specific activity of a source which, if not under control, could cause severe deterministic effects for a range of scenarios that include both external exposure from an unshielded source and internal exposure following dispersal of the source material (see Annex II of Ref. [24]). For each practice and radionuclide used in the practice, the source activity in TBq is divided by the corresponding radionuclide specific 'D' value in TBq, resulting in the dimensionless normalized ratio of A/D.

The final categorization of specific source applications is given in Table 4 (Table 1 in Ref. [23], and a comparison of categories, based solely on the A/D ratio, to those assigned to practices is presented in Appendix I in Ref. [23]. Category 1 sources demonstrate the highest risk in managing sealed sources, while Category 5 refers to the lowest risk.

TABLE 4. RECOMMENDED CATEGORIES FOR SOURCES USED IN COMMON PRACTICES [23]

Category	Categorization of common practices[a]	Activity ratio[b] (A/D)
1	Radioisotope thermoelectric generators (RTGs) Irradiators Teletherapy sources Fixed, multi-beam teletherapy (gamma knife) sources	$A/D \geq 1000$
2	Industrial gamma radiography sources High/medium dose rate brachytherapy sources	$1000 > A/D \geq 10$
3	Fixed industrial gauges that incorporate high activity sources Well logging gauges	$10 > A/D \geq 1$
4	Low dose rate brachytherapy sources (except eye plaques and permanent implants) Industrial gauges that do not incorporate high activity sources Bone densitometers Static eliminators	$1 > A/D \geq 0.01$
5	LDR brachytherapy eye plaques and permanent implant sources X ray fluorescence devices Electron capture devices Mossbauer spectrometry Positron emission tomography (PET) check sources	0.01>A/D≥Exempt[c]/D

[a] Recognizing that factors other than A/D have been taken into consideration.

[b] This column can be used to determine the category of a source, based purely on A/D. This may be appropriate if, for example: the practice is not known or is not listed; sources have a short half-life and/or are unsealed; or sources are aggregated.

[c] Exempt quantities are given in Schedule I of the BSS [11].

If a practice involves the aggregation of sources into a single storage or use location where sources are in close proximity, such as in storage facilities, manufacturing processes, or transport conveyance, the total activity can be integrated and treated as one source for the purposes of assigning a category. Therefore, the integrated, total activity of the radionuclide can be divided by the appropriate D value, and the calculated A/D ratio compared to the

[2] D values were originally derived in the context of emergency preparedness [38] to establish a reference point corresponding to a 'dangerous source' [37] on a scale of the risks that could arise from uncontrolled sources.

A/D ratios given in the right hand column of Table 4, thus allowing a category, based on activity, to be allocated to the practice. If sources with several radionuclides are aggregated, then the sum of the A/D ratios can be used to determine the category in accordance with the formula:

$$\text{Aggregate A/D} = \sum_n = \sum_i A_{i,n}/D_n$$

where

$A_{i,n}$ is the activity of each individual source *i* of radionuclide *n;*
D_n is the D value for radionuclide *n.*

In each case, it should be recognized that other factors might need to be taken into consideration in assigning a category. Furthermore, when considering the accumulation of sources, it is important to recognize that the practice may change, e.g. the ‘manufacture’ of a level gauge is a different practice from the ‘use’ of such a gauge.

3.3. THE IAEA SECURITY GROUPING OF SOURCES

Unsecured sources have resulted in deaths and serious injuries in many parts of the world. The IAEA has published a number of reports that describe the human health consequences, as well as the economic losses of incidents and accidents, due to uncontrolled sources.

Prior to 11 September 2001, the security of radioactive sources was addressed largely by measures protecting the sources from access by inadequately trained personnel or from attempts at theft for financial gain. This assumption has now been modified to also include the need to prevent access to certain sources by individuals deliberately and malevolently seeking to cause radiation exposure or dispersal of radioactive materials.

Ensuring the security of sources requires that measures be applied to prevent unauthorized access to radioactive sources at all stages of their life cycle, as well as loss, theft, and unauthorized transfer of sources. To ensure the safety of radioactive sources, controlling exposure to radiation from the sources is required, both directly and as a consequence of incidents, so that the likelihood of harm attributable to such exposure is very low. Safety and security aspects of sources are intimately linked and many of the measures to address one issue will also address the other.

The IAEA published in 2009 an Implementing Guide on the Security of Radioactive Sources [25], which takes into account the overall security approach established in that publication which some States may have used as a reference in devising their current security regimes. This Guide proposes a graded approach to security using a set of security levels, and the security functions of deterrence, detection, delay, response and security management. The publication has been harmonized with the IAEA categories of radioactive sources [23], the requirements of the BSS [11] and the requirements of the Code of Conduct [14]. Three security levels (A, B and C) have been developed to allow specification of security system performance in a graded manner. Security level A requires the highest degree of security while the other levels are progressively lower.

Each security level has a corresponding goal. The goal defines the overall result that the security system should be capable of providing for a given security level. The following goals have been developed:

— Security level A: *Prevent* unauthorized removal of a source.
— Security level B: *Minimize the likelihood* of unauthorized removal of a source.
— Security level C: *Reduce the likelihood* of unauthorized removal of a source.

Malicious acts can involve either unauthorized removal of a source or sabotage. While the security goals only address unauthorized removal, achievement of the goals will reduce the likelihood of a successful act of sabotage. Security systems that achieve the goals listed above will provide some (although limited) capability to detect and respond to an act of sabotage.

A proper security level should be assigned to each category of radioactive sources specified in Section 3.2.[3] Category 1 sources should have security measures which meet the security objectives of Security Level A. Category 2 sources should have security measures which meet the security objectives of Security Level B. Category 3 sources should have security measures which meet the security objectives of Security Level C.

The BSS [11] include general requirements for the security of radioactive sources. This guide considers that while those control measures provide a sufficient level of security for radioactive sources in Categories 4 and 5, enhanced measures specified in this guide should be applied to radioactive sources in Categories 1, 2 and 3 in order to reduce the likelihood of malicious acts involving those sources. Furthermore, the regulatory body, taking account of its national threat, may wish to enhance the security of sources in Categories 4 and 5 sources in appropriate circumstances. The malicious use of radioactive sources may not necessarily involve sources that are ranked highest in this categorization scheme. Most Category 1 sources, for example, will be held within shielding and inside fixed devices or facilities. Efforts to remove the source would take time and may expose the adversaries to a significantly harmful level of radiation. It is, therefore, possible that adversaries will focus on sources of a lower category, more accessible, less of a hazard to handle, portable, and more easily concealed. The assignment of a radioactive source to a security group is most effectively achieved by using the outcomes of the threat assessment. This allows most flexibility and specificity to account for the variability in threat levels and security environments within Member States. It also permits different choices of security groups for sources in the various stages of their life cycle. Alternatively, some Member States may perform countrywide threat and vulnerability assessments and accordingly make allocations of sources to security groups, based on these assessments.

Consistent with the Code of Conduct [14], each of the categories includes the radioactive material released if any of the sources in the group is leaking or broken. The categorization methodology also allows for aggregation of sources in one location. One reason for a source being categorized in a higher security group could be that the specific threat assessment may reveal that some facilities with sources or some mobile sources are more vulnerable to acquisition, even though they may not be the highest activity sources.

3.4. THE ISO SOURCE CLASSIFICATION

The International Organization for Standardization's ISO 2919 [26] establishes a system for the classification of sealed sources based on test performance. The standard specifies general requirements, performance tests, production tests, marking and certification. Prototypes of sources are tested for temperature, external pressure, impact, vibration and puncture in classes of increasing severity [22]. Sources intended for an application are required to meet minimum criteria outlined in the standard.

The ISO classification of sources, based on the type of radiation and application, is as follows:

— Gamma sources;
— Beta sources;
— Alpha sources;
— Neutron sources;
— Other sources for special use (e.g. gamma and neutron sources for borehole logging).

It should be noted that sources generally emit mixed radiation: Radioactive decay is accompanied by radiation, and radioactive decay daughter products are often beta emitters. Additionally, the conversion of the particle (electron) energy during absorption results in Bremsstrahlung.

[3] Guidance provided here in the form of 'should' statements, or simply in the present tense indicative, describing good practices, represents expert opinion but does not constitute international consensus recommendations on how to meet the relevant requirements.

4. APPLICATIONS, DEVICES AND ASSOCIATED SEALED SOURCES

In nearly all applications, radioactive sources, they are contained within a shielded holder which also contains, or is associated with, other instrumentation or mechanical hardware. This hardware is generally known as a ‘device’. The nature of the device depends on the application. In many cases, the device is also used for the transport of the sealed source to its intended location for use. The device generally incorporates sufficient shielding to absorb radiation to a level at which it is harmless to the public, and a ‘shutter’ which allows a beam of radiation from the source to be directed towards the subject when the shutter is opened.

The following section outlines some typical devices and associated sources used in various applications. The description of various devices is linked with the IAEA Categorization of Radioactive Sources [23]. Since radioactive sources have been used intensively for various purposes in the past, it is important to take into account the historical applications of sources together with the devices used at that time.

4.1. DEVICES AND CATEGORY 1 SOURCES

4.1.1. Radioisotope thermoelectric generators

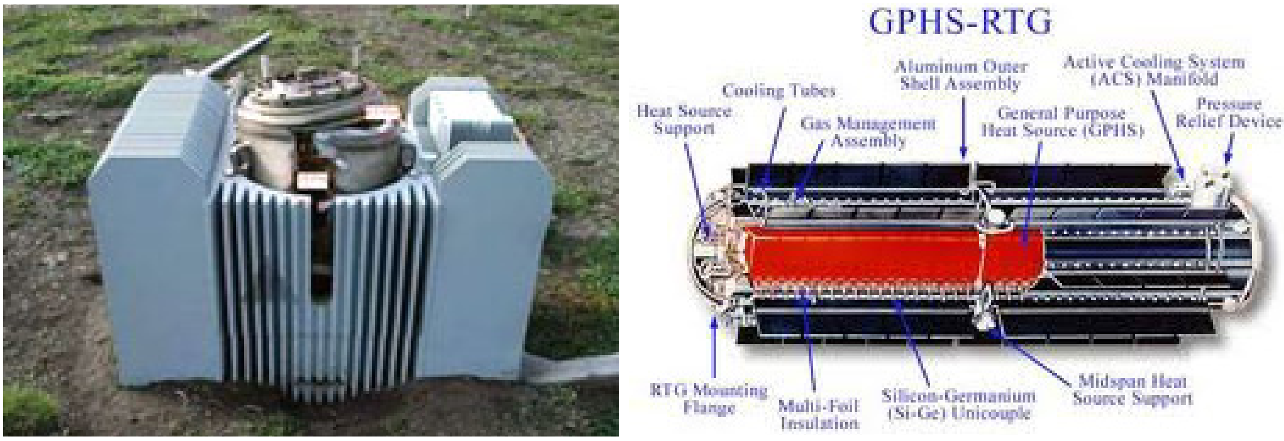
RTGs are devices that use the decay heat of a radioisotope by the absorption of radiation from the radioactive source to generate electricity using a thermocouple device. The two radionuclides that have been most frequently used are ^{90}Sr (330 TBq — 2.5×10^4 TBq) and ^{238}Pu (1–10 TBq). The sources are up to 100 mm in diameter and a length of 200 mm. Strontium is used in the form of ceramic titanate ($SrTiO_3$) and is sealed hermetically and twice into a capsule using argon welding. Several RTGs used ^{90}Sr in the form of strontium borosilicate glass. The capsule is protected against external impact by the thick shell of the RTG which consists of stainless steel, aluminium and lead.

The principal radiation is beta radiation, which is relatively short range, but a dangerous and significant level of secondary Bremsstrahlung gamma radiation is also created by the source. The power that is typically generated can vary from a few watts to tens of kW, depending on the level of activity and type of radioisotope used. There are no moving parts in these devices and they are designed to operate unattended for tens of years.

There are two key applications: space travel and remote location power generation. RTGs have been deployed fairly extensively by the USA and the former USSR in the Arctic region for powering lighthouses and navigation beacons.

The type of RTG produced in the former USSR is shown in Fig. 5(a). Altogether, more than 1000 RTGs have been produced and about 700 are still in use. A US RTG is shown in Fig. 5(b).

Very small ^{238}Pu based RTGs were used until the 1970s in pacemakers to provide lifelong power (Fig. 6). These have been rendered obsolete by improved battery technology, and due to safety and regulatory concerns. The sources are of low activity, which means that these devices are of little concern.



(a) *(b)*

FIG. 5. Radioisotope thermoelectric generators.

FIG. 6. An RTG powered heart pacemaker.

The fact that such devices are deployed in remote regions means that they are susceptible to people moving them, acquiring them for malevolent purposes or dismantling them for the scrap value of their shielding material. In addition, changes in government and/or loss of records mean that the sources can become abandoned and forgotten until rediscovered some time later. Space satellites containing RTGs have also reentered the Earth's atmosphere causing concern over the spread of the radioactive material.

4.1.2. Irradiators

Sterilization or panoramic irradiators

The gamma sterilization plant, or 'panoramic irradiator' is not strictly a device. It is a shielded building in which a large number of ^{60}Co or ^{137}Cs sources (in the range 0.2 to 600 PBq) are housed in an array. The product requiring gamma sterilization is put into the shielded area and exposed to the sources for the period required to deliver the gamma dose required to kill bacteria. Applications include the sterilization of medical items (such as needles, syringes and gloves), preservation of foodstuffs and cross-linking of polymers to improve their properties. Currently, there are over 160 panoramic irradiators in operation around the world.

The sources used in the irradiators vary in size, ranging from large to pencil sized. These sources are installed in dedicated, large, shielded enclosures that employ either a deep pool of water (Fig. 7), or massive lead or concrete for shielding of the source when not in use (Fig. 8). When the source is exposed, the dose rate inside the irradiation enclosure is very high and a lethal dose could be received in a matter of a minute or so. Therefore, these facilities have several safety features, based on the principles of redundancy, diversity and interdependence of safety systems.

FIG. 7. Wet storage of Category 1 sources in the water pool.

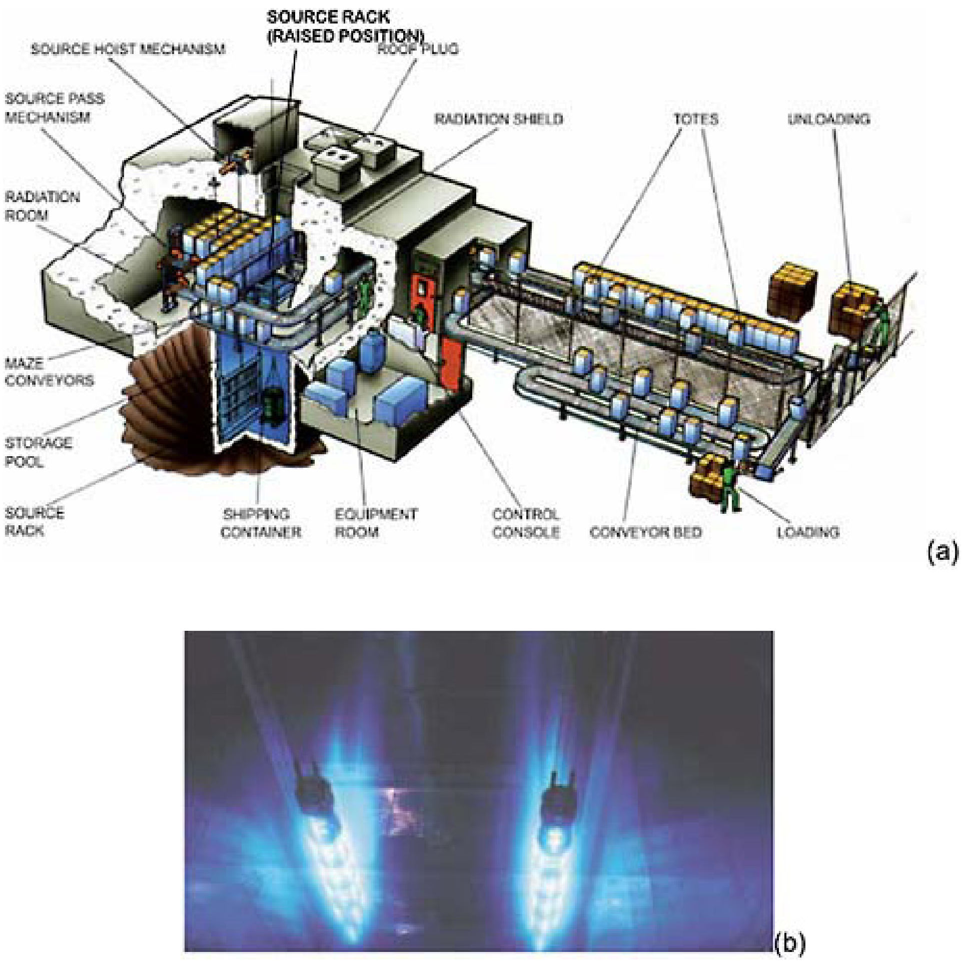


FIG. 8. (a) An artist's rendition of an MDS Nordion JS-10000 panoramic irradiator, which uses a panel type source rack (not necessarily to scale); and (b) different source racks for an MDS Nordion pallet irradiator.

The sources used in sterilization irradiators are usually doubly encapsulated in a stainless steel outer capsule, containing ^{60}Co pellets. The typical range of capsule dimensions is mostly 11 mm diameter × 450 mm length. The most common design of the ^{60}Co gamma sterilization source is the Nordion C188 (Canada) and REVISS RSL2089 type (international consortium), used in industrial gamma sterilization plants worldwide. Sources of similar dimensions are made by a number of other manufacturers, and there are also a variety of other design types, used in both industrial irradiators and small scale irradiators.

The sources encapsulated in stainless steel tubes are called 'pencil' or 'rod' sources. A schematic of a ^{60}Co pencil gamma source is shown in Fig. 9. The rod type high activity industrial source is shown in Fig. 10.

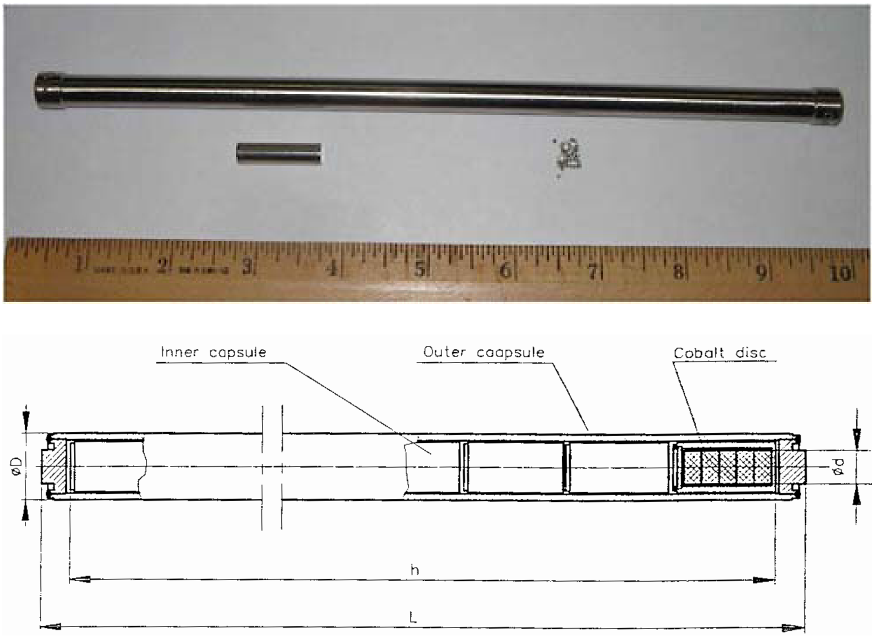


FIG. 9. A pencil type ^{60}Co source.

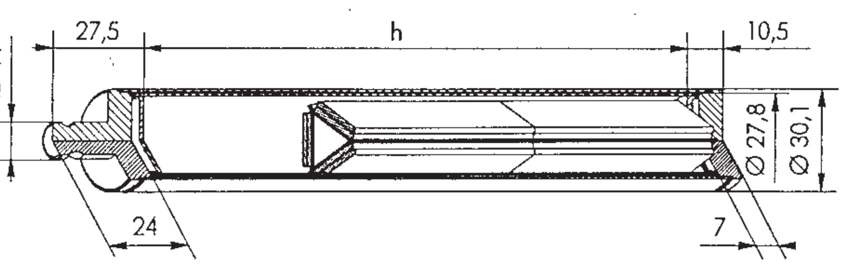


FIG. 10. A rod type high activity industrial source.

These sources are manufactured according to ISO and other standards [21, 27] and are labelled on the surface with an engraved code for identification. The code is also provided in the source certificate.

If pencil sources are produced by recycling, their shape and dimensions could be different from the original ones. The initial nominal activity of a pencil is from 18.5 TBq (500 Ci) to 450 TBq (12 000 Ci). The typical recommended working life (RWL) is 15–20 years.

If irradiation facilities are not maintained properly, there is the potential for objects to interfere with the movement of the source array and to distort the module frames thus allowing a source pencil to fall out. This has occurred on a number of occasions. It provides the potential for a source pencil to fall into one of the 'totes' which transports the product being irradiated out of the facility. Modern irradiators have installed monitoring systems at the product exit points to detect such a situation.

Another consideration is that from time to time a percentage of the source pencils have to be replaced due to radioactive decay. Normally, the suppliers of the sources would undertake this work, and the old sources would be put into specially designed transport containers for return. At this stage, there is the potential for transport problems to cause delays, resulting in the container being put into storage and possibly forgotten about.

4.1.2.1. Self-shielded irradiators

There are a number of smaller irradiators that have been described invariably as self-shielded (or self-contained) irradiators, or blood/tissue irradiators. Although they are smaller in size, they still contain high activity sources. An example of such an irradiator is shown in Fig. 11. The older style blood irradiator is shown in Fig. 12. These devices are used for the treatment of blood and consist of a shielded chamber with a cavity into which a sample of blood in a bag of about 2 L capacity is loaded. Hospitals and blood banks irradiate blood products to prevent transfusion-associated graft-versus-host-disease (GVHD). Transfusion associated GVHD is a deadly transfusion complication resulting when some donor white blood cells.

In addition to sterilizing blood, tissue and seeds, the irradiators are used for gemstone colouration, sterilization of medical equipment, insect irradiation and research into mutation effects on agricultural products. Typically, the design includes a sample chamber with interlocked doors and the sources are moved around the chamber or the chamber is positioned next to the sources. There is no simple way of accessing the sources, however, the irradiator, with some modifications, can also serve as the source transport container.

Some devices, including some kinds of radiation detectors and dosimeters, require irradiation calibration that is both precise and accurate at high doses. Some calibration sources used for these purposes are also considered self-shielded irradiators. Radionuclide sources are typically used for this purpose because the decay energy (and decay rate) is known or readily calculable. These calibration irradiators are, on average, smaller-activity sources than the other self-shielded irradiators, but some hold about 80 TBq (2200 Ci) of ^{137}Cs.

There are some self-shielded irradiator device manufacturers operating today, such as: MDS Nordion of Canada; CIS-US, Inc., a French company that no longer manufactures new machines but is still servicing those in existence, and a US company, J.L. Shepherd and Associates. There are 1341 self-shielded irradiators that use radioactive sources in the USA alone, approximately 85% of which use ^{137}Cs, while nearly all of the remaining devices use ^{60}Co. These include blood irradiators, research irradiators and calibration irradiators.

Few of the fixed devices have been involved in incidents because of their robust nature and design.

FIG. 11. A typical self-shielded irradiator.

FIG. 12. An older style blood irradiator.

While most of these irradiators are fixed, there are some devices, such as the ‘Gamma Kolos’ irradiators, which were mounted on heavy trucks or on trailers and moved throughout the former Soviet Union in order to irradiate seeds as they were being planted. Most of these devices have now been removed from their vehicles, and are currently in storage (Fig. 13).

FIG. 13. Mobile caesium irradiators used in the former USSR.

4.1.3. Teletherapy machines

Teletherapy machines are commonly used in medical institutions, such as hospitals or clinics. Radiotherapy uses ionizing radiation directed at a human or animal body to treat many serious diseases, most notably cancer. High activity radionuclide sources can be used to create clinical ionizing radiation beams in the form of high energy gamma rays in teletherapy machines used for external beam radiotherapy. Only four known radionuclides possess characteristics that make them candidates for use in external beam radiotherapy: ^{137}Cs, ^{60}Co, ^{152}Eu and ^{226}Ra. Europium-152 has not been developed yet for clinical use, and the use of ^{137}Cs and ^{226}Ra was discontinued for practical reasons and because of safety concerns. Cobalt-60 is currently used in external beam radiotherapy devices found mostly in developing countries.

The radioactive source, which is relatively small in size, is securely located in the heavy shielded housing at the end of the rotating arm (Fig. 14). The beam of radiation from the source is exposed when a shutter is opened during use. As ^{137}Cs was replaced by ^{60}Co, it became necessary to renew sources at regular intervals, usually every five to seven years, because of the relatively short half-life of ^{60}Co. Teletherapy equipment was therefore designed to allow the source to be removed from the head and transferred to shielded transport containers in situ.

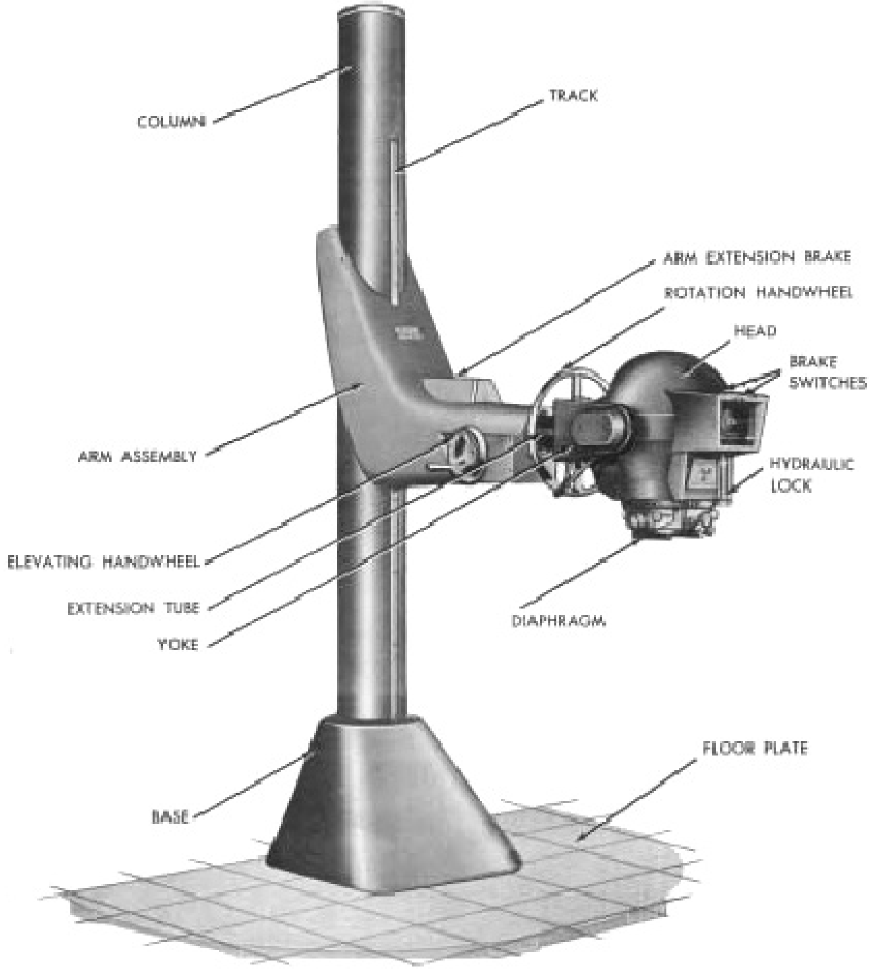


FIG. 14. An old caesium teletherapy unit (circa 1960).

To facilitate the interchange of sources from one teletherapy machine to another and from one radionuclide production facility to another, standard source capsules have been developed for use around the world. Teletherapy sources are usually replaced within one half-life of installation; however, financial considerations may result in longer use of the source. Teletherapy machines are designed to enable on-site replacement of sources by trained technicians (the machines are not returned to the manufacturer for resourcing).

Photographs of the old and damaged heads removed from the teletherapy units are presented in Fig. 15.

FIG. 15. Old and damaged teletherapy heads.

Cobalt-60 sources are generally in a solid, metallic form, being made up of a number of pellets or discs. Sources are doubly encapsulated in stainless steel. They are manufactured in two or three standard sizes, and may be mounted in tungsten spacers within the teletherapy head. The ^{60}Co sources used in various teletherapy machines are shown in Fig. 16.

FIG. 16. Various ^{60}Co teletherapy sources with associated fittings for loading into the teletherapy heads.

Caesium-137 teletherapy sources are usually in the form of caesium chloride in order to yield the necessary high specific activity so that the small sources can be designed for treatment purposes. Once the containment of a caesium chloride source is breached, the high mobility of the material causes a rapid spread of contamination. Thus the problem is greater from sources with chemical forms that can easily be dispersed.

4.1.4. Fixed, multibeam teletherapy (Gamma Knife®) machines

The multibeam teletherapy machine is a similar device, but it uses a large number of sources in the array to focus on well defined treatment areas. This device is used for medical procedures (radiosurgery) in cases of brain cancer and other brain illnesses.

The Gamma Knife® (Elekta, Stockholm, Sweden) is a radiosurgical device that has been associated with, radiosurgery for the past 40 years. Despite great technological advances during this time, the fundamental design and principles of the Gamma Knife® have not changed much since the Swedish neurosurgeon Lars Leksell introduced the prototype unit in 1968. The unit incorporates 201 ^{60}Co sources housed in the central body of the unit. These sources produce 201 collimated beams directed to a single focal point (machine isocentre) at a source–focus distance of about 40 cm. The final definition of the circular beam field size is provided by one of four helmets delivering circular fields with nominal diameters between 4 and 18 mm at the machine focal point (isocentre)

There are approximately 200 Gamma Knife® devices worldwide, including at least 104 in the USA. Elekta, a Swiss/Swedish company is the sole manufacturer of the Gamma Knife, while MDS Nordion is the main source for the small cobalt-60 sealed sources. A Chinese company, GammaStar, has begun to market a competing device and Elekta is now selling a new version of the Gamma Knife® with 192 sources, instead of the 201 used in previous models.

The facilities within which a therapy device is located are specifically designed to include thick, shielded walls, as well as other protective equipment. A typical multibeam teletherapy machine is shown in Fig. 17.

Each of the Gamma Knife® ^{60}Co sources is in the form of a steel capsule with a diameter of 1 mm and a height of 20 mm, containing 20 ^{60}Co pellets. The capsule is inserted into another steel capsule, which is enclosed by a bushing and loaded into the central body of the machine. Each source bushing assembly is aligned with its precollimator (6.5 cm of tungsten alloy), stationary collimator (9.25 cm of lead), and the final collimator (6 cm of tungsten alloy) on one of the four helmets.

FIG. 17. Gamma Knife® installation showing the main body of the unit containing 201 cobalt sources (at 30 Ci = 1.11 TBq for each source), the treatment couch, and a collimator helmet attached to the treatment couch. The inset shows an close-up image of the automatic positioning system used to position the patient for treatment.

4.2. DEVICES AND CATEGORY 2 SOURCES

4.2.1. Industrial gamma radiography projectors

Gamma ray radiography is one of a number of technologies used in industry for safety assessment and quality control purposes. In particular, it is widely used in the chemical, petrochemical, and building industries for radiographic inspection of pipes, boilers and structures where the economic and safety consequences of failure can be severe.

Industrial gamma radiography projectors are used for the radiography of engineered structures. They contain a single source attached to a flexible cable which can be exposed near the object that is being investigated. A radiographic film is attached behind the object, and the penetrating gamma rays expose the film. Variations in the density of the item being radiographed are shown in the image of the film. The devices are often also referred to as radiography cameras (Fig. 18).

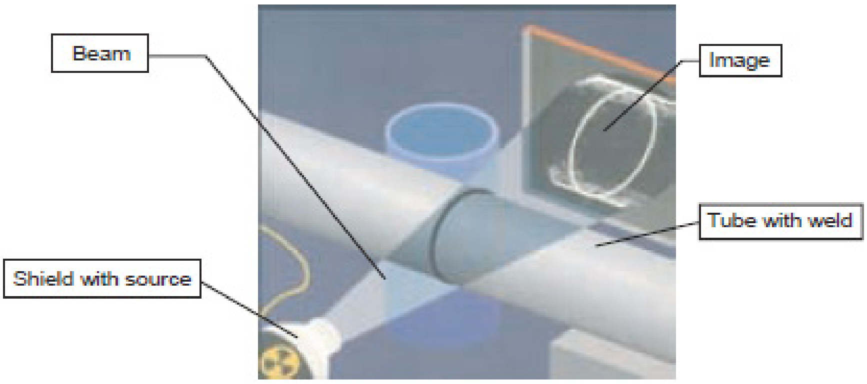


FIG. 18. A typical gamma radiography system.

Most industrial radiography equipment consists of a radiography unit, which may contain depleted uranium as shielding material, and one or more sealed sources (Fig. 19). Currently, sources containing ^{192}Ir or ^{60}Co, or ^{169}Yb, ^{170}Tm or ^{75}Se, are used in gamma radiography. The sources are usually doubly encapsulated in stainless steel, and contain one or more pellets of active material in metal form. The source is held in a flexible assembly, sometimes called a source holder, pencil, shuttle or pig tail (see Figs 20–22). Portable, industrial radiography devices are generally small in size, although they are relatively heavy due to the shielding.

FIG. 19. Typical industrial radiography projectors.

When not in use, the source is located in the centre of the source container. During use, the source is pushed down into the desired position by a remote controlled device. In heavy industries, such as steel foundries or fabrication plants, portable, mobile (on wheels) or fixed radiographic equipment, containing ^{192}Ir, ^{60}Co or ^{137}Cs, may be installed in purpose built enclosures. Because mobile or fixed installations incorporate heavier shielding than portable source housings, they are less susceptible to theft and more difficult to dismantle.

FIG. 20. Typical old gamma radiography source/pigtail assemblies.

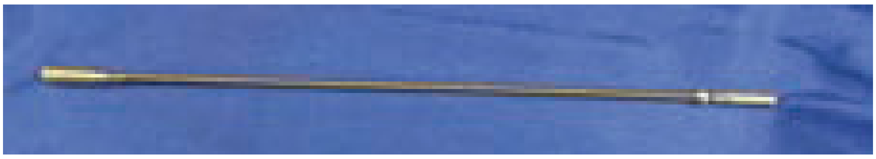


FIG. 21. A typical modern gamma radiography source/pigtail assembly.

FIG. 22. A typical gamma radiography inner source capsule prior to encapsulation in the pigtail.

The housings of portable sources contain several tens of kilograms of shielding material, such as depleted uranium, lead or tungsten, which may be perceived as being potentially valuable. Also relevant is the fact that the portable nature of most equipment allows it to be used almost anywhere. Often this is in remote locations or under extreme working conditions. This situation, coupled with limited or non-existent supervision, provides the potential for entire containers with their sources to be lost or stolen. They can end up in the metals recycling industry or remain in the public domain. These are similar problems to those for disused teletherapy sources, and while the activity levels for industrial radiography are lower, they are still sufficient to produce lethal effects. Perhaps the most significant threat comes from loss of the unshielded source. The large numbers, work environment, activity level and portability/mobility of most industrial radiography sources make them prime targets for the deliberate acquisition for malevolent purposes.

4.2.2. High/medium dose rate brachytherapy machines

Brachytherapy (therapy at a short distance) is a term that is used to describe the interstitial, or intra-cavity, application of radioactive sources by placing them directly in the tumour (breast, prostate), in moulds (skin, rectum), or in special applicators (vagina, cervix). Brachytherapy applications are of two slightly different varieties. These are generally referred to as HDR brachytherapy (Category 2) and LDR brachytherapy (Category 4 or 5). HDR sources, and some LDR sources, may be in the form of a long wire attached to a device (a remote afterloading device).

Afterloading devices may be heavy due to the shielding for the sources when they are not in use. The device may be on wheels for transport within a facility. The remote afterloading device may also contain electrical and electronic components for its operation (Fig. 23). When using these devices, catheters are first inserted into the body and the sources, attached to cables, are then introduced by remote control.

Historically, ^{226}Ra was used for brachytherapy. The sources were encapsulated in platinum in either needles or tubes of a few mm in width and up to 5 cm in length. Currently, most high and medium dose rate brachytherapy is performed with ^{192}Ir, but ^{60}Co and ^{137}Cs are also used. Sources are manufactured in different sizes and shapes, including wires or ribbons.

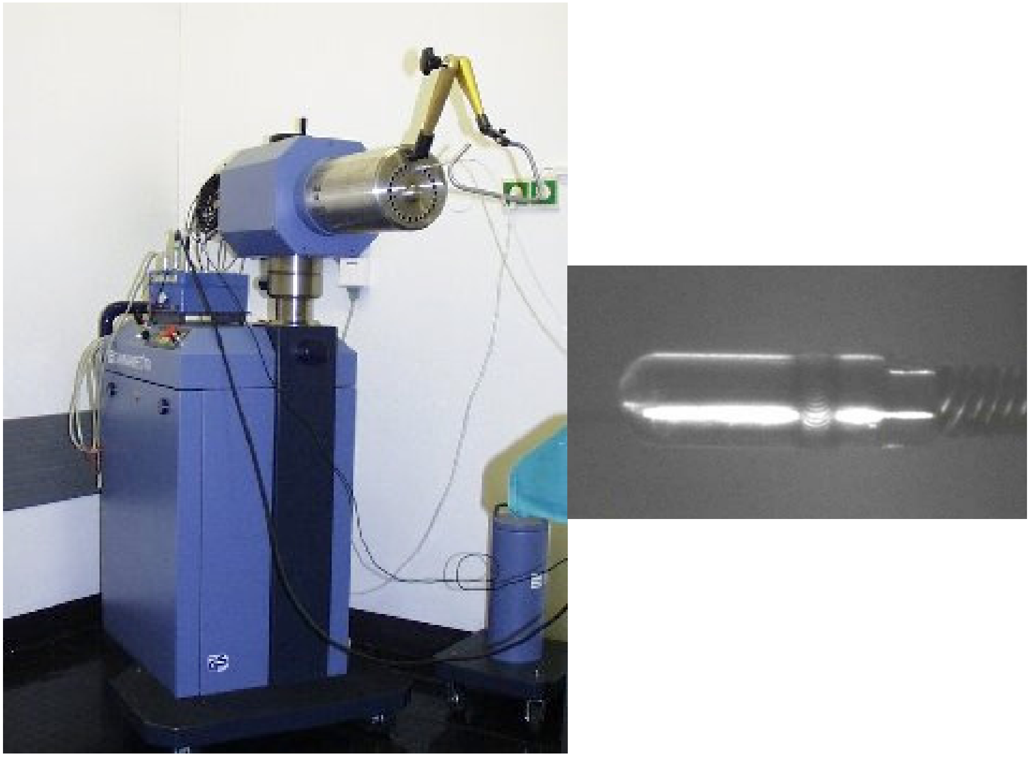


FIG. 23. An LDR brachytherapy machine with ^{192}Ir sources and a ^{192}Ir source.

When not in use, brachytherapy sources are normally stored in lead shielded safes or containers, but there have been cases when the sources were improperly kept loaded in applicators in transport carts. Similarly, sources past their useful life have been left in safes or transport containers. If the cable of a remote afterloader breaks, the sources may become detached. Failure to recognize these problems may pose significant risks.

4.2.3. Calibration systems

Calibration systems use high activity radioactive sources (approximately 15 to 82 TBq (400 to 2200 Ci)) to produce radiation fields of known intensity for calibration of radiation monitoring equipment and dosimeters, whereby the equipment and dosimeters can be evaluated for accurate operation. A source of measured activity is required to calibrate instruments and dosimeters to accepted standards. Figure 24 shows a diagram and a photograph of a typical gamma beam calibration source.

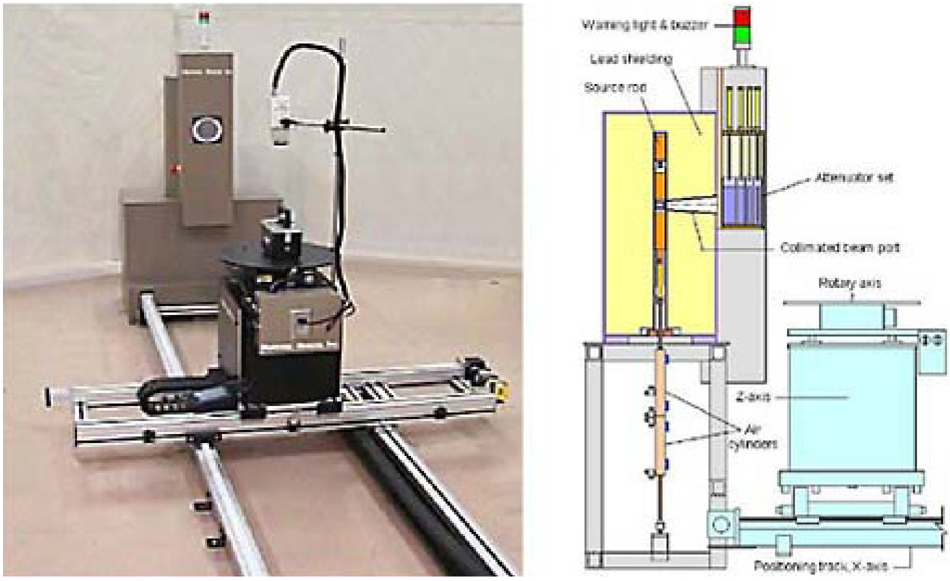


FIG. 24. Typical gamma calibrator configuration for survey instrument calibration.

The system usually consists of radioactive sources, radiation shielding, a mechanism for positioning the source, and a track or internal chamber for positioning the items to be calibrated. Modern calibration systems may contain a computer controller and safety systems, such as video monitoring, radiation monitors, warning lights and indicators, and a safety interlock system.

There are a large number of radioactive sources that are used for instrument and other calibration purposes. Because a wide range of radionuclides and activities are used, these sources cannot be assigned to any one particular category; however, the larger ^{60}Co and ^{137}Cs calibration sources generally fall into Category 2. Some sources could belong to Categories 3 and 4, but most of them fall into Category 5.

Some calibration sources, especially those of higher activity, are in specifically designed, shielded and collimated devices within large shielded facilities. Others are simply individual sources that might be used for a variety of purposes, such in the nuclear industry, environmental protection, and research and educational institutions. A wide range of radionuclides, or a combination of radionuclides, is used in calibration sources and a variety of source designs and shapes are available (Fig. 25).

FIG. 25. Examples of low activity ^{60}Co, ^{137}Cs, ^{90}Sr and ^{226}Ra calibration sources.

4.3. DEVICES AND CATEGORY 3 SOURCES

4.3.1. Fixed industrial gauges

Fixed radioactive gauges are used for measuring the level, thickness, density, moisture content, or the presence of a specific material while it is being mined, manufactured or processed without contacting the material itself (Fig. 26). Depending on the specific application, industrial gauges may contain relatively small quantities of radioactive material, or may contain sources with activities approaching 1 TBq. The larger activity (~100 GBq) ^{137}Cs, ^{60}Co and ^{252}Cf sources, which are used as level, conveyor, dredger, blast furnace or spinning pipe gauges, are Category 3 sources, while most other thickness, moisture/density and fill level gauges fall into Category 4.

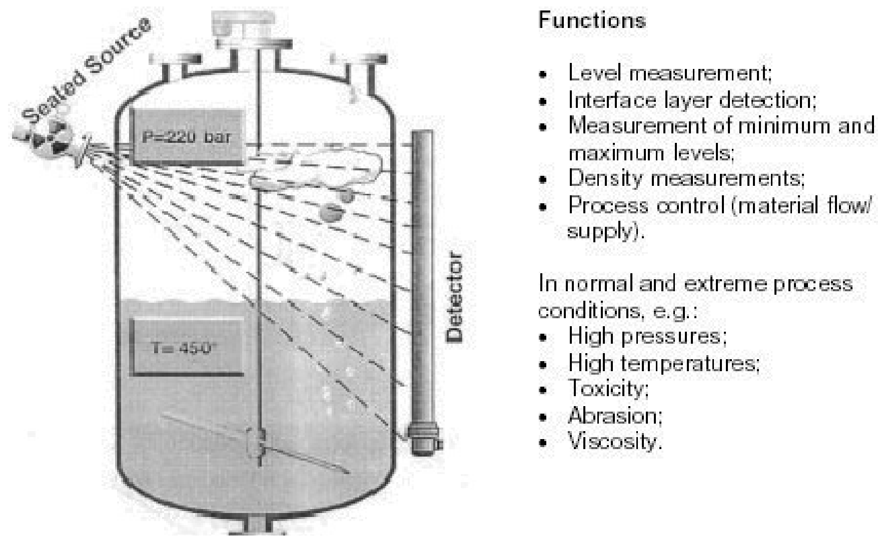


FIG. 26. Various functions of sealed sources in process control.

Blast furnaces, employed in steel making often use ^{60}Co sources to gauge the wear of the refractory lining of the bottom hearth. Spinning pipe gauges use ^{137}Cs sources to measure the wall thickness of pipes as they are passed through the center of the gauge. While pipe gauges are included in the fixed gauges category, they can also be mounted on trucks. However, they can be quite heavy (~100 kg) due to their lead or tungsten shielding (Fig. 27).

FIG. 27. Examples of different types of gauges.

The devices generally are not large, but they may be located at some distance from the radiation detector, which may have associated electrical or electronic components located within its housing. The locations of such devices or sources within a facility may not be recognized, since the devices are frequently connected to process control equipment. This lack of recognition may result in a loss of control if the facility decides to refurbish some plant or terminate operations.

The disused source may end up in the metals recycling industry. If there is no installed monitoring in the metals recycling route, or the system is not working, the source could be melted down, resulting in the contamination of the foundry and radioactive material incorporated into manufactured articles.

4.3.2. Well logging gauges

Well logging is the practice of measuring the properties of the geologic strata through which a well has been or is being drilled. A well log is the trace or record of the data from a downhole sensor tool plotted versus well depth. Its most common application is by the oil and gas industries which seek out recoverable hydrocarbon zones. For oil and gas production, companies would like to have several kinds of information about a geological layer, such as the hydrocarbon content. To measure these properties, sources and sensors loaded into housings called sondes can be lowered into an existing borehole (a technique called wireline logging) or can be mounted in a collar behind the drilling head for taking measurements while the well is being drilled.

A combination of neutron and gamma sources is used for the determination of density, porosity and moisture, or hydrocarbon content, of geological structures. The most common neutron sources employed are ^{241}Am–Be of up to 800 GBq, but some use has been made of ^{239}Pu–Be and ^{226}Ra–Be sources as well. The gamma sources most frequently employed are 50–100 GBq ^{137}Cs sources. Smaller sources, often containing radium, are still in use for reference purposes. The sources are usually contained in long (typically, 1–2 m) but thin (<10 cm in diameter) devices, which also contain detectors along with various electronic components. The devices are heavy, due to the ruggedness needed for the environments in which they are used. Figure 28 shows a schematic illustration of a neutron source and borehole logging equipment. An example of borehole logging equipment and some typical ^{241}Am–Be neutron oil well logging sources are shown in Figs 29 and 30.

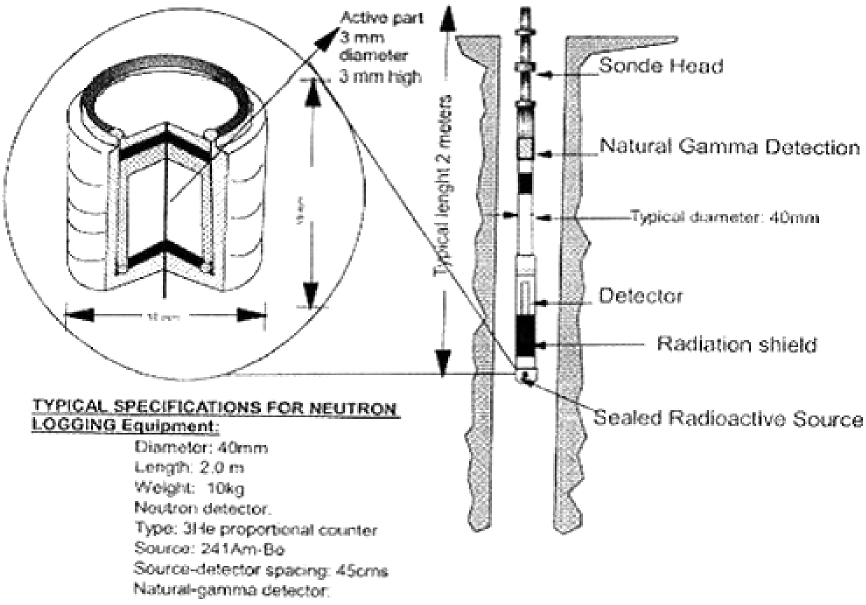


FIG. 28. A schematic illustration of a neutron source and borehole logging equipment.

FIG. 29. A pipeline crawler source head in a shipping container.

FIG. 30. Typical ^{241}Am–Be neutron oil well logging sources.

Figure 31 is a photograph of a gamma–gamma density instrument, showing the source handling device used to insert and remove the ^{137}Cs source.

FIG. 31. Atlas Densilog, which uses a vitrified ^{137}Cs source for wireline density measurements. The rod extending downward is a source handling device. The light coloured circles are windows for the source and detectors.

The housings in which the neutron well logging sources are stored and transported are large and may appear attractive to thieves. The bulk of the shielding will normally be plastic or paraffin wax and may be thrown away as useless by a thief, leading to a potentially hazardous situation. The housings for the gamma sources will normally be shielded with depleted uranium or lead, which could be attractive for its scrap value. The nature of the work using these sources requires that they be easily removed from their housings to be introduced into a borehole. If they were not subject to adequate control, it would be relatively simple for the source to be removed and left in a hazardous state.

4.3.3. Pacemakers

During the 1970s and 1980s, heart pacemakers (Fig. 6) using radioactive material as the energy source (i.e. very small RTGs) were implanted in a number of patients. The most common radionuclide used was ^{238}Pu (with a small amount of ^{241}Am as a source contaminant). One advantage of using ^{238}Pu was that it was relatively easy to shield, thereby resulting in minimal external dose.

It is possible that sources may be discarded after autopsy and end up in recycled metals. The fact that ^{238}Pu sources are easily shielded also means that they are not easily found.

4.4. DEVICES AND CATEGORY 4 SOURCES

4.4.1. Low dose rate brachytherapy sources

Much of the general discussion on brachytherapy under Category 2 sources is also applicable here, except that the activities are lower and some other radionuclides are also used, such as ^{125}I and ^{198}Au.

4.4.2. Thickness/fill level gauges

Beta (Fig. 32) or low energy gamma sources are used for measuring thickness of paper, plastics and thin, light metals, while higher energy, gamma sources are used in steel plate manufacturing (an example is given in Fig. 33). Certain industries, such as breweries or soft drinks bottling plants, use low activity sources in quality control to ensure that the bottles or cans are being filled properly. Cigarette manufacturers also use sources to ensure that the proper packing density is being maintained.

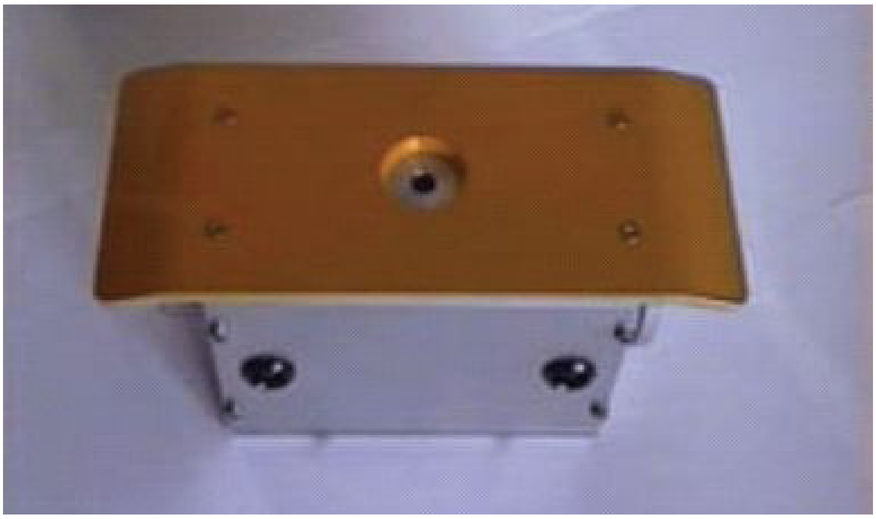


FIG. 32. A detail of a beta gauge source holder.

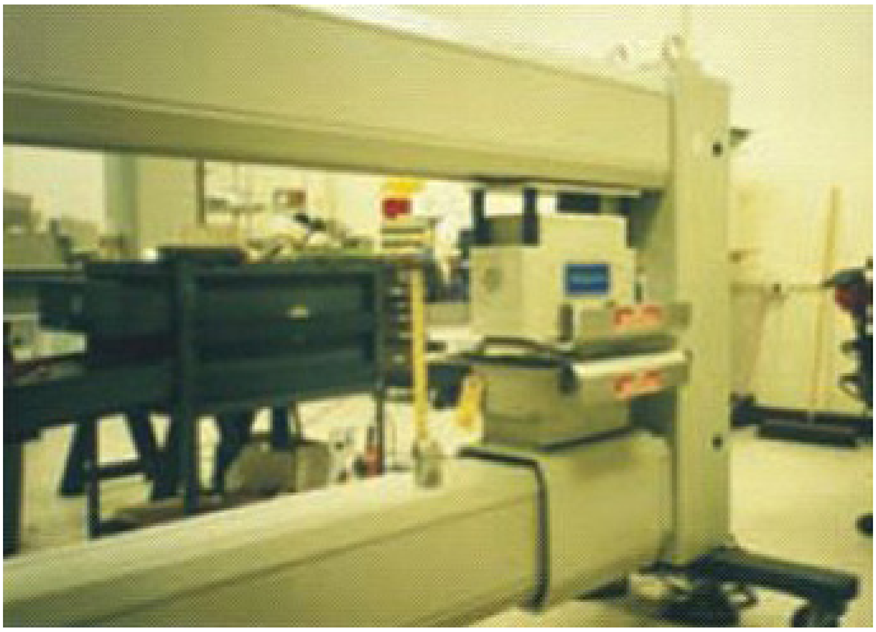


FIG. 33. A beta gauge in place on a web processing mill.

Radionuclides typically used in these industries include ^{85}Kr, ^{90}Sr, ^{241}Am, ^{147}Pm, ^{244}Cm, as well as ^{137}Cs. Activities range from 0.4 GBq to about 20 GBq. The radioactive source is chosen depending on the thickness of the material to be measured, in order to optimize the radiation attenuation characteristics. Strontium-90 is used for thicker, denser applications, down to ^{147}Pm for the thinnest, lower density materials. Examples of Cs sources removed from the gauges are given in Fig. 34.

FIG. 34. Examples of Cs sources removed from the gauges.

4.4.3. Portable moisture/density gauges

These devices use two types of radiation sources together: a ^{137}Cs high energy gamma source of approximately 40 MBq (1 mCi) and a ^{241}Am/Be neutron source of approximately 2 GBq (55 mCi). The devices are portable and are normally used to measure the density and moisture content of soil and building materials. The density is determined by measuring the amount of backscattered radiation from the gamma source, and the moisture content is derived from the gamma measurement and a measurement of the amount of backscattered neutron radiation.

The sources are small in size, typically a few mm long and a few cm in diameter, and located either completely within the device or at the end of a rod/handle assembly. The source holder devices usually consist of a heavy steel case, with the source loaded into the center, and neutron shielding, which may be polyethylene or some other kind of material with high hydrogen content. The device is of a simple shutter type, which is opened to reveal an aperture through which a beam of radiation is transmitted. In most cases, the neutron detector is contained within the same device as the source.

Moisture gauges are used in agriculture to ensure optimal watering (Fig. 35), while combination, or density gauges are often used in road construction to ensure that the appropriate compaction is achieved for the foundation materials (Fig. 36).

FIG. 35. A bulk material moisture measurement device.

FIG. 36. A portable $^{241}Am/Be^{137}Cs$ gauge.

Portable gauges are used in remote road construction sites. This, and their small size, makes them susceptible to loss of control or theft. Sometimes they are damaged by other road construction equipment and may be overlooked.

4.4.4. Bone densitometers

As their name implies, the bone densitometer sources were used in devices designed to measure bone density as part of an assessment of osteoporosis. The radionuclides used in these sources are primarily ^{109}Cd, ^{153}Gd, ^{125}I and ^{241}Am, ranging from about 1 to 50 GBq.

4.4.5. Static electricity eliminators

In many industries, the generation of static electricity during manufacture creates problems, resulting in the settling of dust particles on components, which can be a potential fire hazard. In order to minimize these problems, static eliminators, incorporating sources of ^{241}Am, ^{210}Po and ^{90}Sr, are used.

There are two main types of device: bars (Fig. 37) and guns (Fig. 38). Bar devices emit a ‘cloud’ of alpha particles to a distance of about 8 cm from the surface which ionize the surrounding gas (air) and allow any static charges on surrounding materials to be safely conducted to ground by slow discharge. Gun devices are used on pneumatic air lines, and the air passing through is ionized. The resulting stream of air can be used for blowing dust from objects and eliminating static charge on them which attracts dust. For bars, the foil is contained in a metal casing with a grill to allow free movement of ionized air, but protection to the foil; and for guns, the foil is contained within a tubular metal case which forms part of the air line and gun grip.

The devices vary in size from hand-held devices, a few centimetres in length, to fixed installations up to several metres long and a few centimetres wide (Fig. 37). The geometrical configuration of some of these devices is rather complicated in the sense that the radioactive source material is distributed on the surface of the structure. Since the static eliminators utilize the alpha particles emitted, the source assembly is fragile and cannot withstand physical abuse or fire, either of which can result in the spread of contamination.

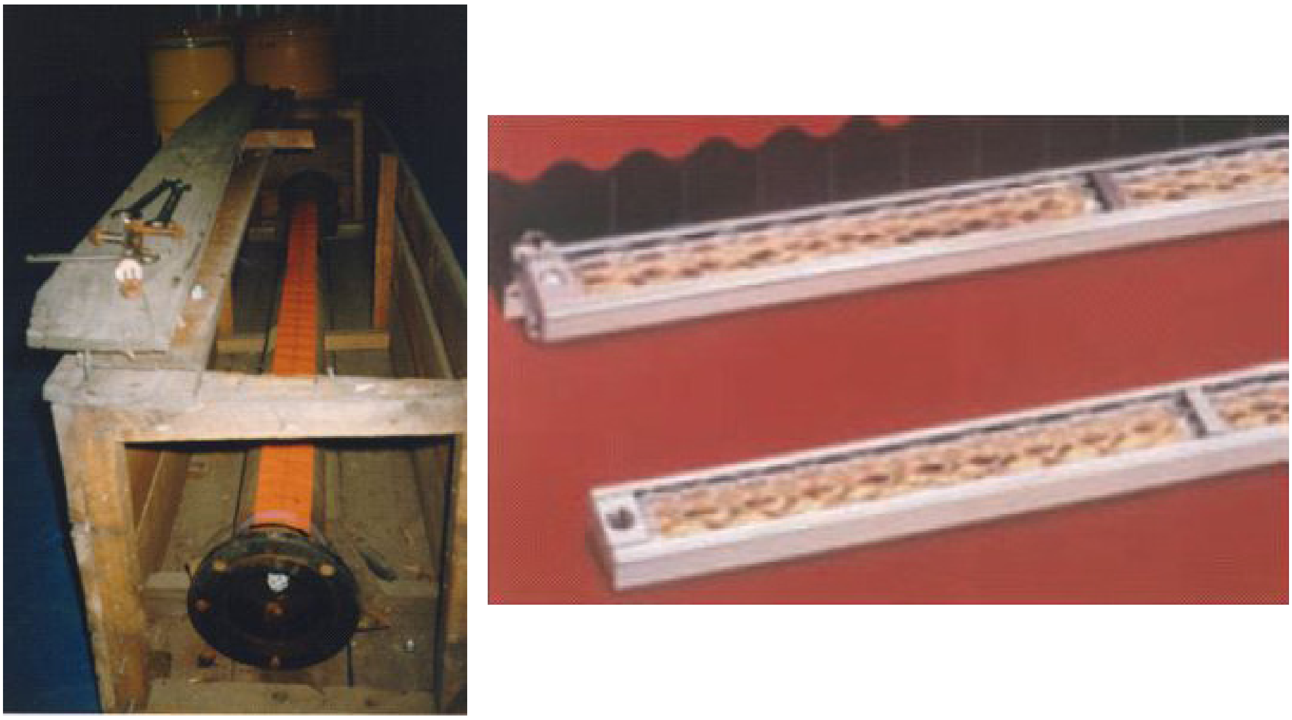


FIG. 37. Static eliminator bars.

FIG. 38. A typical static eliminator air gun.

4.5. DEVICES AND CATEGORY 5 SOURCES

There are a large number and variety of Category 5 sources that are used in: X ray fluorescence, electron capture devices, Mossbauer spectrometry, positron emission tomography tritium targets and smoke detectors (Figs 39 and 40). In addition, superficial treatment of skin and ophthalmic lesions is carried out using ^{90}Sr/^{90}Y sources.

Nasopharyngeal applicators (^{90}Sr) have replaced the ‘Crowe’ radium probe used in the 1970s. Permanent implants were also developed at that time, using ^{198}Au seeds. Today, permanent implants use ^{125}I, ^{106}Ru/Rh and ^{103}Pd.

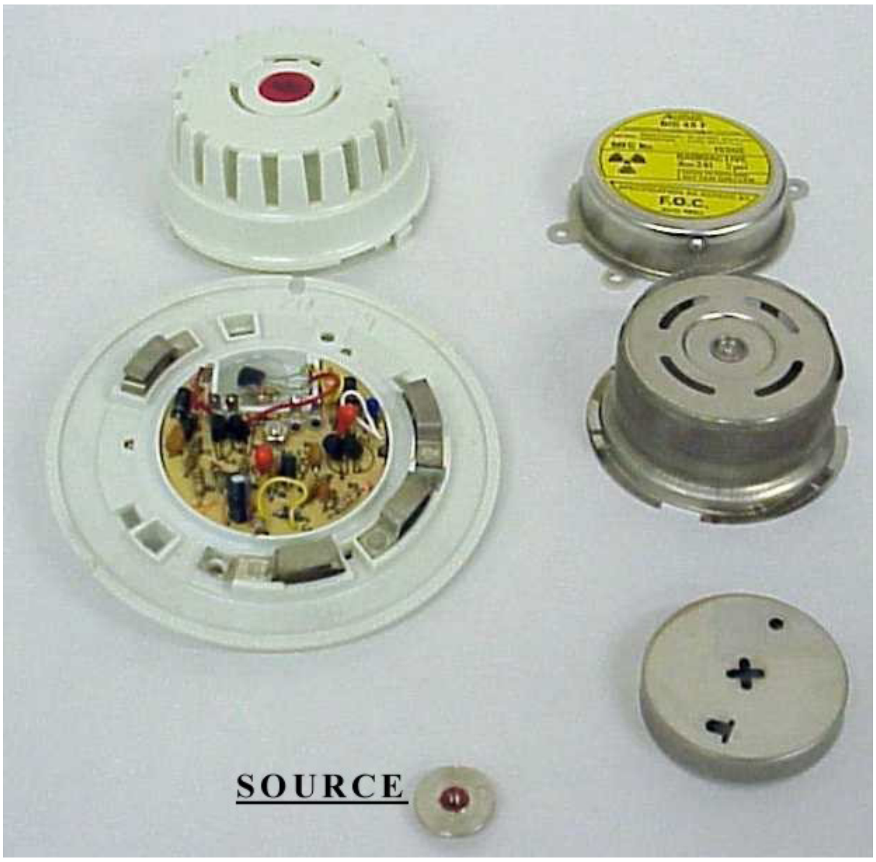


FIG. 39. A disassembled smoke detector.

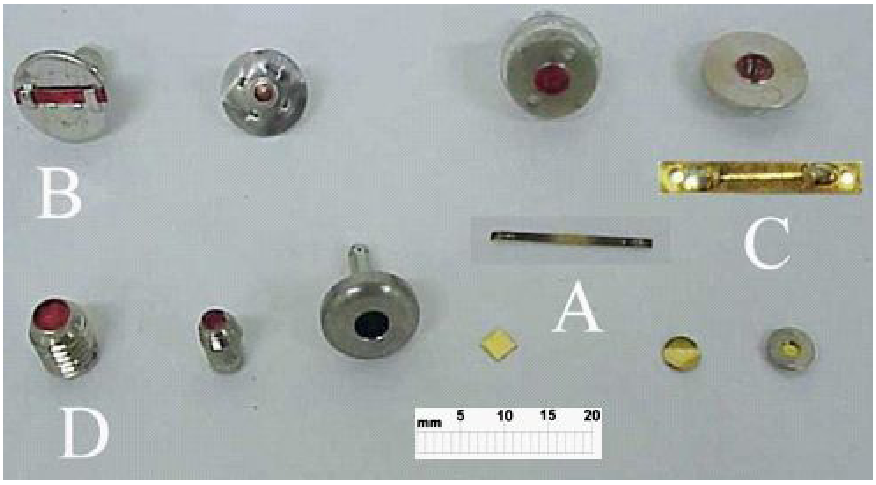


FIG. 40. Typical ^{241}Am radioactive sources used in smoke detectors.

Category 5 sources are of such a low hazard that they generally do not need to be considered in a national strategy. Loss of control of such sources is more of a regulatory and administrative issue than a radiation safety or radioactive source security problem.

4.6. SPECIFIC SITUATIONS

From the viewpoint of management, a particular problem is represented by legacy sources which were used prior to the establishment of appropriate regulatory requirements and are still in storage. The type of legacy sources depends on when regulatory controls came into effect in a Member State. The majority of legacy sources are likely to be radium, but not exclusively.

4.6.1. Lightning conductors

Radioactive lightning conductors (Fig. 41) were installed in many countries. The source radionuclide, such as ^{60}Co, ^{85}Kr, ^{152}Eu, ^{226}Ra or ^{241}Am, increases the effectiveness of the device by ionization of the surrounding air. Where ^{60}Co, ^{85}Kr or ^{152}Eu was used, the radioactive content was encapsulated and shielded to direct the radiation beam upwards. There is no contamination risk, but the dose rate at the top of the rod may reach several thousand mSv/h. Radium-226 or ^{241}Am is not encapsulated, but deposited on foils or mixed with ceramic. The dose rate is lower than 1 mSv/h, but contamination is consistently present. For these reasons, and because the effectiveness of the device was not sufficient, the use of the radioactive lightning rods (conductors) has been discontinued. Since 1986, however, the fabrication and sale of radioactive lightning conductors are forbidden in all the countries of the European Union.

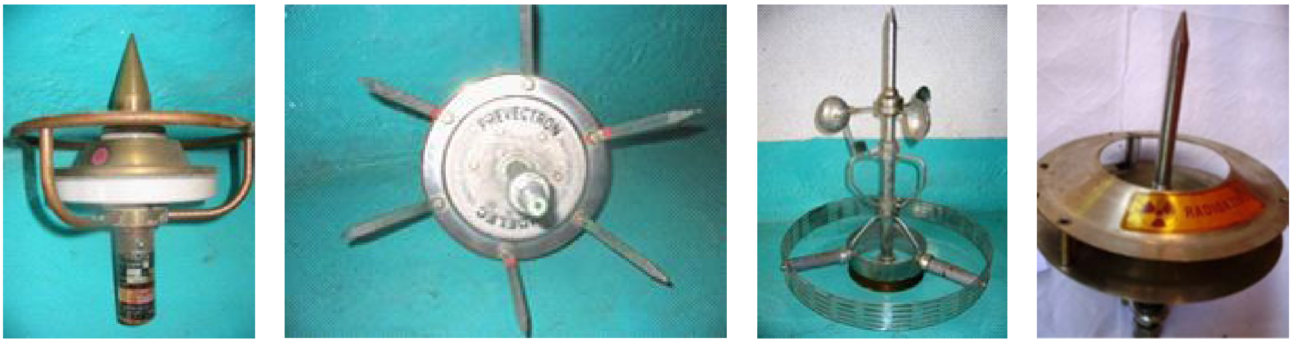


FIG. 41. ^{241}Am lightning conductors.

4.6.2. Research and academic uses

Because of a wide range of applications of radioactive sources in teaching and research, the sources used are briefly discussed here. Practically any radionuclide of any activity can find some application in research work, and therefore such sources can fall into any category.

Research irradiators are used to expose biological and non-biological materials to radiation of various types in order to evaluate the response of target materials to various doses, dose rates, and energies of the applied radiation source. Such units are used in a limited way in materials research and extensively in radiobiological research. They are used to evaluate electronics components and satellite components as well.

Radiobiological research involves either the exposure of bacterial, yeast or mammalian cells to graded doses of radiation in order to evaluate response or the exposure of whole animals or portions of live animals in order to evaluate the response versus dose. Biological exposure may also be a tool to enable other studies to be done, such as causing immunosuppression so that transplantation may be evaluated. Research irradiation has been done with two primary types of irradiators: beam units located in a shielded room and self-contained irradiators with built-in shielding. The beam units are similar to radiotherapy caesium or cobalt units, but are located in a shielded room in a research laboratory. They will deliver dose rates of 1 to 3 Gy/min at 50–80 cm distance. Self-contained units are housed in a dedicated room in a laboratory (see Fig. 42).

FIG. 42. Research irradiators from different manufacturers.

The most commonly used sources in research are, however, low activity and/or short half-life sources. Tritium (^{3}H) and ^{14}C sources are frequently used but they have weak beta emissions, thereby causing potentially less serious radiological hazard, especially when disused. Many such sources are used in electron capture, gas chromatograph, and Mössbauer spectrometry devices. Notable exceptions are the use of large (up to 1 PBq) ^{60}Co and ^{137}Cs sources for irradiation or sterilization. Although some irradiation facilities may be of a scale similar to an industrial one, most are of the fixed, self-shielded type that are designed to accept samples in the irradiation chamber.

Research work is often carried out as part of a student's thesis or under a specifically funded contract. Equipment, including radioactive sources, may have been obtained specifically for a particular project. When the work is completed or the funding runs out, there may be no immediate or further use for the sources, and the person responsible may leave. In many cases the sources are put into storage, but there might not be any clear 'owner' within the organization to take responsibility. So the principal problem with research or teaching sources arises when the equipment falls into disuse and knowledgeable staff leave.

4.6.3. Military uses

In most countries, military uses of radioactive sources are outside of conventional civilian regulatory control. For this and other reasons, the military uses of radioactive sources require separate consideration. The sources used in military applications can cover a wide range of categories. While many of the uses are similar to those found in medicine, industry and academia, there are some applications that are unique to the military, or use significantly larger activities than those found in comparable non-military, civilian devices. Examples of military applications include:

- Radioisotope thermoelectric generators;
- Sources for simulation training for a nuclear weapons attack;
- Technical material (thorium alloys) and gas lamps;
- Gas detectors;
- Tritium and ^{226}Ra in luminous devices (much larger activities than in civilian uses).

It is probable that the military, for security reasons, has a separate inventory from the normal national inventory. Therefore it will be necessary to directly consult military authorities to assess the situation.

4.7. MASS AND DIMENSIONS OF TYPICAL DEVICES

The mass and size of typical devices with SRSs are summarized in Table 5.

TABLE 5. MASS AND DIMENSIONS OF SOME TYPICAL DEVICES

Device	Category	Typical mass	Typical dimensions	Remarks
Industrial sterilization plant	1	n.a.	Building of 100 m × 200 m × 50 m	
Teletherapy machine	1	500–1000 kg	4 m length × 2 m width × 3 m height	
Blood irradiator	1	1500–3500 kg	1 m length × 1 m width × 1.5 m height	
Multibeam teletherapy machine (gamma knife)	1	20 000 kg	4–5 m length × 2 m width × 2.5 m height	Shielded device
Small scale sample irradiator	1	1000–6000 kg	1.5 m length × 1.5 m width × 2 m height	
Seed irradiator	1	Chamber (dismounted) 3000–6000 kg	1.5 m length × 1.5 m width × 2 m height	May be assembled on vehicles
Radioisotope thermoelectric generators	1	500–1000 kg	1.5 m length × 1.5 m width × 1.5 m height	Excluding pacemakers
Gamma oil well logging bull plug	2	500–1000 g	20–60 mm diameter × 100–150 mm length	
Neutron oil well logging bull plug	2	400–1000 g	20–60 mm diameter × 100–200 mm length	
Gamma radiography projector	2	8–35 kg	350 mm length × 200 mm width × 240 mm heigh	Used for Ir-192, Se-75 sources
Gamma radiography source changer	2	40 kg	250 mm length × 210 mm width × 340 mm height	Source changer
Gamma radiography projector (Co-60)	2	100–200 kg	900 mm length × 900 mm width × 900 mm height	Semiportable ^{60}Co device
Gamma radiography pipeline crawler	2	50–100 kg	800–1500 mm length × 400 mm width × 400 mm height	
High energy gamma density, thickness and level gauge	3	20–400 kg	200–400 mm diameter, 300–700 mm length	
Low energy gamma density, thickness and level gauge	3	20–50 kg	200–400 mm diameter, 300–700 mm length	
Beta density and thickness gauge	4	10–20 kg	100–300 mm length × 100–300 mm width × 100–300 mm height	
Bulk material moisture gauge	3	10–1000 kg	300–1000 mm length × 300–500 mm width × 300–500 mm height	
Soil moisture/density gauge	4	30 kg	200 mm length × 300 mm width × 1000 mm	
X ray fluorescence analyser	5	Hand held: 2 kg Laboratory and process control: 20–100 kg	Hand held: 200 mm length × 100 mm width × 100 mm height Laboratory and process control: 500 mm length × 500 mm width × 1500 mm height	
Brachytherapy machine	2	50–250 kg	300–600 mm length × 300–600 mm width × 800–1500 mm height	
Static eliminator	4	Bars: up to 2 kg Guns: up to 500 g	Bars: up to 2000 mm length × 30 mm width × 10 mm depth Guns: 30 mm diameter, 80 mm length	
Radioactive lightning conductor rod	5	2–10 kg	100–300 mm diameter, 500–1000 mm length	
Self-luminous sign	5	1–10 kg	Up to 600 mm length × up to 200 mm width × up to 100 mm depth	
Smoke detector	5	100–300 g	100–150 mm diameter, 15–30 mm height	

5. MANAGEMENT PRINCIPLES AND REQUIREMENTS

The preferred option for managing disused sealed sources is to recycle them for further use. If this is not possible, the preferred management option for disused sealed sources and always for spent sources is the return of the source to its supplier. If no further use is foreseen and it cannot be otherwise removed from regulatory control, the only sustainable long term option is disposal. As such, disused sources for which no recycling or repatriation options exist should be declared as radioactive waste and should be managed as such, in compliance with relevant international legal instruments, safety standards, and good practices.

The IAEA has issued a number of publications related to the responsibilities for safety within a legal and governmental infrastructure for ensuring the safety of sources in its Member States:

- The Safety Fundamentals publication entitled Fundamental Safety Principles [28] sets out the objectives, concepts and principles of protection and safety and provides the basis for the IAEA Safety Requirements, including the responsibility of the government to establish a legal framework for safety in order to provide for the regulatory control of activities involving radiation sources.
- GSR Part 3, the BSS [11], place requirements on responsible parties, particularly registrants, licensees and employers, to put in place a system of control for radiation sources to ensure their safety.
- GSR Part 1, Governmental, Legal and Regulatory Framework for Safety [29] sets out the essential aspects of the governmental and legal framework for establishing a regulatory body and for taking other actions necessary to ensure the effective regulatory control.
- The Code of Conduct [14] provides guiding principles for Member States to achieve and maintain a high level of safety and security of radioactive sources. An important element of the Code of Conduct is for Member States to ensure that arrangements are made for the safe management and secure protection of radioactive sources once they have become disused.
- The Safety Guide on the Safety of Radiation Generators and Sealed Radioactive Sources [30] provides guidance on responsibilities for safety within the legal and governmental infrastructure, on methodologies for performing safety assessments and on specific design and operational measures that should be taken to ensure safety throughout the lifetime of a radiation source.
- The Safety Guide on Regulatory Control of Radioactive Sources [31] provides guidance for the implementation of a national regulatory infrastructure necessary to achieve an appropriate level of protection and safety for radiation sources in medicine, industry, agriculture, research and education.

As follows from the above mentioned Safety Standards and Guides, the following elements of the national system need to be in place to ensure the safe management of disused radioactive sources:

- A rational set of safety, radiological and environmental protection objectives from which standards and criteria may be derived within the regulatory control system;
- Identification of all parties involved in the various steps of the management of disused sources and specification of their responsibilities;
- Identification of existing and anticipated disused sources (national register);
- Resources (financing, technical capability, staffing, personnel qualification and training);
- Management system;
- Public information.

5.1. REGULATORY CONTROL

Regardless of the type of the process involved, the management of disused sources needs to be carried out in accordance with the national regulatory and licensing framework and in compliance with international recommendations. It is important that the Member States develop appropriate regulatory measures for handling, conditioning, transportation, storage and disposal practices on the national level. All these practices usually require operating licenses, which define the scope of the operations, radioactive material possession limits and any specific conditions that are to be observed [32]. The legal requirements for records keeping need to be identified, as part of a management system, which itself may be part of the license requirements.

Most countries have some legislation and regulations in place, governing radiation protection and safety of radioactive sources. There is no specific legislation that deals with the management of disused sources; however, it is generally included in radiation protection or waste management legislation. If it is determined that new or additional legislation is needed, a note of caution is required to minimize overlapping or conflicting requirements for radiation protection and safety.

Not all the general requirements may be necessary or appropriate under specific circumstances. A Member State needs to decide to what extent the requirements are applicable in a particular situation. Furthermore, the organizations involved may exist under a different structure or may have a different name. In order to ensure compliance, it is important to differentiate between the regulatory nature of the work and the operational aspects.

Regulatory control of sources throughout their life cycle will ensure continuity of control when sources cease to be used and become potentially more vulnerable to loss. Information collected as part of the regulatory scheme may also be of use in forecasting the numbers and types of sources no longer in use, thereby identifying the future requirements of the disposal management scheme.

5.2. RESPONSIBILITIES

A fundamental concept in the legislation is that prime responsibility for radiation safety resides with those authorized to possess and to use, manufacture, supply or install radiation sources. "The prime responsibility for safety shall be assigned to the operator" (Ref. [31], para. 2.3).

Authorization by licensing is required by the regulatory body for all practices, other than those to which an exemption applies, that are not otherwise designated as suitable for notification alone or registration [11]. In all cases the operators using a sealed source are, as a minimum, required to submit in support of notification and for application for authorization the information described in requirements 3.32 and 3.33 of GS-R-1 [29]. Most Member States have systems in place that date back to the time prior to the purchase of the sources, currently in use. This means that all sources in current use are likely to be covered by a license.

Sealed sources have a life cycle, beginning with manufacture and ending in disposal. Each source life cycle comprises a number of sequential steps, which are illustrated in Fig. 43. A source life cycle can involve a series of individuals in various organizations, such as regulatory body, source manufacturer, device manufacturer, distributor, user(s) (one or subsequent users), waste processing organization, and operator of a storage and/or disposal facility. The potential involvement of a large number of organizations and their interactions mean that source life cycles are indeed complex and often difficult to establish.

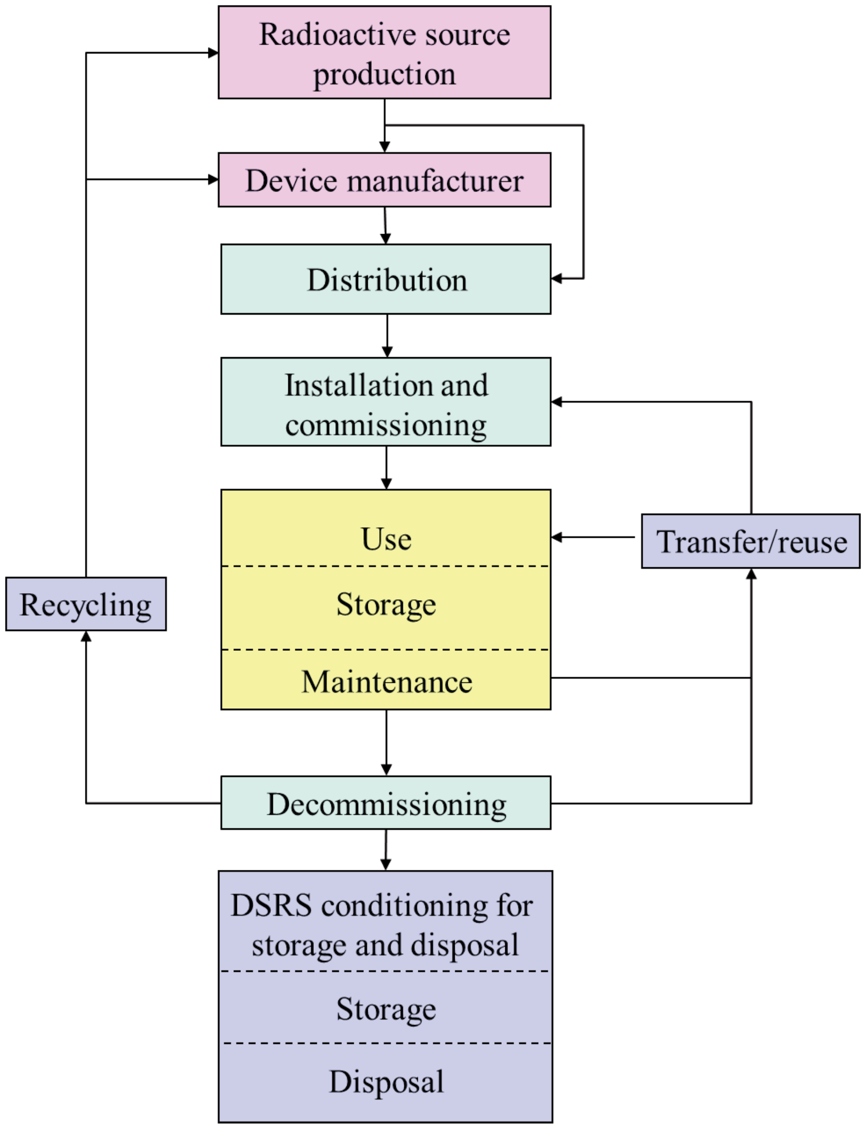


FIG. 43. The life cycle of a radioactive source.

The key issue during the entire life cycle of a SRS is the protection of individuals or groups from inadvertent radiation exposure and minimization of risk from malevolent use of sources.

5.2.1. Source manufacturer

A *source manufacturer* usually accepts ownership of the radioactive material at the time of delivery from the radioisotope production facility. The source manufacturer is then legally responsible for the safe handling of the radioactive material in his possession and for the subsequent transfer of ownership.

The source manufacturer is required to supply to the user and regulatory body a source certificate that contains comprehensive information about the source, such as model and serial number, radionuclide, activity, date of calibration, capsule type, special form certificate number and manufacturer information. This information is critical in demonstrating source specific information for compliance with the requirements for the management of sources when they become disused.

5.2.2. Device/equipment manufacturer

A *device/equipment manufacturer* provides the equipment into which a source is loaded, either before shipment to the user's site or after installation.

The device manufacturer is required to meet national and international standards for the safety of the equipment, including the design approval from the relevant regulatory authority. In addition, the equipment manufacturer is required by regulations to provide to the user all information needed to safely and properly operate and maintain the equipment. This includes all relevant information about the source and source transportation procedures, including the means of securing the source in a safe condition, interlocks, and emergency preparedness.

For high activity radioactive sources, such as teletherapy machines, the equipment manufacturer is required to provide technical services related to the periodic reloading of radioactive sources.

5.2.3. Distributor

A *distributor* authorized by the regulatory body is responsible for carrying out some transport and supply operations in accordance with international laws that pertain to transportation of radioactive materials. These responsibilities could include verifying that the consignee is an authorized person or entity to possess radioactive material in accordance with national regulations and applicable notification requirements.

The source manufacturer/equipment manufacturer (who may, depending on the terms of delivery, continue ownership of the source during transportation) and the distributor have shared responsibilities during transportation and supply operations.

5.2.4. User

A *user* usually accepts ownership of the source material at the time of delivery from the distributor. Users (registrants and licensees) are responsible for setting up and implementing the technical and organizational measures that are needed to ensure the security and safety of the sources. The user is legally responsible for the safe handling of the radioactive material under all applicable laws and licenses, and for its subsequent transfer of ownership. License conditions typically require the user to securely retain a copy of the source certificate information provided by the source manufacturer. Although not usually required by a license, the user needs to retain all technical information about the equipment provided by the equipment manufacturer.

When the source becomes disused, after short on-site storage, the source will be transferred to another place where its long term storage or disposal can be ensured. Then ownership is transferred to another party, such as a source manufacturer or a central radioactive waste management organization (CRWMO). In the event that the user stores the source prior to a formal transfer of ownership (temporary storage), the responsibility for the safety and security issues during interim storage of the source lies with the user.

5.2.5. Central radioactive waste management organization

A CRWMO provides handling, conditioning and storage of disused sources from various applications in the country. It is legally responsible for the safe and secure conditioning and storage of the sources under its ownership, and typically operates under license conditions established by a regulatory body. This responsibility ends when the source has decayed sufficiently to be disposed of as non-hazardous material, or until the source is legally transferred to another organization, such as a disposal facility. As a requirement of its license, a CRWMO maintains an up to date inventory of all sources in its possession, including all specific details provided by the source manufacturer.

In the event that a licensee is incapable of managing disused sources, or the license is revoked, or the licensee no longer exists, the CRWMO may become responsible for the overall management of the disused sources, if requested by the regulatory body.

In large countries, instead of one CRWMO, there could be several regional operating organizations with the same functions.

5.2.6. Disposal facility

A waste *disposal facility* is legally responsible for all radioactive waste including DSRSs accepted for disposal. In most countries this is a centralized facility providing services for the disposition of DSRSs received from all users in the country. The disposal facility may carry out some conditioning and associated operations on the site, in this case its operating license should cover also these activities and facilities if any.

5.3. REGISTRY OF SEALED RADIOACTIVE SOURCES

A specific concern in DSRS management is to ensure that sealed sources are properly controlled after they are no longer in use. This requires tracking of a source during its entire life cycle, commitments for its disposition are made prior to its import, and that a plan is established and implemented for the safe management of the source after it is declared disused.

The Code of Conduct [13] calls national regulatory bodies for establishing and maintaining a *national register* of certain SRSs. This register should, as it is stated in para. 11 of the Code of Conduct, as a minimum, include Category 1 and 2 radioactive sources. For the purpose of facilitating exchange of information on radioactive sources among the Member States, it is important that Member States endeavor to harmonize the formats of their registers.

A *registry system for tracking all sources in the users' possession* needs to be established by the licensee and be consistent with the national registry system. The system should be designed to allow data to be readily accessible and retrievable, as well as secure. An acceptable registry system can range from a manual system (such as card files) to a computerized database. The licensee is required to notify the regulatory body of any significant changes in the information in the records-keeping system. The licensee should ensure that there is a procedure for communicating routinely to the regulatory body details of the source status and the reporting information required.

A source registry system, at a minimum, is required to contain the following information [30]:

(a) Serial number or unique identifier;
(b) Manufacturer's type number and reference to where construction details can be found;
(c) Radionuclide (elemental symbol and isotopic number);
(d) Activity on a specified date;
(e) Physical form;
(f) Physical and chemical properties, including the principal emissions (alpha, beta, gamma, n);
(g) Location of the source;
(h) Where not otherwise evident from the foregoing records, details of the device or equipment with which the source is used, if essential for safety;
(i) When appropriate, a source use history (e.g. a log of source handling operations);
(j) Details of receipt or transfer or disposal of the source.

5.4. DECLARING SOURCES AS DISUSED

There are several factors that may lead to radioactive sources becoming disused. Some main reasons for a source to be considered as disused or spent are discussed in more detail below.

5.4.1. Activity decay

For all SRSs, there is a minimum activity below which the source is no longer useful for its specified purpose and thus, considered as spent (disused). In most applications, the source needs to be replaced when the initial activity has decreased by a factor depending on the particular application. Industrial radiography sources containing ^{192}Ir, which has a half-life of only 74 days, are generally considered spent in two to three months after purchase because of radioactive decay, while ^{60}Co sources used for either industrial radiography or teletherapy need to be replaced every 5–10 years. The working life of ^{60}Co sources produced for industrial irradiators can be 15–20 years. These sources usually remain in use until their activity decreases to 10–15% or the original value. Although the spent sources may not be useful for original purpose they can be still highly radioactive, posing a potential radiation hazard to people and the environment, even after several half-lives have elapsed.

5.4.2. Leakage or damage

Leaking or physically damaged (e.g. bent, corroded, cracked or badly scratched) sources are considered as disused, immediately taken out of service, and subsequently managed as radioactive waste.

5.4.3. Obsolete equipment

All equipment (devices) will eventually reach the end of its useful life. While the source may still be of adequate strength, the equipment may no longer be serviceable (e.g. moisture/density gauge with obsolete electronics). A source associated with obsolete equipment is considered as a disused radioactive source.

5.4.4. Alternative technology

An SRS is usually made for a specific function. The function may be to treat a tumour, assess the quality of a weld, control industrial processes, or sterilize medical disposables. The source provides the ionizing radiation required by the process. Even if the source still provides the required radiation output, the process may be taken out of use because alternative procedures to achieve the desired results have been developed. Wherever possible, both users and manufacturers are moving towards technologies which do not require radioactive sources, e.g.:

— Replacement of ^{241}Am in ionization smoke detectors with optical devices;
— Move to X ray detectors in process control applications, especially those requiring ^{241}Am and ^{244}Cm;
— Ultrasonic methods of density and level gauging in place of ^{137}Cs;
— Linear accelerators in place of ^{60}Co teletherapy.

The alternative procedure might possibly use a different type of source that is easier to work with or manage as waste at the end of its life cycle[4]. The alternative technique may also use a more stable chemical compound[5], a lower level of radiation, radiation or particle generators or accelerators (X ray machine or linear accelerator) instead of radioactive material, or may involve a technique not using ionizing radiation at all.

5.4.5. Changes in priorities

A sealed source is considered disused if the experiment or programme using a specific source is completed or terminated. Some companies or organizations may change their field of work or terminate their research programmes, resulting in sources that are no longer needed. These sources are considered as disused sources, with their ownership subsequently transferred to an authorized organization for possible reuse, conditioning, storage, or disposal.

5.4.6. Orphan sources

An orphan source is a radioactive source which is not under regulatory control, either because it has never been under regulatory control or because it has been abandoned, lost, misplaced, stolen or otherwise transferred without proper authorization [1, 14]. Orphan sources can lead to serious consequences to public health and the environment. An immediate action (e.g. notification, search) is required. When a source is found, it needs to be checked and leak tested before being further managed. In addition, sources recovered by a third party and identified as being radioactive but not traceable to the authorized holder are considered disused sources.

5.5. FINANCING

The principal parties[6] should ensure that: "Financial provisions in accordance with the regulatory requirements for the safe management of disused sources are in place" [32]. A Member State needs to ensure that a waste management practice or facility is appropriately funded and a financing mechanism is established.

Since disposal of DSRSs is likely to take place several decades (or more) in the future (possibly after the generators of the disused sources have gone out of business), it is prudent to collect the financial resources that will

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[4] For example, ^{137}Cs instead of ^{226}Ra for radiotherapy and ^{192}Ir instead of ^{137}Cs for industrial radiography.

[5] For example, glass or ceramic form of ^{137}Cs instead of CsCl.

[6] The BSS [11] state that: "The principal parties having the main responsibilities for the application of the Standards shall be: (a) registrants or licensees; and (b) employers."

be needed for future operations while the users are still in business. Member States use various financial systems to ensure the long term availability of financial resources for decommissioning and disposal. Funds and reserves are the two most common financing mechanisms. The financial resources are usually maintained by organizations independent of the waste generators. In some countries, the financing of radioactive waste management is warranted by the national budget.

5.5.1. Distribution of costs

All parties who own radioactive material during the process of manufacturing, transportation, application, conditioning and storage of sources typically transfer ownership of the material to another party. The final users of the source will normally incur the disused source management costs, which may be quite significant, especially in the case of high activity sources (Category 1 and 2) and sources containing long lived radionuclides. The cost of transport containers and the costs of transportation itself are also passed on to the user as the costs of sources and source replacements. These expenses, which are necessary to meet legal and safety requirements, become additional costs to the user. However, the Member State is required to provide public funds, in case of orphan sources, where ownership information is lost, or where public safety considerations are paramount. In the event that a facility owner becomes insolvent, or a facility is closed due to abandonment, war, natural disaster etc., the assumed method of financing source ownership transfer may no longer be possible. Insurance or emergency funds from public agencies may be available to assist in these circumstances; otherwise, costs of ownership transfer will need to be undertaken by other institutions that may not have participated in the benefits for which the source was purchased. Eventually, the material will reside with the CRWMO, where it will either decay to a safe level or be held pending transfer to a disposal facility.

The costs of ownership and transfer of radioactive material during the manufacture and replacement of a sealed source are reflected in the purchasing price for the original and replacement sources, as this is usually the means by which the manufacturer recovers its costs.

When a source is replaced, the manufacturer usually takes the spent source back as part of the transaction. However, when the facility is eventually decommissioned, the ownership and transfer of the final source in the equipment must be handled as part of the cost to the user associated with return of the facility to general use. In essence, the total ownership and transfer costs are part of the total cost to the user for providing the service for which the source was purchased. For high activity sources, these services include industrial radiography, material irradiation, sterilization and cancer therapy.

5.5.2. Cost uncertainty

Both the user and the source manufacturer incur licensing costs and operating costs as part of the regulatory requirements. Regulatory bodies issue licenses to facilities managing radioactive materials and perform inspections, and at least some of the costs of these activities are passed on to the licensee as licensing fees. Regulatory license costs for the irradiation facility and for the source manufacturer are typically built into the price of the source(s) as delivered to the user, and the user’s costs become an operating expense borne during the time of use of the source. Cost of licensing of transport packages and the costs of transportation are also passed to the user in the costs of sources and source replacements. These expenses, which are necessary to meet legal and safety requirements, become additional costs to the user.

Handling, conditioning and storage costs are usually set by the CRWMO at a realistic level to avoid compromising safety measures. Excessive costs might cause operators to act inappropriately by illegally abandoning or disposing of sources. The exact costs for conditioning and storage for SRSs cannot be precisely established, but they can be estimated. Sufficient funds for the construction and operation of conditioning and storage facilities are a prerequisite for the safe management of disused sources. Additional costs for any reconditioning of sources needs to be considered as well. The cost of long term storage, awaiting disposal, and the cost of disposal are essential components of any costing study.

5.5.3. Unavailability of an ownership transfer path

At the time of decommissioning of the equipment, the original source manufacturer or distributor might not be in business, or might be unable to retrieve the source due to the age or condition of the equipment or changes in applicable regulations. If transportation to the CRWMO is not feasible, then the user will need to store the source safely and securely until a suitable option is available. Although this is not likely to be a high cost on an annual basis, the extension of storage will involve labor and maintenance costs. The storage time could exceed the ability of the facility to reliably ensure safe and secure storage, and could in fact exceed the operational life of the facility. A new (different) authorization (license) for the storage of a DSRS should be requested to and approved by the regulatory body. In these situations, the cost of source ownership and transfer is deferred by temporary storage, but not solved.

5.6. TECHNICAL CAPABILITY

Appropriate technical capability needs to be developed and maintained at every site where sources are operated or managed as disused sources. This capability includes the facility itself, appropriate equipment, and technical competence of the personnel. Acquisition and operation of facilities and equipment need to be commensurate with the available technical capability to facilitate effective and safe operation. The management of disused sources is required both at the user's site and at the central waste management organization where the sealed sources are processed and stored, awaiting final disposal.

5.6.1. User's site

Each user needs technical capability to collect, handle, characterize, segregate and safely store during short term the sources in his possession. The user may not need to be aware of details of how the disused source will be subsequently managed, if the job of conditioning and storage is left to the operators of the centralized conditioning and storage facilities. However, the user should be informed about the subsequent steps of the source management in order to appreciate the need to appropriately segregate or classify the sources during collection. This is also important to eliminate the possibility of the user processing the source in any way that makes future waste management procedures more complicated, more expensive or resulting in additional undue risks.

5.6.2. CRWMO

Since the most advanced technical operations (conditioning and storage) are carried out at the CRWMO, it should be provided with all necessary equipment, tools and instruments depending on the tasks assigned to the CRWMO and the characteristics of the disused sources accepted for processing. Requirements for technical equipment and some examples used at a CRWMO are provided in the following Sections 7–10.

5.6.3. Disposal facility

A disposal facility accepts the DSRS for disposal, and in order to implement this function must be equipped with proper handling and lifting equipment. The design of a disposal facility may include different engineered barriers. Certain measures need to be taken to support the properties of the engineered barriers according to the design intention. In case of institutional control its sustainability must be ensured. The design requirements for a disposal facility are described in Section 12.

5.7. PERSONNEL TRAINING

The handling and conditioning processes require skilled personnel with an appropriate of technical knowledge and practical experience, self-discipline, and responsibility for executing high quality work. Understanding of the design, construction and mounting of the source in the device and the design and function of the device itself are also important considerations. This is particularly true when the removal of a source from the device is attempted. As this work often involves a high level of manual activity, it is important that personnel involved are physically fit.

It is not possible to prescribe the number and skill type of persons needed in various management operations with DSRSs. The IAEA general recommendations for personnel qualifications recommended for radiological work such as conditioning tasks [15] are outlined in Table 6.

TABLE 6. PERSONNEL QUALIFICATION AND EXPERIENCE [15]

Personnel	Qualification/experience[a]
Operations manager	A person with adequate technical education, experienced in DSRS management
Radiation protection officer/supervisor	Experience in radiological protection procedures and regulations[b]
Task manager	Experience in the selected conditioning methods, operations conditioning and quality control[c]
Skilled operator	Practical experience with the handling of radioactive material[c]

[a] Training programmes should be provided as required.

[b] Radiation protection personnel should have experience in working with SRSs of the types and activities to be conditioned. If possible, specific experience on the devices from which sources are to be removed is desired, but at a minimum experience with similar sources and devices is required.

[c] Operators who will be removing sources from equipment shall have training and experience on all tools and equipment to be removed, and when at all possible, hands on experience on the specific devices from which sources will be removed. This is particularly important when conditioning of high activity sources is planned, or removal of sources installed in gauges, instruments or other devices. If experienced operators, source removal instructions, or other specific technical experience is not available, individual qualifications to perform the work should be withheld.

Unlike general radiation protection activities, source handling involves higher activities of radioactive material and concentrations of this material in configurations that offer the potential for high exposures and serious dispersion of radioactive material in the event of an inappropriate or unplanned act. These concerns must be evaluated when designating workers as qualified for performance of these activities.

Training of operators and radiation protection personnel on handling and conditioning of sources should be specific to individual types of devices to be handled and sources to be conditioned, and when possible, work shall be supported by the document defining the steps and techniques for removing the source, if needed. Preferably this document will come from the device manufacturer; however, use of documents generated by personnel experienced in the performance of the work is a reasonable alternative. The training and experience should be sufficient that the individuals performing the work recognize types and degrees of radiological hazards presented with each performance step; differences between devices produced by different manufacturers for the same purpose, and actions to take in the event of a problem or anomaly in performance of the work. If security personnel are required (e.g. during storage), they need to be given basic radiation protection training and familiarization with emergency procedures on a regular basis.

The regulatory body does not usually have the responsibility to act as operator of a waste management facility; however, the regulators are required to have the necessary knowledge and experience to administer laws and regulations and provide clear guidance and direction to the operators of waste management facilities.

5.8. MANAGEMENT SYSTEM

Principle 3 in the Fundamental Safety Principles [28] requires that “Effective leadership and management for safety must be established and sustained in organizations concerned with, and facilities and activities that give rise to, radiation risks. Safety has to be achieved and maintained by means of an effective management system”[7]. The management system is the set of interrelated or interacting elements that establishes policies and objectives and that enables those objectives to be achieved in a safe, efficient and effective way. This system has to integrate all elements of management so that requirements for safety are established and applied coherently with other requirements, including those for human performance, quality, security, economical requirements and so that safety is not compromised by other requirements or demands. The management system also has to ensure the promotion of a safety culture, the regular assessment of safety performance and the application of lessons learned from experience. It shall be aligned with and enable the achievement of the goals of the organization.

General requirements for the management system are established in the Safety Requirements on The Management System for Facilities and Activities [32] and the recommendations in the accompanying Safety Guide on the Application of the Management System for Facilities and Activities [33], which supersedes the earlier Code on Quality Assurance [34]. Guidance on the application of the management system for the processing, handling and storage of radioactive waste is presented in Ref. [35]. Separately, guidance on the application of the management system for the disposal of radioactive waste is provided in Ref. [36]. The basic requirements for radiation protection are established in Ref. [11] and the requirements for emergency preparedness and response in Ref. [37].

5.8.1. Management system challenges

Managing DSRSs involves a variety of technical and managerial activities and may extend over a very long period of time. These characteristics present a series of challenges to the development and implementation of effective management systems. The following aspects warrant particular consideration in developing a management system for DSRSs:

(a) The provision of funds and the organizational arrangements to manage DSRSs could be given inadequate attention if they were to become decoupled from the benefits drawn from the activity that generates them. The organization and funding of the necessary DSRS management activities could be much more difficult to put into place later.
(b) DSRSs can be managed safely on an interim basis, in many cases for extended periods. As a consequence, the selection and implementation of definitive solutions may be postponed by a series of short term deferrals for additional assessment of the options.
(c) If final disposal for the DSRS has not been selected, it may be difficult to define the preferable form of the DSRS package to be produced and held during storage, and the acceptable form of the packages for final disposal. In such a situation, the selection of conditioning methods should balance two concerns. First, the foreclosure of future disposal options (e.g. by choosing to produce an interim package that is both unsuitable for disposal and difficult to convert to a final package that is suitable for disposal) should be avoided. Second, uncertainty about the end point should not be used as a rationale for not taking steps to ensure that the DSRS is managed in a safe and environmentally acceptable manner pending disposal.

Management systems for DSRS activities should encourage the adoption of unified approaches and solutions and international best practices because of the need to ensure continuity between successive human generations, and the uncertainty in the long term of organizational, national and international structures.

5.8.2. Management system procedures

The management system should cover all activities to be carried out for the purposes of DSRS management, irrespective of whether they are individual or composite activities [33]. The management system should provide assurance that the activity (e.g. conditioning) or the product (e.g. the DSRS package) will comply with all applicable requirements, respecting the safety principles. The management system should include measures to be taken in the event that non-conforming DSRS packages are produced.

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[7] At present, the term ‘management system’ is used instead of ‘quality assurance’. The term management system reflects and includes the evolution in the approach from the initial concept of ‘quality control’ (controlling the quality of products) through ‘quality assurance’ (the system to ensure the quality of products) to ‘quality management’ (the system to manage quality).

Management system procedures that should be established and applied include:

(a) Grading;
(b) Documentation and record keeping;
(c) Developing and controlling processes;
(d) Inspection and testing;
(e) Purchasing;
(f) Non-conformance actions and corrective actions;
(g) Management system review.

5.8.3. Graded approach

Organizations involved in DSRS management should identify the relative importance of the various activities, facilities, equipment and DSRS packages in meeting the overall safety, health, environmental, security, quality and economic requirements, with safety and environmental protection being of primary importance. The application of management system requirements shall be graded to deploy resources at appropriate levels, based on:

— The significance and complexity of each product or activity;
— The hazards and the potential impact (risk) associated with each product and activity on safety, health, environment, security, quality and economic elements;
— The consequences of product failure or if an activity is carried out incorrectly.

Grading is intended to guide the degree of control applied to an item in relation to the importance of its required function. It should not be used as a justification for not applying all of the necessary management system elements or required quality controls. Grading means making the stringency of the controls by which the adequacy of such activities is evaluated commensurate with the importance of the activities.

5.8.4. Records management

The DSRS management activities vary in size and complexity, may involve a number of organizations, and may continue over extended periods (e.g. storage awaiting disposal). Particular attention should be paid to ensuring that documents used to control work processes remain relevant, current, understandable and available to the diverse organizations and in the situations in which they are and will be used.

Complete records for all stages of source management are essential for future reference. These records include the information on the origin and characteristics of the source, technical procedures applied, designs of capsules, shielding, containers, packaging and overpacking, and data on the storage location and storage conditions, including assessment, inspection and verifications relating to all activities. All of these data will be required later to support subsequent decisions whether to directly dispose of the conditioned sources or to recondition them in order to comply with the prevailing waste acceptance criteria for the disposal facility.

The responsible authorities, source users, and operators of waste management facilities are required to establish and maintain documentation and records consistent with legal and management requirements and their own needs. These records need to be kept in a condition that will enable them to be retrieved later by individuals different from the personnel involved initially in the operations, and possibly without reference to those who generated the records. Requirements for records retention include, but are not limited to:

— Designation of the records as permanent or temporary;
— Storage of temporary records for a specified length of time;
— Storage of permanent records in perpetuity;
— Designation of the method of records storage;
— Retrievability of the records;
— Security systems and processes sufficient to preclude unauthorized removal or modification of records.

Well kept hard copies, microfiche, optical and/or magnetic media are possible options for the preservation of relevant data. At least two media and two record keeping locations are essential for diversity and reliability. Records need to be updated and transferred as the recording technology evolves.

Records of the sources need to be included with the details of the conditioning process for each package. The data recorded should include a description of the conditioning procedure used and the names of the team members who carried out the operation. Any old records found subsequent to conditioning need to be added to the information on each waste package. Photographic records may prove to be valuable when reviewing documentation for disposal planning.

5.8.5. Developing and controlling processes

The management system should be formalized to assure that DSRS management facilities are designed, constructed, and operated safely in accordance with specified requirements; received DSRS packages are produced in the same consistent manner; that waste acceptance requirements for transportation, storage and disposal are met; and that all regulations and conditions of the license are satisfied.

The management should acknowledge that all activities are processes that can be planned, performed, assessed and improved, while acknowledging that each individual performing these activities is responsible for quality.

Control of the performance of DSRS management facilities includes such elements as design control and verification, peer review, data collection and software control, DSRS package specifications, and control of procured goods and services. Management features for performance also assesses:

— Personnel performance and qualification, and acceptance of items and services;
— Control of work processes, including the interfaces between generation, recovery, processing, storage, and disposal of DSRSs;
— Storage, handling, and shipping operations to prevent accidents, container deterioration and ensure the validity of analytical operations;
— Control of DSRS packages and operational status, including non-conforming packages and substandard operational equipment;
— Identification and control of items important to safety, including acceptance inspection and testing;
— Inspection hold points, surveillance and process monitoring;
— Identification of critical areas for inspection;
— Measuring and test equipment control.

5.9. EMERGENCY PREPAREDNESS AND RESPONSE

If there is a potential for accidents that may cause unplanned exposure of any person (handled sources may drop free from their shields or begin to leak radioactive material during operations), the operator should ensure that an emergency plan appropriate for the source inventory and its associated risks is prepared, operational, and kept updated. The emergency plan is required to define on-site responsibilities and take account of off-site responsibilities of other relevant organizations involved in the implementation of the emergency plan.

Member States also need to provide for emergency planning and preparedness and make such provisions as might be necessary to respond to an accident [37–39]. In some cases, existing emergency response capabilities in the country are reasonably well suited to respond at an appropriate level (i.e. communication, fire protection, traffic control, ambulance and medical services). It is the responsibility of the operators and the regulatory body to inform the local authorities and emergency response personnel of any new activity in their area. They are then aware of the new installation and can assess the equipment and services provided. The Member State may consider providing additional funding to local emergency response organizations in order to address any additional needs that may arise. Review of contingency and emergency plans is a critical part of the planning for work with sealed sources involving source handling.

5.10. SECURITY OF RADIOACTIVE SOURCES

Security of a source refers to measures aimed at preventing unauthorized access or damage to, and loss, theft or unauthorized transfer of, radioactive sources [14]. Source security is essential and an important element to ensure source safety. However, a radioactive source can be secured, i.e. kept under control and physically protected, but this does not necessarily mean that the source is also safe and will not harm people.

The IAEA Nuclear Security Series Recommendations No. 14 on Radioactive Material and Associated Facilities [40], its Implementing Guide No. 11 on Security of Radioactive Sources [25], and the BSS [11] have established the radioactive source security requirements that supplement the broad radiation safety requirements applied to any source. The BSS require, inter alia, that radioactive sources be kept secure so as to prevent theft or damage by ensuring that control of source is not lost, a source will not be transferred unless the receiver possesses a valid authorization and a periodic inventory of mobile sources be conducted at appropriate intervals to confirm that they are in their authorized locations and are secure.

Responding to the global threat, the IAEA recently renewed its strategy and expanded its activities related to radioactive source security. This renewed strategy calls for creation and strengthening of national regulatory infrastructures in order to ensure that significant radioactive sources are localized, registered, secured and controlled during the entire life cycle of the source.

With regard to the security of radioactive sources, it is recognized that there is a necessary balance between managing sources safely and securely, as well as contributing to their beneficial use. Thus, the security level needs to be commensurate with the threat level and with the risk associated with unauthorized acquisition of the source.

A complete programme aimed at addressing the malevolent use of radioactive sources needs to consider a wide range of issues, including: appropriate design and manufacture of sources; various means of acquisition of sources; prevention of the malevolent use of any sources acquired, and mitigation of the impacts, if sources are used malevolently.

Confidentiality of information is also of great importance. Each Member State needs to take appropriate measures consistent with its national law to protect the confidentiality of any information that it receives in confidence under the Code of Conduct [14] from another Member State or through participation in an activity carried out for the implementation of this Code of Conduct. If any Member State provides information to international organizations in confidence, steps need to be taken to ensure that the confidentiality of such information is protected. A Member State that has received information in confidence from another Member State should only provide this information to third parties with the consent of that other Member State. A Member State is not expected to provide any information that it is not permitted to communicate pursuant to its national law or which would jeopardize the security of that Member State.

IAEA Nuclear Security Series No. 11 on Security of Radioactive Sources [25] offers guidance for implementing security measures on radioactive sources. It also provides advice on implementing security related provisions in the Code of Conduct [14]. This document includes guidance and recommended measures for the prevention of, detection of, and response to malicious acts involving radioactive sources. It will also help towards preventing the loss of control of such sources.

5.11. CRITICALITY CONTROL

When numerous sealed sources containing fissile nuclides are collected, packaged and stored, users should evaluate the appropriate quantities of materials placed into single packages for storage or disposal. Both centralized storage facilities and disposal facilities typically contain quantity and packaging limits in their acceptance criteria. Users storing sources containing fissile materials at the user location can obtain assistance from the IAEA in determining safe limits for the sources on hand.

5.12. RADIATION MONITORING

The processing and storage areas need to be controlled as radiological areas to minimize worker exposure to ionizing radiation and to limit the spread of radioactive contamination, if any. Regular contamination and radiation surveys of the work area need to be conducted in order to establish that radiological requirements are met [41, 42]. In addition, if sealed sources containing long lived, volatile or radiotoxic nuclides (e.g. radium) are stored, monitoring of airborne activity levels needs to be undertaken. Detection of airborne or surface contamination is an indication of the presence of leaking sources. Any abnormality needs to be investigated and appropriate actions taken. Depending on the local site requirements, this would be reported to the regulatory body.

Operators should consider the appropriate mix of area monitors, hand-held or installed monitors specific to the work area, and personnel dosimetry, including electronic dosimetry when available. Particular radiation protection requirements include but not limited to the following:

— Appropriate radiation monitoring equipment shall be installed and maintained in the immediate work area.
  - If available, alarming instruments should be used, particularly if tasks to be performed could result in rapid changes in radiological conditions;
  - Personnel dosimeters should be worn as directed.

— At each point in an operation at which a barrier to dispersion of contamination is removed or opened, contamination levels should be assessed.
  - Allowable contamination levels should be established and clear for each step in the planned work;
  - Response to contamination levels exceeding allowable levels should be completed immediately and work paused or stopped as defined in work controls.

5.13. PROBLEMS ENCOUNTERED AND LESSONS LEARNED

There are some issues which may give rise to potential problems in the safe management of DSRSs.

5.13.1. Regulatory system peculiarities

The system of regulatory control is core to the safety and security of radioactive sources. Any assessment of the safety and security of radioactive sources in a country must start with a review of the current and past degree of regulatory control over such materials. Many countries have used radioactive sources prior to the development of their current regulatory infrastructures. In addition, infrastructures are occasionally changed, being reviewed and brought into line with new technological, legal and political realities. Thus, for all countries, their regulatory infrastructure is continuously evolving and the probability of loss of control of sources depends not only upon their historical use of sources, but also upon the status of their regulatory infrastructure as a function of time.

When determining, and analysing, the regulatory infrastructure, it is most useful when the focus is on those elements that have a direct influence on the probability of loss of control of sources and particularly those sources in the higher risk categories [43]. These elements will include such topics as: licensing, import, possession, use and disposal of radioactive sources. Much of the information will be in regulations, with the regulatory bodies or other organizations that have specific oversight of radiation or radioactive materials. However, for other information of relevance, such as checks for competence and legitimacy of those wishing to hold and use sources, it may be necessary to look at other legislation and other regulatory or intelligence bodies.

As an example of the importance of the degree of regulatory control, consider a typical problem where an industrial gauge is inadvertently transferred to a scrap metal recycling plant [43]. This is a growing problem and in the past, it has caused deaths and serious injuries as well as necessitated costly decontamination. There are many reasons why the problem exists, but basically, it involves two fundamental regulatory deficiencies:

(1) Lack of effective regulatory control through notification or authorization and inspection;
(2) Lack of regulatory requirements for, or enforcement of, security and accountability of sources.

This particular problem appears to be most acute in countries where the regulatory infrastructure is weak or essentially non-existent. Typical source related problems have been identified by the IAEA [43] and they are listed below in no particular order:

— Lack of suitable laws and regulations governing radioactive source control;
— Lack of independence of the regulatory body;
— Lack of, or inadequate, authorization, licensing, or registration process for radioactive sources;
— No specific authorization or licensing for government owned radioactive sources;
— Lack of, or inadequate, inspection, enforcement and follow-up;
— A licensing fee structure that encourages undesired behaviors on the part of users;
— No prioritization of regulatory efforts, with all sources being given the same amount of work regardless of their potential hazard;
— Prioritization of effort based on geographical regions, political regions, or uses rather than on the categorization of radioactive sources.

There are major differences in the regulatory infrastructure in the various Member States. In a few countries, all or most activities involving sealed sources are the responsibility of a single regulator. In several countries, however, there are two or more regulators sharing responsibilities for different activities or stages in the source life cycle.

The complexity of multiple regulators makes overall control of sealed sources difficult and a high degree of communication is essential for the source management policy to be implemented effectively. For instance, where specific approval of source transfers, imports, transport, etc. is obtained from a regulator who is different from the one responsible for license issue; it is unlikely that the proposed source transfer can be compared against the consignee's license. The same problem can also exist in a large regulatory organization where separate departments are responsible for different activities. A fixed period licensing system having been introduced in some Member States has the benefit that it acts as a prompt to users to re-assess their source stocks, status, management system, etc. and ensures that the regulator has up to date records of users. However, the process of renewal of licenses must not be unnecessarily long.

5.13.2. Quality of source registry

The existence and the quality of a national registry of radioactive sources will be a prime indicator of the probability of DSRS management problems within a country. The following information, in principle, can be used for the creation of a list of sources [43]:

— The inventories of sources maintained by users (in some regulatory frameworks);
— The records of source manufacturers;
— The records of source distributors;
— The records of companies servicing devices that include sources;
— The records of transportation or shipping companies, including customs declarations;
— Information contained in event reports and notifications;
— The information contained in user licensing records.

It is likely that radioactive source information gathered in this manner will be incomplete. For instance, the records may only identify the existence of a device but not the individual sources or sources within the device. Multiple discrete sources can be used in a single device during the lifetime of the device. Another problem with the information is that it will not necessarily indicate the likelihood of identified sources having been disused. In some instances, licenses are granted for the possession of up to a certain activity of a particular radionuclide and this arrangement can present some inventory problems. The licensee may have none, one or more discrete sources up to that quantity. For all of these reasons, a degree of follow-up may be necessary.

Even if a national registry exists, it is quite likely that it will be incomplete. If it is incomplete, then the implication is that not all disused sources have been identified and became orphan sources. Therefore, an existing inventory needs to be critically examined to check its quality, reasonableness, internal consistency and likely completeness.

Typical problems identified in this area are listed below:

- — Only some licensees have their own inventory;
- — A local or regional inventory only;
- — Only sources that are under one government ministry or department (such as the Health Department) are included;
- — Only sources of a certain type, or used by a certain industry are included;
- — Only sources acquired, or added after a certain date are included;
- — No military sources are included;
- — Significant data missing;
- — Obviously incorrect data;
- — Out of date information.

Different approaches have been adopted in different countries to the establishment of source registries. In countries in which the source market is relatively small and a single regulator is responsible for sealed sources, it has been possible to keep an accurate database that includes up to date information on all individual sources. In countries, where there are a large number of sources, a regional approach has been used. Some countries with long standing and widespread uses of ionizing radiation would find it difficult to change the established system to a centralized approach.

In developing a national registry, or evaluating the completeness or accuracy of an inventory, priority needs to be given to the higher category sources. For example, there should be a high degree of assurance that all Category 1 and 2 sources are included in the registry. Checking that Category 4 and 5 sources are on the registry can be managed with a much lower priority over a longer time. The other aspect with regard to the quality of the inventory relates to the type, accuracy and completeness of the information that is recorded for each of the radioactive sources.

Under most circumstances, the best method of generating and maintaining an inventory of radioactive sources is to use database software, rather than spreadsheet or word processing programmes, as have been used on occasion. Once set up, a source database enables searching, sorting and reporting to be much more easily accomplished. There are a number of commercially available, radioactive material inventory programmes, as well as the IAEA's Regulatory Authority Information System (RAIS) [44], which has a source inventory module.

5.13.3. Exemption

Most Member States operate some level of exemption from regulatory control, based broadly on activity limits for individual radionuclides and depending on their radiotoxicity or on justified practices. Some countries use a combination of both approaches. However, there is considerable variability in the actual practices with regard to exemption levels in the various Member States.

5.13.4. Financing

Once equipment has been purchased and delivered, a facility might not provide for the cost of ownership transfer of the source when the equipment is eventually retired. This can be the case because the facility owners do not have a budgetary mechanism for accruing for a cost that will be realized only well into the future (perhaps decades) and for which the exact value can only be estimated. It could also be because the facility assumes that it can cover the ownership transfer cost out of its operating budget or as a condition of purchase of new equipment. This can lead to financial pressure when the time for ownership transfer arises, with the corresponding temptation to use less expensive options. These alternatives could result in a higher likelihood of loss of control of the spent source.

A number of Member States provide government funding, expertise, and facilities for disused and orphan source recovery, conditioning, storage and disposal. This is especially effective for problematic high-risk sources. This practice can be applied with or without user's fees.

The introduction of an annual license fee discourages long term storage of disused sources by introducing a financial penalty. Such a system operates in Finland.

5.13.5. Records management

Lack or records for the early years of storage concerning the location of the stored sources makes it difficult to retrieve the sources, including the estimation of operational doses, safety assessment, and the explanation of the results of radiation monitoring.

If waste generators use a source tracking system, it is beneficial if this system is compatible with the storage facility's waste tracking system. This may reduce duplication of effort and/or enable transfer of some information amongst databases. Experience has shown that using commonly used identification methods (for example, painted numbers in the exterior of the drum or paper labels, even if protected with plastic) are not sufficient to guarantee identification for long time storage. The labels must be more durable, for example, metallic labels fixed on the cement matrix inside the container can be used. Special care must be taken to keep database backups updated in terms of hardware and software. Computer technology can be rapidly altered over time. Delays in updating software and hardware components can put the DSRS database at risk, making redundant systems necessary. Much information has been lost in the past due to poor record keeping. Entries made in logbooks were often cryptic or ambiguous. Significant effort has and continues to be directed at 'translating' some of the old records. Maintaining a source tracking database requires continuous effort.

It is important to verify records. Examples exist where records do not accurately reflect the actual nature, location, and quantities of sources. Historical databases do not have sufficient information to enable cost effective management of waste that has been stored for extended periods. The problem being experienced is that the current database is an operational one and may not be usable in future in its present state.

It is not only difficult to establish a reliable long term record keeping system, but the incentive to commit resources to the task is sometimes lacking.

5.13.6. Management system assessment

The adequacy of the management system is usually verified by assessment. The assessment includes activities by management on product verification, self-assessment, and independent verification. The assessment applies to all elements of the DSRS management and can measure their interface and effectiveness. Years of experience have shown that any management system left on its own will deteriorate over time. The management system assessment therefore becomes the most important part of the overall management system because it provides a measure to determine system effectiveness before, during, and after disposal is completed, and for continuous quality improvement of the entire process.

6. MANAGEMENT STRATEGY

The Code of Conduct [14] requires that:

> "Every State should, in order to protect individuals, society and the environment, take the appropriate measures necessary to ensure that the radioactive sources within its territory, or under its jurisdiction or control, are safely managed and securely protected during their useful lives and at the end of their useful lives".

There is no single comprehensive end of life strategy applicable for all States. Management strategies reflect variations in: (i) the maturity of legislative and regulatory system; (ii) the presence of a nuclear power programme; (iii) the inventory and the characteristics of disused sources in the State; (iv) the financial and human resources available; and (v) whether the State is a supplier of radioactive sources. Disused sources are likely to be the most important consideration with regard to radioactive waste management in States without nuclear power programmes. For some States with a nuclear industry, it can be a challenge to ensure that sufficient priority is given to disused sources. In many countries, the policy for DSRS management is specified in the national radioactive waste management policy. Issues to be addressed at the policy document level are specified in Article 28 of the Joint Convention [13] and in other IAEA publications [29, 44, 45].

Independent of the size of activities and significance of risks involved every Member State should have a strategy for implementing national policy. The strategy should outline a systematic approach, including clearly assigned responsibilities, detailed knowledge on present and foreseen disused source inventory, well defined sequences of all management steps for each source or a category of sources, and existence of appropriate technologies. The strategy needs to be considered as a management plan, facilitating systematic planning and safe implementation of all management activities. After its approval by the authorities, the management plan provides a basis for the granting of funds for the management of disused sources.

The development of this strategy could be responsibility of a licensee or CRWMO. If the number of sources is small and no CRWMO is available, the regulatory body in coordination with the user may come to a suitable national solution for the management of DSRSs.

6.1. PREREQUISITES FOR STRATEGY DEVELOPMENT

In order to develop or update a national strategy or the strategy of one of the implementing organizations, the persons involved should, among other things, have an understanding of the topics listed below.

— Current and future use of sources in the country;
— Inventory of DSRSs in the country;
— Source categorization system;
— Characteristics of DSRSs;
— DSRS management strategies in other countries;
— Knowledge of existing DSRS management facilities (hot cells, storage and disposal facilities);
— Availability of resources (funds, manpower, infrastructure);
— Existing regulatory regime (requirements for acceptance and return of disused sources);
— Concerned parties' expectations and interests;
— National classification scheme for radioactive waste.

Some countries may prefer formulating a strategy in two levels: principal matters are prescribed in general terms as a national strategy by government, and its detailed implementation is delegated to particular source owners (company strategies). This approach can be recommended to improve coordination of DSRS management, increase its safety and security, and to efficiently exploit national resources. Typically, a single national store/repository may be planned instead of several facilities owned by large license holders or centralized handling and conditioning services may be created.

6.2. STRATEGIC MANAGEMENT OPTIONS

The management option selected for a particular source will depend on a variety of relevant factors, including activity, radioisotope content, half-life, terms of the purchasing contract, and physical condition of the source. After the management option has been selected, the licensee will notify the regulatory body regarding the decision taken. The licensee is required to interface with the regulator in all matters pertaining to the management of DSRSs.

The following general management options may be considered for disused radioactive sources:

— Transfer to another authorized user (for further authorized use);
— Return to the supplier/manufacturer;
— Temporary storage in its original shielding (for example, for radionuclides with half-lives of less than 100 days);
— Conditioning (for example, over-packing);
— Storage (such as in a dedicated or centralized storage facility);
— Disposal.

All sources entering the waste management process must be characterized to establish their activity, the radionuclide content and other important characteristics. Based on the source characteristics, specific management options could be identified. Figure 44 describes in general the management options for DSRSs, taking into consideration the potential reuse/recycle of a source and various disposal options, based on source characteristics, including its half-life and physical condition.

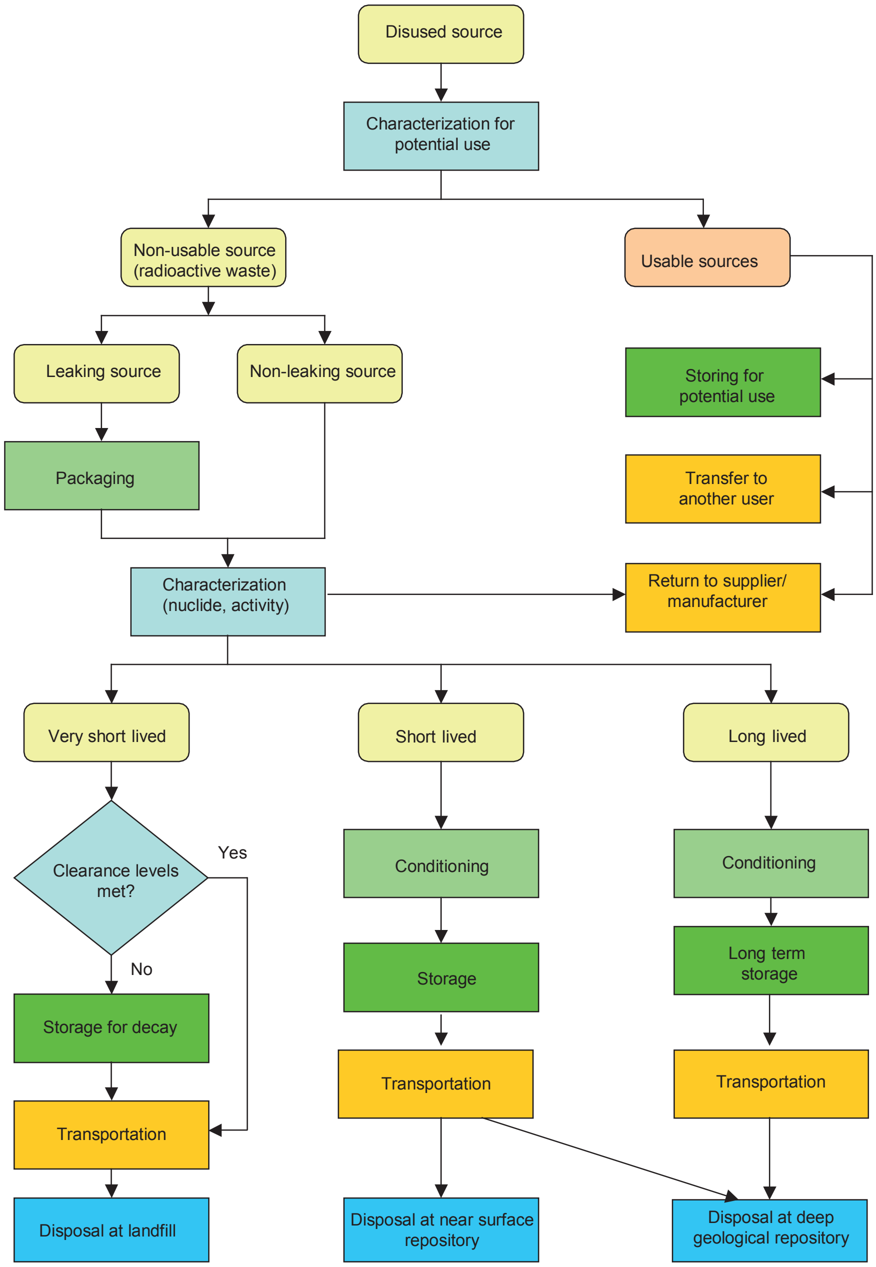


FIG. 44. A flow diagram for the management of DSRSs.

Decommissioning refers to the removal of licensed radiation sources and associated devices from a facility and the administrative and technical actions undertaken to remove some or all of the regulatory controls [30]. Some facilities may have only one installed radiation device, such as a teletherapy machine. Other facilities may include licensed premises in which many individual devices are installed (such as a production line containing industrial gauges) or stored (such as a store for mobile devices). Decommissioning may involve the removal of a large number of sources prior to the termination of a facility's license. Decommissioning may also involve the removal of part of a facility's inventory of devices prior to the issuing of a new license and the installation of replacement devices for future work. Source replacement within an existing device is not considered to be decommissioning. The guidance on the safe management of decommissioning activities for medical, industrial and research facilities [46] should be followed in the planning and execution of decommissioning.

For facilities using SRSs, decommissioning may involve only the authorized removal of all sources from the facility. In more complex situations where on-site dismantling of equipment containing sources is to be undertaken, decommissioning activities should be carried out by appropriately qualified and experienced staff, in areas that are suitable for the types of procedure to be undertaken. Many users of equipment containing sources will not have the staff or authorization for the full dismantling of equipment involving removal of the sealed source.

6.2.1. Transfer to another authorized user

If the activity and physical condition of the source allow utilize it further, the DSRS can be reused in other applications. Transfer of sources to other users offers both economic and environmental benefits. However, the transfer should be carried out in a controlled manner and the recipient of the source should be made aware of the relevant regulatory requirements. The arrangement needs to ensure that the user site is licensed to receive the source, the infrastructure required to accommodate the reused source at the new user's facility is available, and that the relevant documents are exchanged between the former user, the new user, as well as the national regulatory body. Reuse of sealed sources might be considered prior to their purchase, if circumstances permit.

Special attention needs to be given to ensuring that sealed sources are in a serviceable condition and are suitable for the intended new application. Copies of all relevant information on the history of use of the source (such as conditions of use and maintenance logs) should be provided to the new owner. At a minimum, this should include the source's serial number, radionuclide content and activity. For high activity sources, it is likely that the relevant serviceability checks could only be carried out in a specialist facility. Therefore, direct transfer to another user may not be appropriate for such sources; transfer should be done through a source manufacturer or supplier, or other competent body.

Transfer to another user within national boundaries is particularly applicable for ^{137}Cs and ^{60}Co used for clinical therapy. A source can be reused in its original holder without dismantling a capsule. Preferably, sealed sources provided to other users are packaged and shipped in the original shipping container. If the original shipping container is not available, provisions need to be made to acquire an appropriate container or to contract a specialized nuclear transport organization.

6.2.2. Return to supplier/manufacturer

When reuse is not possible, the DSRS may be returned to the original or alternative supplier/manufacturer. Given that the manufacturers and/or suppliers are aware of the economics of recycling and the demand for sources of various types, they are in an ideal position to make appropriate decisions regarding the final disposition of the sources. The return procedures may include the following legal arrangements:

- The user of an SRS includes a clause in the purchase or leasing contract permitting or requiring the return of the source. This has become a common practice in many countries;
- A copy of the contract, showing the return clause, is submitted to the regulatory body before a source is imported.

Arrangements with a supplier and/or manufacturer for the return of a source, if not agreed upon at the time of purchase, may be made at any time during the life cycle of the source. Sources being returned to suppliers/manufacturers need to be packaged and transported in accordance with applicable transport regulations [47]. Sometimes the return is not possible, especially for older sources where the supplier is not known or is no longer in business.

Return to the original supplier and/or manufacturer is often the preferred choice for Category 1 and 2 sources; however, attempts must be made to return all the DSRSs to the supplier and/or manufacturer which are to have all necessary equipment for reuse/recycling.

Re-encapsulation and recycling of relatively high activity DSRSs are carried out in hot cells. Re-encapsulation is typically conducted for ^{60}Co, ^{137}Cs and Am–Be neutron sources. The raw material removed from the capsules can be used to produce new sources for other purposes. For instance, ^{137}Cs sources in the form of caesium chloride from old teletherapy units can be recovered and processed into small sources for other applications, such as brachytherapy.

The recycling approach is also used for neutron sources such as ^{252}Cf. The sources that contain less than 40 mg ^{252}Cf could be accepted for disposal at low cost, while the ones containing higher activity might be recycled and utilized for manufacture of new sources.

Re-irradiation is not typically used for most isotopes. A notable exception is ^{75}Se, which is obtained by irradiation either of natural Se or of highly enriched ^{74}Se. The highly enriched ^{74}Se is a very expensive raw material. Spent ^{75}Se sources can be repeatedly irradiated in order to obtain new sources with the same performances as before.

As an alternative to purchasing, leasing of sources is becoming increasingly common option. Under such an arrangement, the user never owns the sources, but leases them from the supplier for a specified period of time after which the source is returned to the supplier/manufacturer. In some respects, leasing improves the safety of sources as the manufacturer retains ownership of the source and, with it, the responsibility to recover the source for disposal. However, continuing responsibility for day-to-day safety remains with the principal party. Source leasing may be an option available to users for a short duration, or for sources of low activity or short half-life.

6.2.3. Storage prior to disposal

Sources may be stored prior to disposal specifically to allow the radioactive decay of short lived radionuclides *(short term storage),* thus simplifying the disposal arrangements, or may be stored while disposal arrangements are being made. However, the protracted storage of disused sources for reasons other than radioactive decay is not encouraged. The choice of how best to manage the period of storage while awaiting final decommissioning and disposal should be made by the principal party, with the approval of the regulatory body, with account taken of the particular circumstances in the facility. For example, if the facility contains a large number of sources on a disused production line, the option of gathering these sources into a secure location should be considered. Such action should in any case be taken if retaining control of the sources cannot be guaranteed within the disused premises.

The DSRSs with short half-lives (e.g. ^{32}P, ^{125}I, ^{192}Ir, ^{210}Po) may be stored for periods, allowing radioactive decay to clearance levels acceptable for release of radioactive materials from regulatory control. Disposal of decayed disused sources as non-radioactive material into municipal waste facilities, or other non-radioactive waste landfills, is not to be carried out until it is confirmed that the residual activity to be released to the environment meets clearance levels established by the regulatory body.

In establishing clearance levels, or just in clearing disused sources from further regulatory control on a "case by case" basis, the regulatory body needs to take into account the exemption levels established in national radiation protection legislation. As recommended in the BSS [11], a clearance level for a particular nuclide should not be higher than the exemption level for that nuclide. For the radionuclides, which are suitable for the radioactive decay storage option, some examples and their exemption levels are recommended in the BSS.

Only sources that meet the specified requirements for storage could be accepted for storage either on site or at centralized storage facility (see Section 9). In order to meet these requirements the source should undertake some conditioning that makes it suitable for safe and secure storage. Conditioning of a source for storage should take into consideration the potential to retrieve the source for subsequent recycle/reuse, or for repackaging for disposal (see Sections 10 and 12). For example, conditioning by embedding it in concrete may be counter-productive with respect to source retrieval and subsequent recycling and reuse, or repackaging for disposal in the future.

In most countries, suitable disposal facilities for DSRSs are not available. There may be long delays before a disposal facility can be developed. Therefore, *long term storage* facilities are required. These facilities could be operated at the national, or regional level, and require appropriate regulatory oversights.

6.2.4. Disposal

If no recycle/reuse, or return to the supplier/manufacturer option exists and a suitable repository is available, then the user needs to consider disposal of the source as radioactive waste in accordance with the applicable requirements. Disposal is the final phase in the life cycle of radioactive sources.

Disposal options for DSRSs vary depending on the activity levels and types of radionuclides in the sources [48]. Near surface repositories may be suitable for low activity, short lived sources. However, the specific radiological characteristics of many DSRSs do not comply with the waste acceptance criteria set up for these facilities. The problem in this respect is that they constitute high, localized concentrations, or 'hot spots', in the facility and could give rise to unacceptable radiation doses in the event of inadvertent human intrusion. For long lived disused sources with activity levels exceeding the criteria for disposal in a near surface repository, underground deep disposal is the preferred option. Deep geological disposal offers the highest level of isolation available among the disposal concepts currently under consideration. For countries without the prospect of such repositories, the possible development of multinational geological repositories in the future would be of interest. Another possibility is the development, on national territory, of a special type of borehole disposal facility intended specifically for the disposal of DSRSs [48].

Safety analysis for any disposal option needs to be carried out and a license for such use, prior to implementation of the option, obtained.

6.3. FACILITY TYPE

In addition to general management options described above, there are some technical approaches that countries may consider for the management of their DSRSs. These approaches include the sharing of facilities, the centralization of facilities and the use of mobile processing facilities.

6.3.1. Shared facilities

Countries may consider sharing dedicated radioactive waste management facilities with other countries. This approach has the benefit of decreasing the cost of DSRS management for all countries involved.

Shared facilities could include multilateral facilities for storage and disposal. Such proposals have been made in the framework of the Joint Convention [13] and discussions have taken place between interested countries [49].

6.3.2. Centralized facilities

A strategic choice can be made between centralized and site specific DSRS management facilities. Each approach has its merits. A centralized facility capable of processing, storage and, possibly, the disposal of all, or a large part, of the DSRSs in a country is usually more economic than the individual site approach, requires a smaller workforce than multiple individual sites and is likely to be more secure. On the other hand, managing the source at the site at which it became disused has the advantage of reducing the need for source transport.

In fact, the choice is rarely made on purely economic grounds because there are usually local political factors, national historic nuclear development aspects, geographical factors and public opinion aspects to consider. Nevertheless, if strategy is being developed or upgraded, the choice between these options should be given proper consideration for all or parts of the waste management activities in the country.

6.3.3. Mobile facilities

A possible partial alternative to centralized DSRS management facilities, which has many of the same economic advantages, is the use of mobile processing facilities. Such facilities are operated in ‘batch’ mode because a certain minimum amount of sources is usually needed for their efficient operation. The DSRS management costs for individual users can be reduced if such processing systems are shared. An example of the mobile facility that is used for conditioning of high activity sources is the IAEA Mobile Hot Cell Facility (See Section 10.7).

6.4. DEVELOPMENT OF A MANAGEMENT STRATEGY

Strategies for the management of DSRSs should be consistent with and address the specific situation in the Member State. A national strategy for the management of DSRSs may consist of three phases [50]:

(1) *Assessment:* Deciding on the scope of the strategy.
(2) *Development:* Identifying and prioritizing actions for solutions, and developing the plan accordingly.
(3) *Implementation:* Obtaining the necessary commitment and resources, implementing the solutions, finally evaluating the impact of the plan.

In developing an overall strategy, the Member State will need to assess the benefits and detriments of various options and make judgments with regard to their priorities. In general, a national strategy focus could be based on:

- — Source categories (e.g. Categories 1, 2 and 3);
- — Source type (e.g. industrial radiography sources);
- — Industrial sector where problems have been identified (e.g. scrap metal recycling);
- — Geographical region or area (e.g. the capital city);
- — Sources in use prior to a national regulatory body being established.

A realistic evaluation of the resources for both the development and implementation of the national strategy is critical to ensuring that the effort is successful. Some countries may be able to devote significant effort in the development of a comprehensive national strategy that anticipates future conditions and provides the actions appropriate to those conditions.

The assessment phase of establishing a national strategy for the management of DSRSs involves gathering information and then evaluating it in order to reach conclusions regarding the nature and magnitude of the problem. The assessment phase will be an ongoing, continuous process as a Member State's situation evolves. The assessment phase of this process is not intended to be the only decision-making point; rather, it is the point at which major decisions on the need, direction and content of the national strategy are made.

Evaluation of the information will take place both during and upon completion of information gathering. The quantity and type of information obtained might identify the need to modify the scope and methodology of the assessment. When appropriate information is obtained, actual conditions can be compared to the relevant national laws and regulations, as well as international standards and guidance [28, 51], to determine the existence and extent of discrepancies with respect to the national waste management strategy. The Code of Conduct [14] is useful as an international guidance document on this matter.

6.5. PROBLEMS ENCOUNTERED AND LESSONS LEARNED

6.5.1. General issues

The country in which a source was used is likely to have obtained the maximum practical and commercial benefit from it and it can be argued that the country should take responsibility for its disposal if a suitable disposal route exists or is planned. However, due account needs to be taken of the economic benefits of consolidating large numbers of sources of a similar type for recycling or disposal in a single facility. Such a facility may well be in the country of manufacture, although this is not necessarily the case.

Sometimes, there are ineffective regulatory controls (inspection, enforcement, etc.) in place. In such cases, a system of inspection to enforce the provisions introduced in compliance with the relevant regulations needs to be established. The regulations should empower the authorities to apply penalties for breaching provisions of the regulations. The penalties can be proportional fines or the suspension or withdrawal of the license. General provisions of the Criminal Code should also apply.

6.5.2. Transfer to another authorized user

Experience gained from dealing with actual accidents with disused sources shows that risk of accidents increases when sources are physically transferred to another user without passing associated information and responsibility.

When there is a shift in responsibility, either within the same institution (from the former operator to a person in charge of temporary storage) or from one institution (old owner) to another (new owner), any information gap between the two users or institutions is a potential source of new risks.

6.5.3. Return to supplier/manufacturer

In many Member States, return of a source to the supplier/manufacturer is encouraged or required by regulators in Member States. However, in certain cases, this option would be difficult to implement for the following reasons:

- — The original supplier is unknown, or no longer exists, or is untraceable;
- — Source certificates or special form certificates have expired;
- — An appropriate transport container is not available;
- — Adequate transport means are missing;
- — Funds needed for packaging and transportation of DSRSs are not available;
- — Regulatory system imposes some import/export restrictions.

These obstacles contribute to some degree of confusion among the parties involved, particularly considering the restrictions and difficulties involved in the transboundary shipment of DSRSs. Given the restriction on transfer of radioactive waste from one country to another, there have been special cases a number of times (on both sides, i.e. consignor as well as consignee) to transfer disused sources from the user to a party that accepts them for, at least, partial reuse. In these cases, it appears to be common practice that consignee accepts the shipment (containing several sources) and declares the unnecessary sources as waste, shortly after receipt of the shipment. However, security issues concerning DSRSs have provided the impetus for returning these sources to the suppliers. The key issue towards the solution could be reconsideration of RWL (recommended working life) by manufacturers and regulators as an important tool in the decision making process on the status of a disused source. This area could be improved with the adoption of a common policy, which should take into account the points listed below.

6.5.4. Storage prior to disposal

There is evidence of a large numbers of disused sources in store at users' premises throughout Member States. Some sources are actually owned by private clinics, and hence ownership is an important issue in declaring the sources as radioactive waste. Most storage of sources at users' premises is being done primarily for economic reasons. Such sources may be stored for several decades in containers, some of which may be in poor condition. In some instances, the high cost associated with disposal, or the lack of appropriate disposal options, may be a deterrent to disposing of the sources safely, and thus requiring the sources to being stored, often for an indefinite period. Because the sources are in storage and not in use, the accountability for the sources may be lost over time, or unauthorized removal or theft may occur.

The Code of Conduct [14] expects that every State should ensure that sealed sources are not stored for extended periods of time in facilities that have not been designed for the purpose of such storage. Central storage of disused sources reduces the likelihood of loss, particularly where generic regulatory control is applied. While many Member States operate central interim stores capable of receiving most of the sources, there are limits, in some cases, on the types of sources that can easily be handled and stored. In several cases, store capacity also becomes an issue in a few years time.

Technical and non-technical factors affecting the selection of waste conditioning technologies are analysed in Ref. [52]. These factors are partially applicable for a DSRS if the source is considered as radioactive waste and must be taken into account while developing a management strategy for waste.

6.5.5. Disposal

While a number of Member States have or are planning to develop disposal facilities for radioactive waste, others are not, and in some cases the small number of sources and other radioactive wastes may not justify the development of a disposal facility, especially for high activity or long lived sources.

Small countries without a nuclear infrastructure should not be required to develop a source disposal route and should be allowed to use disposal routes in other Member States. Ideally, this should be the country of manufacture, but if a practical alternative exists, then this need not be the case.

7. CHARACTERIZATION OF DISUSED SOURCES

Characterization is defined by the IAEA in Ref. [1] as the “determination of the physical, chemical and radiological properties of the waste to establish the need for further adjustment, treatment, conditioning or its suitability for further handling, processing, storage or disposal”. Knowledge of the quantities and characteristics of disused sources is essential for the selection of a management option and demonstration of the safety of management methods.

7.1. REQUIRED INFORMATION

Each disused source needs to be characterized, prior to undertaking any management steps. As a minimum, the following information is required:

- — Nuclide identification;
- — Activity estimation;
- — Physical properties of the source and/or device, including the weight and dimensions;
- — Chemical form;
- — Type of shielding;
- — Source condition (e.g. damaged/leaking/modified).

Acquiring these data is considered to be the absolute minimum requirement for handling, conditioning, transportation, storage and disposal of DSRSs. In addition to the above data, the following information will be useful in developing a management strategy for a particular source:

- — Method of sealing of the radioactive material;
- — Source and device numbers;
- — Date of manufacture;
- — Name of manufacturer and country of origin (for the source and the device);
- — Last user or owner;
- — Current location;
- — Any information that may aid in the characterization of the source.

7.2. CHARACTERIZATION GROUPS OF DISUSED SOURCES

Preliminary characterization of sources may be necessary to allow them to be segregated into manageable types. For example, segregation of SRSs from other waste, segregation of low activity sources and those containing short lived radionuclides and removal of the sealed radioactive source from its cement encapsulation matrix. Leaking sources must be segregated from other sources and separately collected to avoid cross contamination. It may be possible to carry out an initial segregation of waste according to the history of the facility, the existing recorded waste data and existing measurements. Thus, depending on the completeness and robustness of existing data, only a simplified characterization programme for verification and validation could be implemented.

From a characterization viewpoint, DSRSs fall in the following groups:

(a) *Controlled (documented) sources*: ‘Controlled’ use of a radioactive device, source or transport package may be defined as being used for the intended purpose and that has an identifiable owner. If these requirements are not met, then the device, source or transport package may be considered to be ‘uncontrolled’. Controlled sources have appropriate documentation that objectively provides information on the characteristics of the source. This documentation could typically include the following:

  - — Manufacturer documentation (certificate);
  - — Permanent marking on source, or equipment/gauge;

— Certificate of traceability;
— Non-destructive assay data;
— Inventory documentation.

All this documentation can be used as long as there is traceability between the documentation and the associated sources, and their activities have been verified. For inventory tracking documentation, the activities need to be verified.

(b) *Uncontrolled (undocumented) sources:* Sources that lack appropriate documentation on the characteristics of the source. This group will require additional efforts in identifying isotopes and determining associated activities. Orphan sources, in most cases, belong to the group of undocumented sources, i.e. similar actions need to be implemented to characterize the orphan source. In addition to the characterization process, finding the former source owner is important. It can help to track the route of the orphan source from the last (previous) owner to the lost status, and justify whether only one source was lost or other sources also need search and follow up.

(c) *Leaking sources:* Sources in which the confining barrier no longer prevents dispersion of the radioactive material. This group of sealed sources may include leaking sources that have appropriate documentation (controlled) and those that lack appropriate documentation (uncontrolled). Leaking sources are categorized separately because they may require encapsulation and/or other additional conditioning options.

7.3. SOURCE IDENTIFICATION

The best method of identification is by the serial number if it is present and readable. Visual inspection is a very useful technique for identification of a number of parameters, which will assist in the characterization of SRSs [53]. These parameters include information on the physical condition of the source, dimensions and its shielding/housing.

Mirrors, magnifier glasses, binoculars, remote controlled video cameras and others can be used for visual inspections and are highly recommended for obtaining initial information subject to compliance with the ALARA (as low as reasonably achievable) principle. Endoscopes can be used for remote visual inspection of sources and containers. For example, it could be used for detection of markings/labelling of SRSs, or evidence of corrosion and moisture inside the waste containment system.

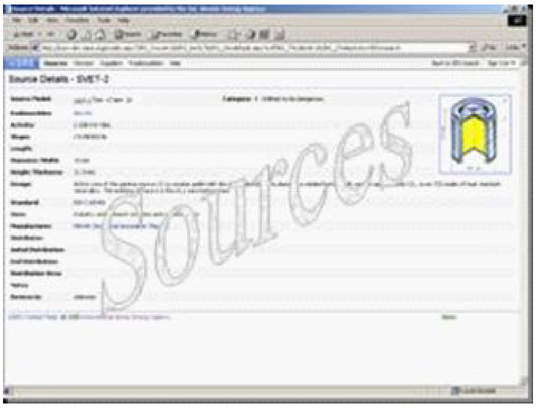
Identification of sources is eased by the recognition of associated shielding and equipment. In many cases devices and transport packages are also labelled. Depending on the shielding of the package, the category labels are not indicative of the quantity of radioactive material, type of radiation or hazard of the material. However, the nuclide, mass number and activity must be written on the label. The ‘categories’ referred to in the context of labelling packages are not to be confused with the IAEA categorization system, which rates radioactive sources according to the level of danger. The shapes and sizes of sources depending on their purposes vary considerably; however, the specific design of devices or housings containing radioactive sources may assist in visual recognition of the sources. Data collected in the past of typical sealed radioactive sources encapsulating and holding structures could give an indication of which radionuclides might be present and their approximate activity content.

The IAEA has developed a comprehensive system of data on SRSs. The system includes data on the actual SRS, as well as on the devices housing the sources. The package is in the form of a computer database and is called the International Catalogue of Sealed Radioactive Sources and Devices [54].

This catalogue provides vital information on various individuals and organizations related to industrially manufactured radioactive sources and devices, designated as ‘source models’ and ‘devices models’. It facilitates source identification, based on limited information available (or ‘found’) for given radioactive sources or devices, and thereby assists in the safe handling of sources.

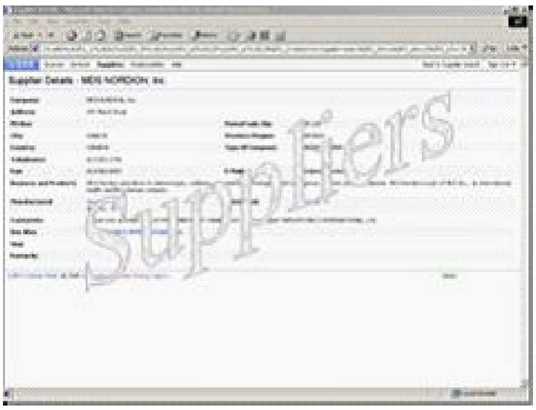
The catalogue utilizes a vast amount of data in order to provide information on a given unknown source or device where the available data are very patchy. The information is managed through three main linked databases.

— Source models. This database contains data on source models (i.e. radionuclides, activity, category, shape, size, manufacturing details, uses, manufacturer/distributor, etc.). At present, the catalogue contains 6800 source models.



— Device models. This database contains data on device models, including transport containers (i.e. description, applications, manufacturer/distributor and identification of authorized sealed sources inside the device). At present, the catalogue contains 8000 device models.

— Suppliers. This database contains the addresses of manufacturers and distributors of SRSs and devices housing such sources. At present, the catalogue contains information on 1200 manufacturers/distributors.



The catalogue options include an identification system (browser), in which the inquirer fills in a form displayed on the screen. When the form is completed, the catalogue provides the identity of the most likely source or device.

The target group for use of the catalogue is wide-ranging, and includes regulators, professionals dealing with orphan sources, manufacturers, distributors, emergency response teams, users of sources/devices, law enforcement organizations, customs authorities, scrap yards and metal production plants, and waste management companies and organizations.

For making the catalogue a useful tool for Member States, the IAEA is planning to maintain and update it on a regular basis, with particular emphasis on QA/QC and testing of devices when they are incorporated.

7.4. CHARACTERIZATION OF UNDOCUMENTED SOURCES

When the aforementioned information is not available, it should be obtained by different characterization methods. It is recommended that a characterization system be set up and performed according to an adequate management system. The management system should provide confidence that environmental, technical and safety requirements are fulfilled.

7.4.1. Characterization system requirements

Before establishing an SRS characterization system, it is necessary to provide a specification which will identify the system requirements [55, 56]. This can be a detailed specification for a particular piece of equipment, if the operator is confident that this equipment is required. Alternatively, a functional specification can be provided which describes the problem (including the tasks to be performed and the required outputs) and allows the supplier to use professional judgment on the choice of system. This may, for example, allow the supplier to propose integrated or single systems, depending on the problem.

The following issues need to be addressed:

(a) Details of the DSRSs, including their history, age, expected radionuclides and physical form of the SRSs, waste matrix including materials (e.g. neutron absorbers), which may interfere with the measurement techniques, dimensions of packaging;
(b) Details of the overall process, including a description of the facility which will contain the characterization system(s), working environment of the equipment, constraints on the dimensions of the equipment, throughput requirements, maximum times available for measurements;
(c) Details of interfacing equipment (e.g. if the proposed new characterization equipment is to be used in conjunction with existing equipment);
(d) The accuracy required, including acceptable precision and sensitivity;
(e) The acceptance tests required at the factory and at the intended equipment location to demonstrate that the system (including the software) is fit for purpose;
(f) Identification of any additional validation to be carried out by the purchaser;
(g) Degree of expertise necessary and available to operate the equipment;
(h) Statement on required maturity of the equipment, for example if innovative technologies are accepted;
(i) Spares to be held, identification of times to repair malfunctioning equipment and maintenance frequency requirements;
(j) Available finances (if this is a constraining issue) and an indication if the equipment is to be hired or purchased;
(k) Provision of a compliance matrix showing where the proposed new equipment is (and is not) compliant with the above requirements;
(l) Provision of operational and training procedures.

The operator needs to provide evidence that all the above concerns are addressed. On the basis of these requirements, an SRS characterization plan should be produced which includes the justification of selected methodology and techniques. The plan should be in accordance with the waste acceptance criteria of the storage or disposal facility which will receive the disused sources. Moreover, it should be drawn up according to the retrieval and conditioning options and techniques already defined.

All information on the source needs to be collected and filed in a structured manner to facilitate retrieval when needed; it should be retained in duplicate and in separate locations. The operator needs to carry out audits at regular intervals to ensure that the recorded information is correct.

7.4.2. Retrieval of historical data

Historical data recovery, collection and processing are the first step in the characterization process [53]. During data retrieval it may be necessary to consult former or retired employees who may be able to provide any relevant information. A list of data retrieval actions may include:

(a) Identification of SRSs;
(b) Collation of information on the relevant SRSs, including physical, chemical and radiological properties, manufacturer's name, drawings, serial number, date of production, users of SRSs, leak test certification, measured dose rates, conditioning materials (if applicable);
(c) For those SRSs which have been conditioned, identification of those encapsulated in concrete, polyurethane foam, paraffin wax and/or other matrices;
(d) Identification of the types of additional shielding used for the SRSs (e.g. lead, cement, depleted uranium);
(e) Identification of the packaging used for conditioned and unconditioned SRSs (e.g. plastic bags, specific shielded transport containers, drums, metal and wooden boxes);
(f) Group the SRSs for characterization.

7.4.3. Characterization by NDA methods

If retrieval of historical data is not possible, all efforts should be undertaken to characterize the sources using the non-destructive assay (NDA) methods specified in Ref [53]. If the non-destructive assay of the source within the associated device fails to give sufficient information to adequately characterize the SRS, a step by step retrieval of the source from the device and shielding structures may be considered. During retrieval and characterization operations, all necessary precautions should be taken to ensure that the risk is maintained as low as reasonably achievable.

A number of sealed sources containing strong gamma energies can be identified by gamma measurements [53]. To this group the following radionuclides belong: ^{22}Na, ^{60}Co, ^{85}Kr, ^{133}Ba, ^{137}Cs, ^{152}Eu, ^{226}Ra, ^{239}Pu–Be and ^{241}Am. Some compound neutron sources like ^{241}Am–Li, ^{238}Pu–Be, ^{241}Am–Be and ^{226}Ra–Be can also be identified by measuring the high energy gamma ray produced by the following reactions ^{1}H(n, γ)^{2}H, ^{9}Be(α, nγ)^{12}C and 7Li(α, αγ)7Li. Moreover, high energy gamma rays produced by neutron activation reactions (n, γ) on housing materials (e.g. aluminium, iron, titanium) and neutron shielding materials (e.g. borated paraffin) may be used for identification of the neutron sources. The radionuclides ^{238}Pu and ^{239}Pu are not suitable for identification by gamma measurements due to low intensity of gamma radiation.

It may generally be necessary to obtain additional information using other more advanced techniques (e.g. gamma assay methods [53]). Gamma spectrometry allows the identification of the different radionuclides and under certain conditions their activity. For quantitative analysis, gamma ray absorption in the waste matrix and/or shielding material of the SRSs must be known; this is mainly accomplished using a priori information (e.g. measurement geometry, density, matrix composition) or transmission measurements.

The sealed radioactive sources listed below can be detected by neutron measurements, passive and/or active neutron counting methods [53]. This group includes ^{226}Ra–Be, ^{238}Pu, ^{238}Pu–Be, ^{239}Pu, ^{239}Pu–Be, ^{241}Am–Be, ^{241}Am–Li and ^{252}Cf. The most commonly used neutron detector in NDA systems is the ^{3}He gas proportional counter. The ^{3}He counter is a thermal neutron detector and it is used for detection of neutrons by combining it with a moderator, e.g. high density polyethylene. Some types of hand-held neutron dose rate meters are equipped with BF_3 detectors that could allow detecting neutron sources by contact measurement around shielding or waste packages.

The use of sophisticated and costly characterization methods is not justified for SRSs, which do not represent a radiation hazard and which are not important for the safety of the post-closure phase of the future disposal facility.

7.4.4. Characterization by destructive methods

Destructive methods should be considered only when it is absolutely necessary. If a sealed radioactive source has been submitted to a laboratory for destructive analysis it would no longer be considered a sealed source and would require subsequent treatment and conditioning in conformance with relevant waste acceptance criteria. More details of sampling and analysis methods are given in Refs [55, 56].

7.5. CHARACTERIZATION OF LEAKING SOURCES

Before the handling of a disused source, smear tests on the source need to be carried out to check for any leakage (see Fig. 45). Alpha, beta and low energy X and gamma ray contamination monitors could be used for detecting source leakage by the wipe test method.

FIG. 45. Smear tests for contamination control.

7.6. LESSONS LEARNED

Most disused sealed sources will have associated beta and/or gamma emissions. These can be detected with unsophisticated equipment such as an end window or a thin walled Geiger–Müller (GM) tube monitor. Scintillation monitors, if available, are preferred because of their shorter response times. This basic equipment is not applicable or not reliable if the source is an alpha or neutron emitter, or if a beta source is positioned in a shielding housing. Instruments sensitive to alpha or neutron radiation may be required if sources with such radionuclides are expected to be encountered.

Gamma dose rate measurements give the primary information on the existence of gamma radiation and can under certain conditions to assess the activity of the sources. The activity of the SRSs can be quantified by using the measured dose rate, the dose to activity conversion factor and the nuclide composition of the SRSs (if known). Experience shows that dose rate measurements are insufficient to fully characterize the SRSs because they require additional detailed information such as radionuclide composition, encapsulation materials, structure materials, matrix and shielding.

Most detectors used in gamma spectrometry use either NaI(Tl) scintillation (low resolution), HPGe (high purity germanium) semiconductor (high resolution) and CdTe (medium resolution) detectors. Systems varying from hand-held devices to specially installed systems using these methods have been available for a number of years. Low resolution systems require less maintenance and no cooling. A disadvantage is that only simple spectra (less than 10 well resolved peaks in an energy range from 35 to 1500 keV) can be collected and analysed. However, it can be used to identify SRSs in historical waste if the activity level of SRSs is high enough and taking into account that SRSs are mainly 'mono' nuclide sources. Medium resolution systems (CdTe) are a good compromise between low and high resolution systems. High resolution systems require cooling (liquid nitrogen or electro-cooling) and are normally expensive and less robust than room temperature devices. The advantage of a high resolution system is the ability to deal with a very high number of different gamma ray peaks.

From the measurement point of view, shielded alpha or beta sources are the most difficult to detect and measure. Inferential techniques based on key nuclides, which may be used to characterize well qualified waste generation and conditioning processes, are not applicable for characterization of SRSs.

8. SOURCE HANDLING

Source handling includes any physical manipulation of a source, including moving, transfer, relocation, removing from or putting in a container, disassembling the part of equipment containing a source, removing a source from the equipment, measuring, inspecting or testing.

As discussed in earlier sections, sealed sources contain radioactive material that is much more concentrated than other radioactive waste typically handled in a facility. When planning and executing work involving source handling, the potential increase in severity of loss of contamination control and the potentially high exposures that can be received during source handling, must be considered. While handling disused sources, industrial and radiation safety need to be observed.

Sealed sources may be an integral part of the equipment. This equipment may be connected with a chemical/ physical process and special precautions may be required to avoid certain dangers. Sealed sources may also be in a unique chemical/physical form that may require special precautions. Sources may also be leaking, which would again require specific radiation safety measures.

8.1. HANDLING SAFETY REQUIREMENTS

Users must ensure that all national and facility/installation radiation protection requirements [11] are met, and that the appropriate controls are in place to both reduce the potential for dispersion of radioactive contamination and to ensure that individual exposures are minimized. The basic principles outlined in this section are valid for handling of all sources whether in use, identified as potentially disused, or declared as disused. These principles are also applicable to all stages of the management of disused sources.

The facility where a source is used should be equipped with appropriate capabilities for source handling, including lifting/hoisting tools, adequate lighting and power sources, remote and hand held radiation and contamination monitoring instrumentation. The complexity and sophistication of handling capabilities are directly related to the potential hazards of the sources to be handled.

When disused sources are handled, some precautions need to be taken to prevent mechanical damage to the source (e.g. dropping from a height, struck by a handling machine or a fork lift); to ensure functionality of the safety systems of the source holder (e.g. locking mechanism of the sources is intact); and to provide radiation protection of the operating personnel. Consequently, general and industrial safety rules need to be observed.

8.2. WORK PLANNING

Sealed sources pose a potential radiological risk during handling. This risk depends on the type of radionuclide, source activity, chemical and physical form, physical condition of the source and the possibility of leaking. It is important to fully assess the type and nature of all risks involved before undertaking any source handling operations. Radiation exposure dose estimation needs to be carried out for the specific handling procedure to provide for safety and radiation protection measures.

In planning and implementing the handling of sources, consideration should be given to the factors that may affect the safety of the source and lead to potential exposure of the workers and the public, and/or contamination of the environment. These factors need to be taken into account, regardless of a source being handled: bare, in a container, in a transport package, or in its original housing/enclosure in which it had been used as a part of an apparatus. All handling operations should be planned, tested and implemented jointly with the radiation protection staff.

In addition to radiological protection concerns, source handling typically requires manipulation and movement of heavy, bulky objects, use of rigging/hoisting and other material movement equipment, and use of standard tools for opening and closing containers. All industrial safety hazards and protection methods should be evaluated and used as appropriate.

Planning should include:

(a) Review of licensing documents issued by regulatory body, ensuring that the source handling operations to be conducted are authorized and that any specific requirements of the license are met;
(b) Review of facility characteristics to ensure appropriate access and egress pathways exist, shielding and air handling is appropriate as installed or can be supplemented to support specific work, tools and equipment requirements are identified and satisfied, staging and storage areas are available;
(c) Sources to be handled are identified;
(d) Tasks to be performed are clearly defined and sequenced;
(e) Operators are trained and qualified to perform the work, and include those with specific experience in both the tasks to be performed and the types and activities of sources to be handled;
(f) Response to incidents or emergencies is identified and adequate.

8.3. ROUTINE SOURCE HANDLING

8.3.1. Collection

The first handling step for a disused source is to collect it from the user, or from the place where it was recovered, for safe storage, pending a decision on the future management step. This work is usually carried out by the CRWMO or a similar organization, e.g. the national radioactive waste management agency. Prior to collection, all possible information on the source needs to be gathered.

The most immediate measure to be taken once an orphan source has been located is to ensure that members of the public in the vicinity are adequately protected. The hazards presented to the public from an orphan source will vary in both the type and severity of the hazard depending on both the source and the conditions where the sources is located, thus the most conservative and yet most effective protective measure that can be taken, under all circumstances is to isolate the public from the source. The potential for both external and internal exposures could be reduced by restricting access and keeping the public away from the source. Establishing access control at the site of an orphan source can be completed through erection of barriers, putting up signs/labels, covering the source, personal communications or other means.

Proper collection of a leaking source is a challenging operation since it may result in the spread of contamination. Therefore, suitably qualified and experienced personnel are required to perform the operation, involving leak testing. The leaking source needs to be overpacked, and the areas where leaking sources are handled need to be covered, for example by a plastic sheet in order to facilitate decontamination and prevent the spread of contamination.

8.3.2. Segregation

Taking into consideration the need to optimize the following waste management operations (i.e. ability of handling equipment, shielding equipment, monitoring equipment, packaging, storage containers), the disused sources may be sorted and grouped based on the management option to be applied, or by characteristics of the source (radionuclides, half-life, activity, chemical and physical form) or unique source types, such as radium sources or neutron sources.

One of the first factors in sorting/segregating sources is whether the source is installed in a device, or is a free standing source. All sources that are installed within a device that require device disassembly should be segregated and staged in an appropriate storage area.

The next group of sources that could be segregated as a unique inventory are those with low activities and extremely short half-lives, meeting the requirements of the Member State for allowing the source to decay until no further detectable activity is measured. This typically is restricted to sources containing nuclides with half-lives less than 120 days. After segregation of devices that will require disassembly and removal of those sources with nuclides that can be allowed to decay away for disposition, the remaining sources can be sorted and segregated based on a combination of characteristics including potential disposition pathways, special types of sources, and high activity sources that preclude source handling by short or long handled tools.

The sources remaining for storage and disposal can be sorted further as shown in Fig. 46. Beta–gamma sources and short half-life alpha emitters (non-transuranic) are likely to be disposed of in shallow land disposal facilities with similar disposal configurations. The long half-life alpha emitters are in most cases probably not suitable for disposal in shallow land disposal facilities, and thus will remain segregated, in storage, until suitable disposal is available. Neutron sources, radium sources, and high activity sources are to be segregated due to specific conditioning and handling requirements.

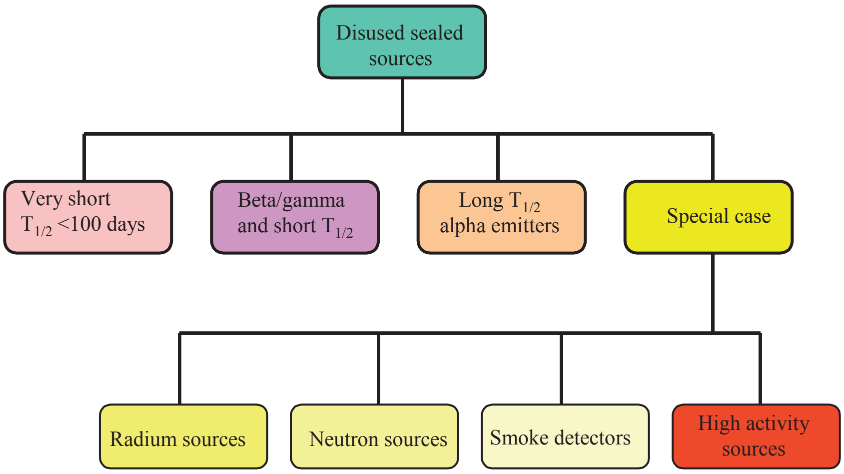


FIG. 46. Operational segregation of disused radioactive sources.

Sources with like characteristics affecting storage and disposal should be packaged together. At this stage it is also possible to limit the contents of the container to ensure compliance with limitations on activity and dose rates.

If a source is damaged, the possible leakage will have to be contained. Leaking sources need to be segregated from other sources and separately collected to avoid cross contamination. The devices should be checked for contamination and then placed into packaging consistent with the storage facility requirements. The temporary containment of devices can be provided by, for example, wrapping the housing in plastic sheeting, or putting it in a rubbish bin or steel drum and sealing the lid. These devices can normally be maintained in long term storage with or without additional packaging until further disposition is available. In some cases, placement of multiple devices into large storage containers will be required. A complete inventory of all devices within each large container should be generated, maintained, and supplied to the storage facility as required. With the exception of security considerations for high activity sources and very large numbers of devices containing smaller sources, there is typically no justification for removal of the sources from the device for maintenance in storage if no disposition path is available.

8.3.3. Removing sources from devices

The storage and disposal of radioactive material is usually expensive, and, therefore, in case of a large number of DSRSs, the removal of the sources from the original devices and grouping them together with similar sources for storage or disposal may be considered. This option results in the reduction of the volume of DSRS packages intended for storage or disposal.

The sources, once removed from the devices can be transferred into a shielded container for storage. The storage containers can be standardized and safety and security measures can be optimized. However, care must be taken to prevent damaging the source or affecting its physical integrity during the removal process. Damaged and leaking sources require extra precautions, as well as specialized equipment providing both shielding and containment.

The shielded container, which eventually will house the source, should be designed to result in an acceptable surface dose rate and also provide for the protection of the source as per relevant regulations, as well as minimize the possibility of unauthorized source retrieval. These containers should offer large internal capacity and considerable flexibility for source storage. When possible, a container should only include one configuration, either sources removed from devices, or sources remaining in devices. No containers should include both.

However, removing sources from devices involves the manipulation of bare sources, which needs special expertise, well designed shielded workplace and tools to protect the operational personal from possible elevated radiation exposure and radioactive contamination. Such experience and infrastructure are only available with organizations regularly manipulating bare sources, for instance, with source and device manufacturers, source/device maintenance staff or staff of waste management organizations regularly managing large number of disused sources. In principle, for occupational radiation protection reasons, Category 1 and 2 sources must be handled only in designated hot cell facilities or mobile hot cell, by qualified and licensed operators available at source manufacturers and recycling organizations. The manipulation of bare sources of Category 3 and of the upper range of Category 4 still needs special expertise, equipment and license.

The rationale for removing the source out of the original container needs to be carefully evaluated on a case by case basis. For sources with no defined disposal path, it could be more appropriate to leave the sources in the devices until such time as a disposition path is available or when storage space is becoming limited. In addition, no one should attempt removal of sources from these types of devices without training and qualification. For high activity sources, the removal of the source from its original holder is not considered until it is absolutely necessary.

In the course of preparations for source removal, the following points need to be taken into consideration:

(a) Knowledge of the dose distribution inside the source's original equipment in the 'on' and 'off' position is desirable;
(b) A maintenance manual (especially regarding the SRS movement mechanism, trouble shooting and miscellaneous repairs) should be available and well understood;
(c) Tools, materials, parts or special equipment required for the work should be available and checked;
(d) Design data, diagrams and any photos/illustration could be helpful;
(e) Power supplies and safety interlocks for the source mechanism or other tools or equipment should be guaranteed to be on the 'on/off' position as required and that it cannot be inadvertently turned on or off by tampering with during work;
(f) Source drawer movement and unloading port alignment should be guaranteed and should not require direct inspection or manual adjustment during the source transfer;
(g) Unexpected problems due to jammed mechanisms should be well studied and solutions must be available to such potential problems prior to actual work. It should be kept in mind that maximum protection is guaranteed when the source is in the original equipment or the target storage shield.

8.3.4. Relocation within the site

Relocation within the site means the movement of a source on the site of the licensee. After declaring a source disused, it should be removed from the place of operation and relocated to a storage area. Movements of SRSs on the site of the licensee are usually not covered by the national transport regulations. The relocation of an SRS on the licensee site is typically regulated by local site regulations. It is notable that many licensees, especially at small companies with limited staff, are authorized to use the source, but not allowed to manipulate it themselves. In these cases, the licensee needs to contract an external, authorized firm to do so.

8.4. EQUIPMENT AND TOOLS FOR SOURCE HANDLING

In routine operation, radioactive sources are handled in the original devices, transport containers or in other shielding which protect the operators from high radiation doses. The packages can be handled manually or using a forklift. When, for specific reasons, bare radioactive sources have to be handled, the operator should be as far away as possible from the sources in order to minimize the dose.

Handling of sealed sources can be deceptive in terms of contamination control. Even old sources that have been in use for years can maintain the appearance of a new source. It is not uncommon for experienced operators handling sources to become careless, assuming that the sources being handled are intact and there is no leakage. Users should encourage an attitude that sources and devices containing sources are contaminated until proven otherwise.

8.4.1. Tongs and temporary shielding

Low activity sources emitting low energy radiation typically can be handled manually (Fig. 47) or with short handling tools such as tongs or forceps (Fig. 48). Sources of this type include calibration sources, sources used in medical applications, check sources, and some sources used in industrial devices. Handling such sources normally does not require any shielding.

FIG. 47. Source manipulation by hand.

FIG. 48. Short tools for manual handling of sources.

Some sources of higher activity and dose rates than the ones described above can also be handled manually with suitable tools as long tongs (Fig. 49) but shielding of these sources is needed to reduce the doses received by the operator (Fig. 50). The most common sources in this group are LDR brachytherapy sources containing caesium and the sources in thickness gauges (^{85}Kr, ^{90}Sr), fill level or thickness gauges (^{137}Cs), density gauges (^{137}Cs), moisture density gauges (^{241}Am–Be–^{137}Cs), bone densitometry (^{109}Cd), and static electricity eliminators.

FIG. 49. Long tongs and manipulation of source with them.

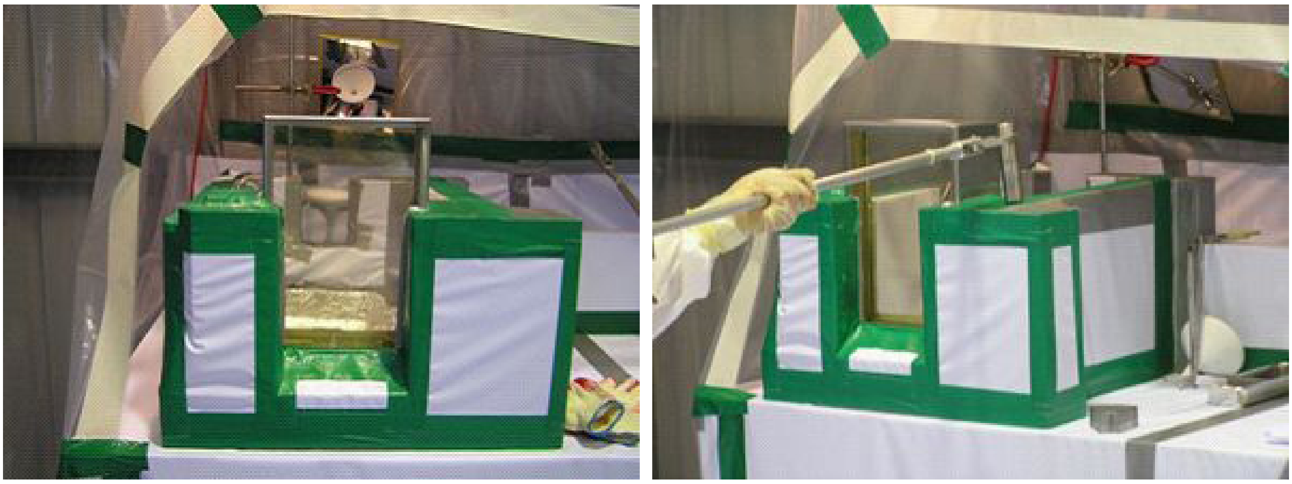


FIG. 50. Installation of lead shield and lead glass and source manipulation.

Temporary shielding can be employed effectively during source handling operations to reduce dose to workers. When selecting and employing shielding, users should consider:

- — Shield in excess or located in ways that impede work activities can actually increase dose to workers. Work performance against the potential dose reduction offered by shielding should be carefully evaluated to find an effective balance.
- — Appropriate shielding materials should be selected for use.
- — Leaded glass or other windows through which users can see when employing shielding between them and the source should be provided.

8.4.2. Fume cupboard

If leaking/contaminated low activity or radium sources are to be handled, a fume cupboard (or a glove box) is a simple, safe and effective means of protecting the operator and preventing the spread of contamination. A fume cupboard is a safety cabinet with an opening through which the operator can carry out manipulation inside the cabinet and with air being continuously exhausted from the cabinet at sufficient rate to prevent the escape of airborne contamination generated within the cabinet (Fig. 51). Temporary shielding in the form of lead bricks could be assembled inside the fume cupboard to reduce operator dose when handling high dose rate sources. This approach would minimize cost and maximize the flexibility of providing a safe working environment for operators.

FIG. 51. Glove box handling of low activity sealed sources.

In the fume cupboard, where space is at a premium, the maximum separation of operator from sources can be achieved by the use of forceps or long tongs (Fig. 52).

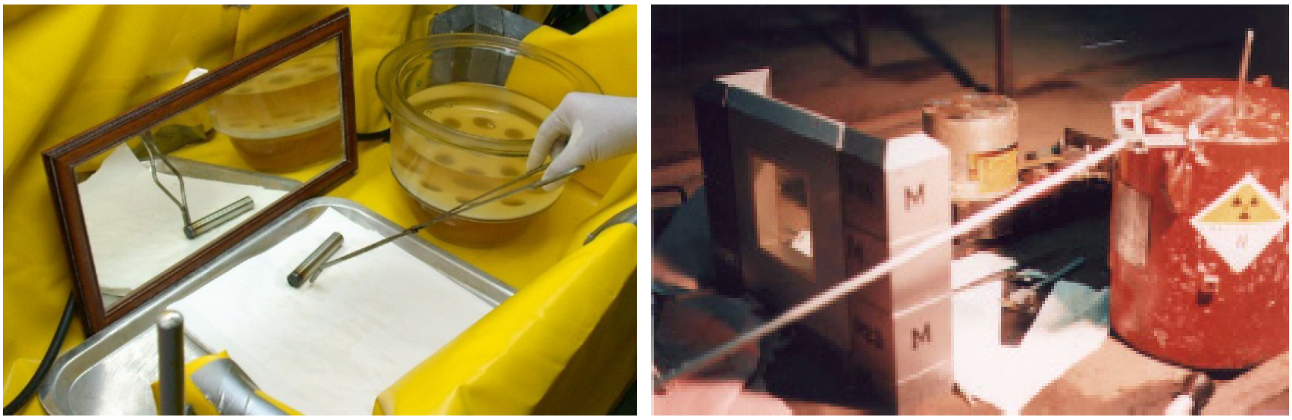


FIG. 52. Moving a sealed source using long handled tongs.

It must be recognized that handling work using tongs and forceps makes it possible to lift only small masses (maximum 2 kg in comfort).

8.4.3. Hot cells

It is not always possible to remove the high activity source from the equipment at the user's premises. This may be because the equipment was designed to be de-sourced in a shielded cell, or because insufficient technical information is available to do this safely outside a shielded cell. In such cases, it is necessary to transport the source in its operational shielding to be de-sources on receipt at a shielded facility such as a hot cell. Hot cells equipped with remote/slave manipulators vary widely in sophistication and complexity, but most of them are perfectly adequate depending on the sources to be handled (Fig. 53).

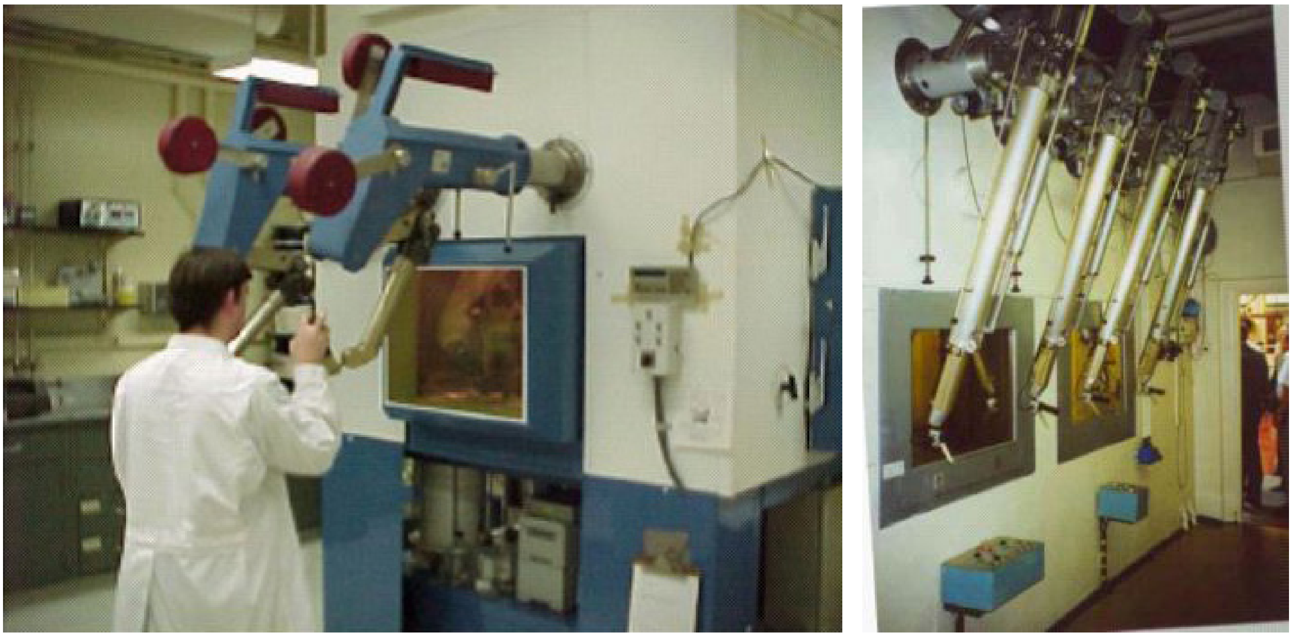


FIG. 53. Hot cells with remote/slave manipulators.

8.4.4. Containers

When relocating the disused sources on the site of the licensee, it is important that they are kept in the original container. In case of radiography or teletherapy equipment, the disused sources need to be properly kept in their shielded location. If other than original containers are used, the new container design should take into account the geometry of the source, radionuclide, its activity, and handling requirements. An example of a typical container used for on-site relocation is shown in Fig. 54.

FIG. 54. A container for sealed beta–gamma sources.

Containers or devices used to relocate an SRS on-site need to be appropriately labelled to warn of the potential hazard. It is important that the warning sign is in the local language, as well as the manufacturer's language. The use of the trefoil symbol on its own is not sufficient as people may not understand its meaning.

The main design requirements applicable to containers used for the relocation of SRSs on-site are as follows:

— The package shall retain containment and shielding integrity during the relocation process. The container needs to be mechanically closed when subjected to the physical stresses associated with transfer during relocation.
— The maximum dose rate on the container is required to be ALARA and in accordance with the licensee radiation protection requirements. In either case, the maximum dose rate should not exceed the dose rate limits stated in the IAEA Transport Regulations, i.e. <2 mSv/h on the surface and <0.1 mSv/h at 1 m from the surface of the package at any time during the transfer [47].
— Radioactive contamination of the container surfaces should be as low as possible and in accordance with the licensee radiation protection requirements. In either case, the radioactive contamination should not exceed limits stated in the IAEA Transport Regulations: 4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, and 0.4 Bq/cm^2 for all other alpha emitters.

8.4.5. Lifting and transfer equipment

Various lifting and transferring equipment is used for disused sources depending on their activities, size and weight. An example of the lifting equipment used for a heavy teletherapy head is shown in Fig. 55.

FIG. 55. Rigging and lifting of a teletherapy head.

Normally, a hand pulled trolley, with a 500 kg capacity would be adequate for the transfer operation. A manually operated forklift with drum grab attachment would be required in the store to off-load the source from the trolley. An electric forklift (Fig. 56) would certainly require less manual effort, and would be most appropriate for heavy disused sources and if a large number of sources were to be handled in a short space of time. In addition to a fork lift, a jib attachment to it will allow the lifting of heavy sources (Fig. 57), their transfer around the facility and for removing shielding pots from transport containers, as well as lifting straps, shackles, chains and eye bolts.

FIG. 56. An electric forklift truck.

FIG. 57. Handling a 200 L waste drum with a forklift truck.

8.5. PROBLEMS ENCOUNTERED WITH HANDLING OF HIGH ACTIVITY SOURCES

The source preparation for storage can take two forms: source may be removed from its operational location and transferred to a storage site within the control of the user organization (this option is applicable to Category 1–5 sources). Alternatively, the source may be put in safe storage at the operational location (this option is considered mainly for Category 1 sources).

If the first option mentioned above is selected for Category 1 and 2 sources, sufficient infrastructure (i.e. industrial and nuclear) is required to implement the option. The process at this stage includes neither separation of the sources from the working shield nor disabling of any interlocking mechanism or safety feature, thereby retaining the source within its shield and in the unexposed position. Transfer of the source from its working shield to a transport container needs to be carried out by trained personnel according to approved procedures. The transport container is specifically designed for the equipment, in which the transfer of the source can be completed without exposing the source. It is important to emphasize that the effectiveness of the original shield and any safety/security features is maintained at this stage of the operation.

If the Category 1 equipment is facility fixed, on-site storage is an option that could be implemented, keeping the source in its unexposed position (Fig. 58). Measures need to be taken to guarantee that the source is maintained in the unexposed position, protected from environmental conditions, and the possibility for intrusion is minimal. Inspection of such a facility needs to be carried out on a routine basis. If the source's safe storage status (shielded position) is achieved by wet storage (in case of pool-type irradiators), the quality and level of the water must be maintained for the entire duration of storage.

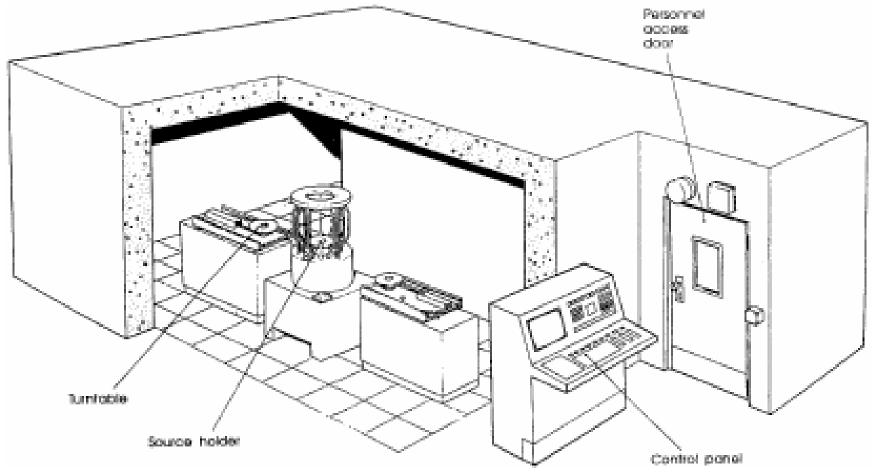


FIG. 58. A panoramic view of a typical dry source storage irradiator.

The Category 1 source needs to be further secured by adding securing mechanisms to ensure that the source is not exposed inadvertently. However, the mechanisms need to be designed in such a manner that source removal is possible at a later date. A durable tag needs to be attached to the security mechanism, identifying its function, reason for installation, warnings or precautions that should be made known, and reference to any instructions and authorization that may be needed for their removal.

9. STORAGE

Storage is defined as the holding of radioactive sources, spent fuel or radioactive waste in a facility that provides for their/its containment, with the intention of retrieval [1]. It is by definition an interim measure, which might be arranged on-site or at a specifically designed and constructed storage facility. The Code of Conduct expects that every State should ensure that sealed sources are not stored for extended periods of time in facilities that have not been designed for the purpose of such storage. The choice of how best to manage the period of storage while awaiting final decommissioning and disposal should be made by the principal party, with the approval of the regulatory body, with account taken of the particular circumstances in the facility [30].

Storage at the user premises (so-called on-site storage) of a DSRS may be required either to allow the source activity to decay to clearance levels [11, 57–59] or prior to its transfer to another location. With the approval of the appropriate regulatory body, a source containing a total activity or a concentration of activity less than the exemption levels specified in the BSS [11] may be may be exempted from some or all of the requirements of the BSS for notification, registration or licensing, and could be disposed in an approved landfill. The on-site storage period should be as short as practicable. It should be noted that keeping a DSRS in on-site storage without following appropriate requirements is the most common cause of accidents and loss of control of sources. However, it should be recognized that there might be no viable alternative to on-site storage for some time to come.

Administrative controls and security are not likely to be sustainable at the user’s facility for the time period required for the source to decay to required levels. On-site storage needs to include plans for such a transfer, and the condition of sources in storage needs to be maintained to facilitate transport and source retrieval from the source holder at this stage.

Countries that make extensive use of SRSs and with DSRSs in many institutions need centralized storage and an appropriate storage system for DSRSs. An IAEA reference design for a centralized storage facility for DSRSs is described in Ref. [60]. It needs to be emphasized that most of the Member States do not have appropriate disposal facilities available and, therefore, in most cases, long term storage is the only alternative management option for DSRSs in the foreseeable future. In practice, a central store is typically not used exclusively for conditioned DSRSs, but for other types of low and intermediate level radioactive waste generated in the country.

A package containing a DSRS shall be considered as the first barrier to release of radioactivity to the environment. The most significant barriers are first and foremost the source capsule itself, and secondly the container. The final physical barrier to the release of radioactivity is the storage building. The storage building will need to provide sufficient protection to the stored sources so as to optimize the life of the packages, and this may necessitate control and monitoring of the building’s environment. Safety requirements for the protection of human health and the environment shall be met by appropriate design, construction, operation and maintenance of the respective facilities and by appropriate design of the packages intended for storage.

9.1. DESIGN REQUIREMENTS FOR DSRS PACKAGES

Each waste package, containing a DSRS and intended for storage, is expected to meet a basic set of requirements (typically called waste acceptance criteria (WAC) or waste acceptance requirements) specified by the storage facility operator [61, 62]. These requirements are based on the safety assessment and related considerations, as well as on technological and legal issues. The requirements are normally reviewed and approved by the regulatory body or can be specified by the regulatory body itself. The general storage acceptance requirements for waste packages are described in Ref. [61]. In application to DSRS, a package intended for storage shall:

(a) Consist of a container and an incorporated source and may have an additional containment system if required (e.g. liner or overpack) that holds the radioactive contents during storage and ensures that any releases of radioactive material remain below the specified limits.
(b) Have a lid with fastening devices to prevent the lid from detaching from the container body during routine handling and storage activities.
(c) Have the contact dose rate and contamination level in compliance with the requirements of the storage facility. If a package is contaminated, measures need to be taken to contain the contamination during the

expected interim storage period. A maximum allowable dose rate at the surface of each package needs to be established for specific interim storage facilities or parts of facilities.

(d) Provide adequate passive cooling of the high activity sources (heat generating waste) if present.

(e) Have a certain mechanical strength to hold a stack of several (to be specified for a particular storage facility) packages.

(f) Be uniquely identifiable and have a nameplate that includes package type, serial number, weight, and register ID (examples of the labels are given in Fig. 59).

FIG. 59. Labelling of packages prepared for storage and transportation.

If a disposal facility is available, the repository WAC need to be compared with the WAC of the storage facility and the most limiting criteria should be chosen for the DSRS packages. Source packages may be subject to additional constraints due to limitations, or special conditions, present at the storage facility, which do not exist at the disposal site. For instance, floor loading and entrance dimensions may limit the package size and weight permitted for storage.

9.2. DESIGN REQUIREMENTS FOR STORAGE FACILITIES

Functional requirements for the storage system must take into account all requirements of the system's users, including their own specificity and interests; they must be based on objectives and tasks of the system. The safety requirements established in Ref. [27] relating to the protection of human health and the environment are applicable to the storage of radioactive waste, including the storage of DSRSs.

The design requirements for the waste storage facilities are described in detail in Refs [61–63]. If appropriate, a storage facility should have a simple robust design, contain minimal installations, avoid sophisticated automatic systems, rely on passive safety, and keep operation simple and cost effective.

General design requirements for storage facilities for DSRSs are as follows:

(a) Storage facilities should be designed to minimize the probability and consequences of incidents and accidents. Retrieval of sources for conditioning, reconditioning or for relocation in the event of an accident shall be provided.
(b) The store shall be capable to maintain the integrity of the source and its container or device until those are dispatched to another location (i.e. repository). Consideration needs to be given to ensure protection against environmental effects, e.g. rain, moist, flood and fire.
(c) Location of the store needs to be separate and remote from working places or other areas regularly visited by personnel or public.
(d) Easy access, including transfer of sources to and from the store (e.g. lift transfer rather than a staircase) is required.
(e) Floor loading capacity needs to be taken into consideration.
(f) Physical barriers against intrusion, which could include, as appropriate, surveillance, high- security locks, alarm system, trained guards or any combination of these. The physical protection measures need to be viewed as a whole, taking into account the combined effect of individual precautions.
(g) Clear on-store and perimeter markings and warnings are needed to indicate presence of radioactivity and restricted, unauthorized access. Warning signs should be designed to ensure that the nature of the risk is obvious to personnel who may encounter it. These signs need to be installed even though security measures are in place and written in languages that are understandable by the persons who could possibly enter the facility.
(h) The store needs to be large enough to permit the sources to be stored in an orderly manner and able to visually identify the individual groups of sources.
(i) Smooth surfaces are needed in the store to facilitate possible decontamination.
(j) The store design should allow for the storing separately of DSRSs and non-radioactive material.
(k) The store design should allow for the storing separately (in clearly separate areas in the store) of the sources for decay storage, sources in use, and sources not suitable for decay storage.
(l) Category 1 and 2 high activity sources need to be stored preferably in a separate store, or at least separately in a clearly identified area. Persons authorized to access this store or area should have appropriate training regarding the presence and significance of these sources.
(m) The store design should provide shielding (either as walls or movable shielding material) to ensure that the dose rate at any accessible point within or outside the store does not exceed the applicable limits prescribed by the regulatory body. Self-shielding principles could also be applied, thus arranging sources in such a manner that it provides shielding for other sources. Where frequent personnel access is needed to the store, it is important to consider installation of appropriate shielding.
(n) Appropriate ventilation needs to be provided if the release of airborne radioactive material can be expected, in particular when significant quantities of ^{125}I, ^{131}I or ^{226}Ra are stored.

Some old storage facilities consist of above and below ground compartments. Generally speaking, the underground facility is favourable in terms of shielding. However, in the underground part, a more humid environment was noticed.

It is important that the storage facility is licensed by the regulatory body, in case it was not already included in the operational license. The license may include some specific requirements for the particular facility.

9.3. OPERATIONAL REQUIREMENTS FOR STORAGE FACILITIES

The operations carried out in a storage facility are limited to receipt, emplacement, integrity control (if required), retrieval, and preparation for dispatch of DSRS packages. The storage operations are essentially passive for the long period of time when packages are waiting pending retrieval until the repository facility is established. All operations concerned with storage need to be carried out in accordance with the written authorized procedures.

9.3.1. Receipt and emplacement

The storage areas are designated and operated as controlled areas to limit the spread of contamination and to minimize the exposure of workers to ionizing radiation. Adequate protective clothes/equipment need to be made available and worn/used as required.

The DSRS receipts should be planned in advance. The store operator examines the information to confirm that the source package is acceptable for storage, e.g. that it conforms to the storage WAC. If unacceptable, the details should be recorded and the documents returned to the consignor with an explanation, or request for further information. In the case of external contamination, the package has to be decontaminated and rechecked before acceptance for storage.

The design of the facility should usually permit package stacking, sorting, and visual inspection. On acceptance, the store operator needs to prepare the appropriate documentation to store the sources. At the store, a suitable location for the DSRS package needs to be identified and the location details recorded. The package should be placed in the designated location. Segregation of sources is desirable to facilitate retrieval for further reconditioning or any unplanned retrieval, which is deemed necessary by periodic inspections for possible degradation of source containers, or in the event that there are particular categories of sources to be emplaced eventually in particular disposal facilities. The records of the store inventory need to be updated, and periodic checking of the store contents against the records is required.

An example of segregated storage is shown in Fig. 60.

FIG. 60. Segregated storage of radioactive waste, including DSRSs.

9.3.2. Additional shielding

Additional shielding to that envisaged by the design in the store may be provided for the packages with high contact dose rates and where a large number of packages with low contact dose rate are placed in the store.

9.3.3. Integrity control

As the long term effectiveness of engineered or natural barriers against the release of radioactivity into the environment cannot be guaranteed for all future conditions, a monitoring programme for the storage area needs to be established. If technically feasible, monitoring is needed between the individual barriers (e.g. the package, the storage boundary and the facility boundary) so that migration of radioactivity is detected well before spreading outside the facility. In this case, measures need to be taken to minimize the spread contamination. Therefore, it is advisable to perform and record initial background measurements of the storage facility before it is commissioned. The frequency of monitoring will depend on the number and types of DSRS packages.

The effectiveness of the ventilation system needs to be included in the surveillance programme. Radiation monitoring and personal dosimetry is mandatory.

9.3.4. Retrieval and dispatch

Following receipt of the request to retrieve a package from storage, the store operator needs to obtain the details of the particular package from the store's records and pass them to the appropriate party. If the details are in order, the package may be approved for retrieval from the storage facility. Once the store operator has authorized the release of the package, the package is retrieved from the store and taken to the dispatch area. Here, the package is subjected to radiological monitoring for contamination and radiation levels before it is released. The details of the package are transferred to the transport records, and the package is submitted for transport in accordance with the transport regulations [47]. The package storage records need to be amended to record the date of dispatch and the receiving party.

9.3.5. Security systems

Security systems to prevent intrusion need to be an integral part of a storage facility. A typical security system includes features to delay access, detect unauthorized access and provide an alarm and response system. An example of the secure storage facility is given in Fig. 61. The operational personnel shall ensure its uninterrupted service under all foreseeable circumstances.

FIG. 61. A secure storage facility.

Access to the storage areas needs to be strictly controlled in order to prevent losses of stored materials, since this may not be detected until some considerable time after the removal has occurred. In the stores, security is usually achieved by locking the premises. Personnel with authorized access need to be kept to the minimum. Seals can be used for the detection of any unauthorized access. Other appropriate security measures (such as guards, barbed wire fencing, surveillance cameras, alarm systems, etc.) and regular stocktaking need to be considered in the context of the prevailing security situation. The effectiveness of the security system needs to be regularly audited and updated.

9.4. EXAMPLES OF ON-SITE STORAGE FACILITIES

A large number of alternative storage systems may be envisaged, which would meet the aforementioned requirements. Depending on the number of sources to be stored, arrangements for storage can range from an in-floor safe and a shielded cabinet to a dedicated building. This report only gives a few examples to illustrate possible storage options. A user may find that one of these options will meet his/her individual requirements, but it should be stressed that other arrangements may be also be suitable, taking into account the local conditions. Among the various suitable options available, the most cost effective option needs to be evaluated.

9.4.1. In-floor safes

This option, which is only suitable for smaller sources and a limited number of small size containers, utilizes in-floor safes that are mass produced, inexpensive, readily available and recognized as a secure system. Unauthorized intrusion is quite difficult. The removal of the safe itself would be very difficult, in particular if the safe is installed in the building foundation. A photograph of a typical in-floor safe is shown in Fig. 62.

FIG. 62. A typical in-floor safe.

The safes, with storage capacity ranging from 30 to 60 L, provide protection from various physical attacks, such as use of levers, sledge hammers, grinders, drills, oxyacetylene torch and explosives. These safes can be capped with reinforced concrete and converted to a system that provides long term storage where access is restricted and the required surveillance is minimal.

9.4.2. Intrusion resistant rooms

This scheme is suitable for all sizes of packages. An intrusion resistant room would typically be constructed with concrete walls, equipped with a secure door, high security locks and an intruder alarm. Small and medium sized packages can be placed on shelves (Fig. 63), while large containers are placed on the floor (Fig. 64). As an additional security measure, in-floor safes, each housing several small packages, may be located in an intrusion-resistant room. This system can provide secure storage for a large number of sources, but still offering easy access when required.

FIG. 63. Storage of DSRSs on the shelves.

FIG. 64. Storage of DSRSs on the floor in the intrusion resistant room.

9.4.3. Concrete bunkers/vaults

A reinforced concrete bunker or vault could be used for the storage of small, medium and large containers, depending on the size of the bunker. A relatively small bunker with a capacity of a few cubic metres and designed with a heavy lid could serve as an inexpensive but secure system for the storage of small and medium size packages.

A larger vault with a heavy lid could house large packages, as well as small and medium size ones, and would be useful where there are a large number of sources for storage (Fig. 65). If required, these bunkers could easily be converted into long term storage facilities by sealing the entrance with reinforced concrete, requiring minimal surveillance.

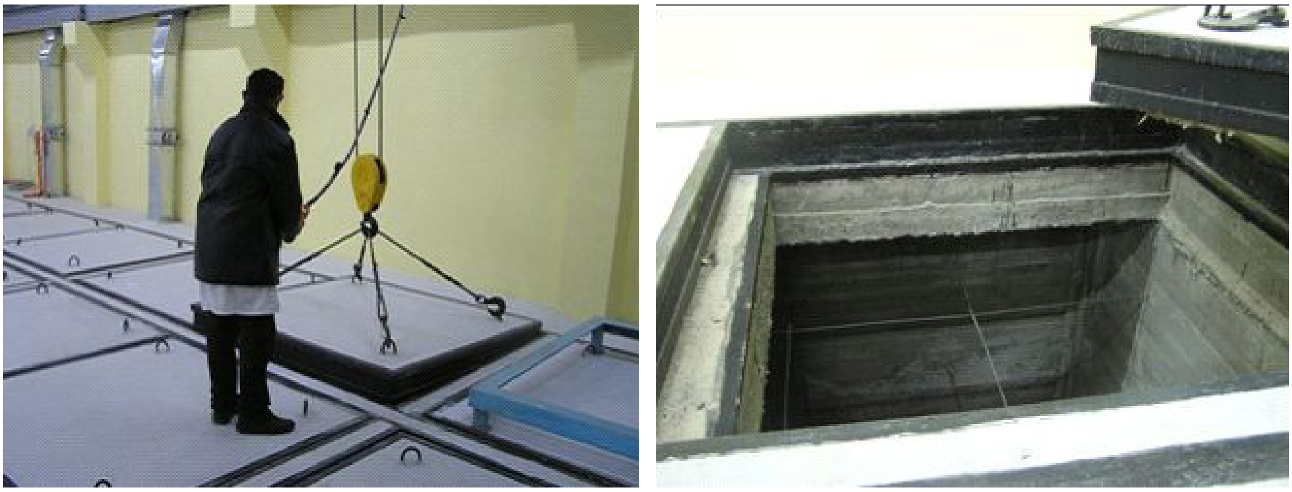


FIG. 65. A concrete vault for storage of DSRSs.

9.4.4. Comparison of the on-site storage systems

The storage facilities described above are compared in terms of various characteristics given in Table 7 [15]. These characteristics represent the key features of the various storage options, offering individual users a simple means of selecting an appropriate option.

TABLE 7. COMPARISON OF ON-SITE STORAGE SYSTEMS [15]

Type	Safe	Intrusion resistant room	Intrusion resistant room with safes	Concrete bunker
Capacity	Low/medium	High	High	High
Cost	Low	Medium	Medium	Medium
Flexibility (container size)	Limited	High	High	High
Containment	Good	Good	Good	Good
Radiation protection	Medium	Good	Good	Good
Security	Good	Good	Very good	Good
Access	Good	Very good	Good	Poor
Surveillance required	Regular	Regular	Regular	Infrequent

9.4.5. Problems encountered and lessons learned

9.4.5.1. Insecure and unsafe storage

Storage under insecure conditions can lead to access to DSRSs (sometimes of very high activity) by unauthorized personnel, followed by potentially serious radiological consequences. An example of insecure storage conditions is provided in Fig. 66: the head of a disused teletherapy machine (i.e. the radioactive source) was accessible, with just a cover hiding it in the corridor of the hospital.

FIG. 66. An example of insecure storage conditions.

Dismantling of the source from its holder is not recommended at the user's site, but only the removal of the holder from the equipment is advised. It is important that the shutter is placed in a locked position. This, however, should only be attempted by personnel trained in the use of the specific equipment as the safety of the holder could be compromised by the dismantling. The dismantling of the teletherapy unit by untrained personnel can lead to radiation exposure and physical injury (see Fig. 67).

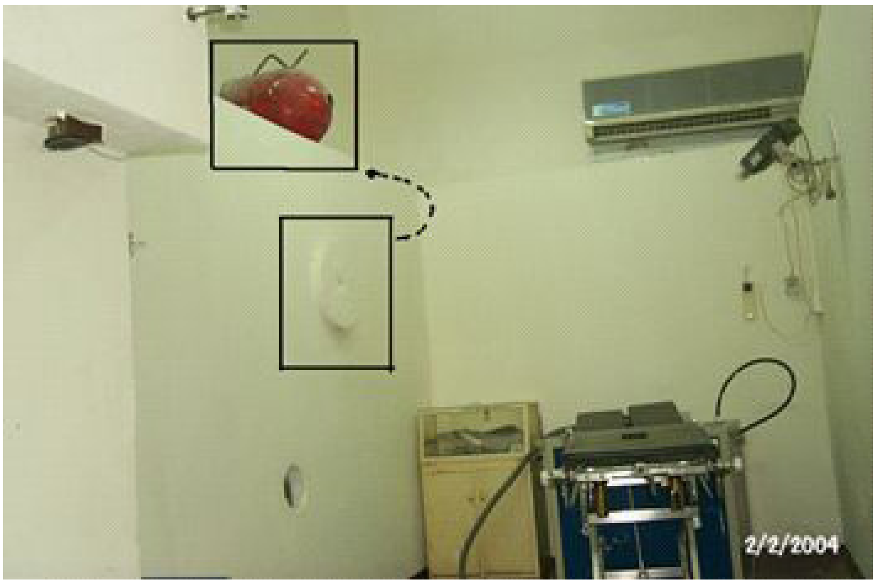


FIG. 67. A partially disassembled teletherapy machine (the head was cut although the drawer was in the machine).

When a source is left intact in the installation, it can lead to a potentially hazardous situation. For example, a former radiotherapy room was used as a dressing/storage room by the staff of the hospital (Fig. 68). The employees did not recognize that a radioactive ^{60}Co source was left stored in that room. Fortunately, the source was rather weak, so no significant exposure occurred, although the source drawer was not locked in the storage position.

FIG. 68. The drawer containing a ^{60}Co source was not removed from the teletherapy machine.

In some cases, storage facilities are not in compliance with the security requirements and, as a consequence, unauthorized persons can enter the store and steal the sources or the shielding material (Fig. 69).

FIG. 69. The seldom and irregularly visited radium sources store.

9.4.5.2. Unfavourable storage environment

Adverse environmental storage conditions, including high humidity, temperature fluctuation, may lead to the degradation of the source or container by corrosion (see Fig. 70) and may damage labels on sources and containers (see Fig. 71). Care should be taken to ensure that source data are not lost and that all labels are protected and their information recorded during the relocation operations.

From experience, it has also been found that corrosive conditions in a storage facility may lead to holder deterioration and failure of the shutter mechanism, which can contribute to difficulties in source removal.

FIG. 70. Corroded containers.

FIG. 71. Deterioration of the label on a source container.

9.4.5.3. Lack of radiation warning

Sometimes, the storage facility is not labelled properly to warn of the presence of radiation hazard (see Fig. 72). For example, the labels are not written in the local language and the significance of hazards is not understood by the local population. It should be noted that sometimes the warning signs are not placed on doors by management purposely to avoid the attention of people who do not understand the meaning of the signs or the word 'radioactive' and believe that some valuable goods are stored behind the locked door. This may lead to intrusion of unauthorized persons into the on-site storage facility.

FIG. 72. A storage building without a warning sign or label.

An additional risk to the personnel and general public is when radiation and contamination levels are not regularly measured.

9.4.5.4. Fire risk

If DSRSs are stored with other non-radioactive material, for example inflammable material, it may cause damage or start a fire (see Fig. 73).

FIG. 73. Inadequate storage of DSRSs.

9.5. EXAMPLES OF CENTRALIZED STORAGE FACILITIES

Centralized storage facilities available in Member States fall mainly into two categories — surface facilities and subsurface (underground) storage facilities, some of which were originally intended for waste disposal. A surface and subsurface storage facility could be fully engineered or partially engineered [61].

Subsurface storage basically is the emplacement of waste packages in engineered near surface (subsurface) facilities, frequently featuring a solid base of concrete with suitable backfilling material, which still allows retrieval of the waste.

Surface storage refers to any building or structure on the surface destined specifically for the storage of waste packages. Surface store designs are, in many cases, based on the need to handle large volumes of waste packages in drums or boxes. These stores may range from basic enclosures to highly engineered facilities, incorporating shielding structures and remote handling equipment, and provided with ventilation, effluent collection, and instrumented controls.

In the past, area storage was used for temporary storage of Category 1 sources in cases when no adequate subsurface or surface storage facilities were available (Fig. 74). The lack of protection of the waste packages from the environment and unsatisfactory security conditions made this storage option inadequate and unacceptable according to modern safety and security requirements.

FIG. 74. Inadequate area storage of RTGs.

9.5.1. Subsurface storage

There are various options for the subsurface (underground) storage of DSRSs. The storage options include dry storage, such as well type stores (Fig. 75), tube stores (Fig. 76), or shielded vaults (Fig. 77). This type of storage provides very good physical protection and shielding of stored DSRSs. A storage facility may need to use more than one of these options in order to provide appropriate storage for the full range of disused sources that are received at the facility.

FIG. 75. Preparation and loading of ^{60}Co DSRSs in a well type storage unit.

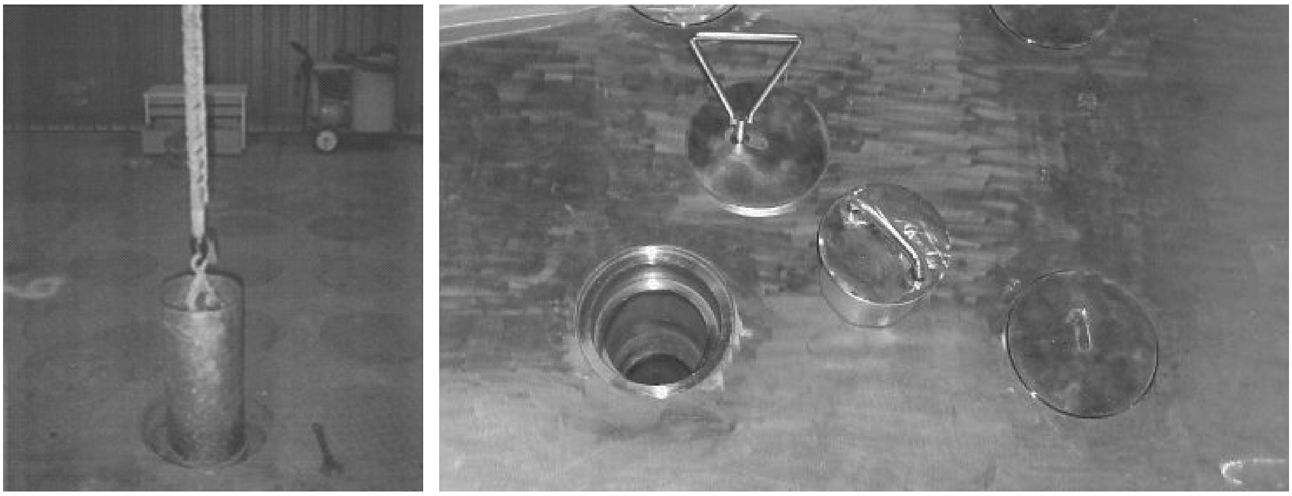


FIG. 76. A pipe store for sealed sources.

FIG. 77. The concrete vaults used to house concrete boxes.

Following a period of interim storage, it is likely that the waste containers will be retrieved for further conditioning and repackaging prior to disposal. Practical issues that need to be considered when using this approach include:

— The need to segregate sources when placing them in the store;
— Heat generation, activity and dose rate limits for each container and for the store;
— The future need to retrieve, condition and transport the consolidated sources;
— The need to ensure that the highest level of groundwater is below the bottom of the vault.

9.5.2. Surface storage

Engineered storage facilities for DSRSs may be different by design due to radiation risk involved. An engineered storage facility for Category 3–5 DSRSs may be of simple construction, for example a building on a concrete base pad with a steel frame construction and corrugated metal sheets covering the walls and the roof (Fig. 78). Alternatively, a warehouse type construction with no arrangements for package handling and heating or ventilation is widely used.

FIG. 78. A light construction waste storage facility.

More sophisticated engineered stores with full engineered features are more appropriate for longer period storage of the DSRSs exhibiting high surface dose rates. The storage facilities may include arrangements for package handling, shielding with concrete (or equivalent), remote inspection, ventilation, temperature control, effluent collection, and building surfaces prepared to facilitate decontamination. The minimum construction standard for these stores is an adequately shielded, warehouse-type building with a solid floor and adequate safety provisions for waste package inspection (Fig. 79).

FIG. 79. A robust waste storage facility.

Another type of area storage is the placement of DSRSs in the larger container which, at least, provides better physical protection of the stored packages. An example of a simple area storage facility (ISO shipping/storage container) is given in Fig. 80.

FIG. 80. Large scale ISO freight containers.

The container can be placed in a suitable place, i.e. at a centralized collection site, in a small nuclear research centre, a nuclear power plant, or a guarded area under government control. Depending on the size, between 40 and 70 200 L containers can be stored inside. Later, when a repository is available, the containers can be transported directly without requiring additional reloading steps.

At the end of the storage period, it is important to ensure that identification, retrieval and transport of the conditioned sources to the disposal facility are possible. Packages need to be stacked in a systematic manner to allow easy access and retrievability, if required, taking into consideration the use of forklift or crane access to all locations, as well as the ability to reach and retrieve any package.

9.5.3. Problems encountered and lessons learned

9.5.3.1. Subsurface storage

Underground wells (shallow boreholes and vaults) have been used for the storage of DSRSs in many Member States for many years. Generally speaking, the underground facility is favourable in terms of shielding and security. However, this storage option has been reconsidered in some Member States. Originally, some facilities were intended for disposal of DSRSs and the retrievability of sources was not considered. The cost of retrieval of these sources today, coupled with the risk involved, has demonstrated that this option is not a prudent one, especially for long term storage of DSRSs (conditioned and unconditioned). Sub surface storage may be considered where storage time is very short and climatic conditions are favorable i.e. dry climates and location remote from inhabited areas.

9.5.3.2. Surface storage

Location of the storage facility

Some storage facilities were located in areas with a potential risk of flooding (low lying area). This resulted in the degradation of containers with DSRSs.

In some cases, the storage facilities have been constructed too close to the site boundary, thereby restricting the dose rate of disused sources stored in the facility and/or requiring additional shielding within the facility. This also restricts handling high activity sources in the vicinity of the storage facility. In other cases, storage facilities appeared to be located too close to the national borders because of political changes leading to the creation of new independent states.

Beyond the technical and political aspects to be considered in the siting of storage facilities are the issues of acceptance by the local population of these facilities. The acceptance of the facility and plans play a major role and may have a relevant influence in the technical field.

Design features

Environmental storage conditions

Past experience demonstrates that in some facilities waste packages with DSRSs could be stored without any degradation during tens of years but over the same time period revealed deterioration of waste packages in other facilities after a certain period of storage. Degradation of waste packages over time becomes a very important issue, particularly when the storage time needs to be extended.

Experience shows that the atmospheric conditions inside the storage facility have a major influence on the longevity of the packages. Depending on the climate, air quality control systems could be installed inside. Cooling or dehumidifying equipment could be installed to avoid or minimize external corrosion/degradation of the waste container. In the design, not only the conditions in a completely loaded facility should be considered but also situations where the facility is partially loaded: air conditions, air flow and humidity conditions might be very different under partial and full load conditions.

Failure of DSRS packages during storage has occurred sometimes owing to mechanical damage of the container during handling. The damages ranged from paint scratches which accelerated corrosion of the container material to destruction of the container. Container defects tend to manifest themselves early, and this is a good reason to segregate sealed sources by the date of conditioning. In this way, systematic problems with container integrity can be avoided. The longer the DSRS is stored, internal or external influences can make package failure more likely.

Experience also shows that many containers that had been designed for transport of sources are inadequate for extended storage. If transport regulations are not an immediate concern, i.e. for extended storage, then alternative and less costly storage solutions for containers should be considered.

Past experience has also shown that the design of the storage facility should allow for flexibility, modification and expansion, particularly when disposal options (including waste acceptance criteria) are not finalized and the storage time needs to be extended. In this regard, it is advisable to design and construct modular extendable storage facilities, allowing for expansion if necessary. Such modular storage facilities already exist in some countries including the United Kingdom and Slovakia.

Smaller source containers are usually stacked to enhance the capacity of storage buildings. Older sources were often packed into non-standardized containers, often not qualified for stacking. It is practicable to put those irregularly shaped packages into standardized (temporary) overpacks to facilitate stacking and thus increase storage efficiency.

As result of different operational storage activities, or as result of penetrating water into the storage facilities, some small quantities of usually very low level secondary liquid radioactive waste aroused. This confirms the necessity of the installation of an appropriate system for collection and treatment of such waste. Similarly small amounts of solid waste result from monitoring activities (e.g. probing for surface contaminations on packages and the inner wall and bottom) and from handling activities (e.g. protective clothes). Measures for its collection and treatment need to be proposed by design.

Retrievability

Even if carefully evaluated, the failure of single packages or groups of packages cannot be excluded during storage. In early periods of operation, DSRSs were placed into boreholes or concrete bunkers which were subsequently backfilled with sand and then covered with concrete. Inspection of these sources was simply impossible. This has significantly complicated the process for retrieving these sources, and the addition of the sand has significantly increased the volume of radioactively contaminated waste that will need to be placed into a disposal facility. This practice is not considered appropriate, either for short term or for long term storage.

Maintenance

In some cases building structures of storage buildings have failed in the past. Reasons for those failures were the use of building materials with inappropriate ageing properties, missing quality control, wrong static building layout, underestimation of settling properties of the structures or underground, etc. Replacement of those failed structures is difficult, costly and may require temporary removal of waste containers to another location. Experience shows that storage facilities must have high quality in design and constructive materials and techniques in order to reduce the need of these operations. During operation of the storage facility building structures need to be inspected closely and settling should be regularly measured.

Control measures may include measurements of the structure and foundation and regular inspections and they need to be planned in advance. Installation of monitoring equipment in high radiation areas is hazardous and should be suggested in the design stage. Frequently almost all space in storage facilities is filled with containers, making finding problems difficult.

Other attributes of importance to be monitored include the operability of cooling equipment where heat generating sources are stored, as well as the operability of monitoring instrumentation.

Access to store and packages

In some cases, old storage facilities have been designed and constructed with the same access for operational staff and for transport vehicles loaded with radioactive waste. This was the reason for some accidents and it infringes the radiation protection rules. Taking into account this lesson, the storage facility should include double and easy access.

The storage facility must be designed to guarantee access to all waste packages. This is very important to facilitate placing the containers but also assure regular control and inspection of packages.

Communication

Many storage facilities are located away from other operating nuclear facilities and are often visited by a single individual, emphasizing the need for communication. In the facility design a proper level of internal communication should be ensured between any staff performing works and the central control room.

Operational procedures

Inspection of packages

Although past practices have not always permitted the periodic surveillance of DSRS packages in storage, inspections and monitoring of the contents of the storage facility are now required unless the packages are subject to a comprehensive management system (former the quality assurance) from the time of generation.

Containers should allow proper manipulation, monitoring, inspections and repackaging of sources. Stacking in arrangements, such as columns, facilitates access and ease of handling and permits inspection. Handling and lifting devices require inspection and monitoring, as they are just as susceptible to corrosion as the waste containers themselves. Sufficient funding and staff must be available for this purpose.

The storage shed is usually filled from the back to the front. At the time of retrieving the containers, a corridor or a back door can allow to retrieve the older containers first. Otherwise, one must to empty the whole shed to reach the older containers.

The accumulation of dust inside the storage facility has been observed that may complicate the access to the packages and demand cleaning operations which can be costly in terms of radiological protection.

Environmental monitoring

Despite efforts during design and operation to make structures leak-tight and watertight, water ingress has occurred. Significant efforts have been spent determining the source of water in storage structures. An extensive groundwater monitoring programme is needed to identify unanticipated releases from waste encased in, for example, concrete. In other cases, it has provided evidence that storage facilities are functioning well after many decades.

10. CONDITIONING

Conditioning, according to the IAEA Safety Glossary [1], is "those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, packaging of the waste in containers (encapsulation) and, if necessary, providing an overpack."

Conditioning of DSRSs ensures containment of the radioactive material, provides for greater confinement of leaking sealed sources, provides sufficient radiation shielding, reduces storage/disposal volume by allowing for consolidation of multiple sources into a single storage/disposal container, facilitates transport operations and contributes to safety and security as well.

The ability of an organization to condition disused sources depends, in part, on the parameters of the sealed sources, the end-point; the conditioning process adopted and the resources and materials available.

10.1. IMPACT OF PACKAGE ACCEPTANCE REQUIREMENTS

The optimum conditioning of a disused source would result in a package that meets all requirements for transportation, repatriation, storage and/or disposal, allowing for the handling of the disused sources one time. These requirements may overlap, may differ, or may not even exist. In any case, the source conditioner must ensure that the packages containing the sources are in full accord with the best engineering practices and experience of the Member State. The regulatory body and organizations operating or planning to operate transport services and storage and disposal facilities should be consulted in deciding which types of conditioning are necessary.

Typical WAC address a wide range of physical, chemical, and radiological parameters that are essential to safe and effective performance of the waste package. Some considerations for the WAC for storage of DSRSs are given in Section 9 and for disposal in Section 12. The IAEA Transport Regulations [47] place a set of overlapping criteria on the waste packages, which are transported from production or use to a storage facility and/or from storage to a disposal facility. These include surface dose rate, surface contamination limits, weight, size, total activity, and structural integrity requirements. Since some packages have a limited design life outside a disposal facility, WAC are considered important in providing assurance that, after storage, the waste package can still be safely retrieved and transported.

Under conditions of storage awaiting disposal, the DSRS package is required to maintain its physical and chemical integrity. Disused sources may need to be removed from their original shipping/storage containers and reconditioned and repackaged to comply with the waste acceptance requirements for a long term storage facility. The storage facility operator can refuse to accept packages that do not comply with WAC in accordance with the operator's license. Currently, in most countries, the waste packages for disused sources are developed solely for storage since no disposal facility is available for use.

It addition to the waste acceptance criteria for storage and disposal facilities, the potential for recycling/reuse, and repatriation of sources may introduce requirements for packaging and certification as well. Member States actively conditioning sources for storage with or without a currently identified disposal path should ensure that any actions taken in the conditioning process are reversible, as needed, to comply with future packaging requirements. For sources to be repatriated, the receiving Member State requirements might seem overly restrictive or involved, however, compliance with these requirements are essential for repatriation.

10.2. WASTE PACKAGE SPECIFICATIONS

Waste package specifications are a set of quantitative parameters that need to be satisfied in production of a DSRS package prior to storage or disposal [64]. These specifications are intended to control the radiological, physical, and chemical characteristics of the package to be produced, processed, or accepted from another organization. Waste specifications normally emphasize the performance of waste packages, or control of operating facility processes, and may be used as a contractual vehicle to control subcontracted conditioning operations. Waste package specifications, like WAC, should be cognizant of intended storage/disposal facility parameters and transport regulations, and incorporate relevant parameters of WAC, or in lieu of WAC, when those have not been developed.

While WAC are generally facility or site specific and may embrace many different types of package, waste package specifications are specific to a particular type of package, and used to define the characteristics and attributes of a waste package. The final waste package specifications should be consistent with the values used in safety assessments for the activities, especially assessments involving extended storage and disposal.

A potential weakness in the conditioning and storage of disused sources is the preservation of information on the conditioned radioactive material. Therefore, it is important to include all relevant information both outside and inside the package, using appropriately durable material available (stainless steel, aluminum, brass or copper, with punched or engraved data). It is essential to link a unique identification number to the archived records and to the waste package.

The following information should appear on the labels:

Encapsulation container	Unique identification number Isotope Activity Date of loading
Temporary housing (if operation is interrupted)	Unique identification number Approved radiation labels and warnings Isotopes and total activity
Waste package	Unique identification number Approved radiation labels and warnings Isotope and activity Date of conditioning Dose rate (at surface and at 1 m)

Conditioning of sources of one nuclide per container simplifies records and allows for easier subsequent management steps.

10.3. DESIGN REQUIREMENTS FOR CONDITIONING FACILITIES

The requirements for conditioning facilities will vary according to the volume and characteristics of the sources such as the nature of the radionuclides, the activity, the chemical composition and physical form of the source, its weight and dimensions.

Conditioning plants could be free standing or mobile facilities and may be adjacent to storage facilities to reduce the need for the transport of packages between locations for conditioning and for storage. In both cases they should be located in appropriately defined radiological zones.

Facilities for the conditioning of DSRSs should have sufficient technical abilities to condition different sources taking into account uncertainties in the availability of facilities for disposal. These abilities may include the equipment needed for the characterization of disused sources (radiation detectors, counters and spectrometers) and for dismantling of devices and other related structures such as hot cells. If the activity of disused sources is sufficiently low, safe handling may be performed in a glove box or fume cupboard with the use of appropriate shielding and tools (See Section 8.2).

In the design of a conditioning facility due consideration should be given to the need for:

(a) Protection against radiation exposure (by shielding and containment);
(b) The control of access to areas for source conditioning and storage and the control of movement between radiation zones and contamination zones;
(c) The retrieval of stored packages;
(d) Inventory control: archive of source and container designs;
(e) The inspection of the DSRS packages;
(f) Dealing with DSRS packages that do not meet specifications;

(g) The control of liquid and gaseous effluents;
(h) Ventilation and the filtration of airborne releases of radioactive material;
(i) Maintenance work and eventual decommissioning;
(j) Fire protection and the prevention of explosions;
(k) The prevention of criticality and safeguards control;
(l) Controls for the physical security.

10.4. OPERATIONAL REQUIREMENTS FOR CONDITIONING FACILITIES

Conditioning of disused sources is an activity for which an operating license has to be obtained. A safety analysis report is required as part of the license application. The operating license needs to define the scope of the conditioning operation, as well as any specific requirements that needs to be observed.

The detailed technical procedures need to be qualified with emphasis placed on the realistic capability within each country. These qualifications give assurance that the acceptance requirements can be met during the design and construction of the facility, the development of the technical procedures and during the actual conditioning.

Health and safety aspects need to be addressed in the operational procedures dealing with source conditioning. It is important that the conditioning process is properly planned, prepared and documented. Exposures, radioactive releases, and contamination levels need to be kept below authorized limits. Some operations, such as dismantling, encapsulating, remote-controlled welding, weld testing, and source leak testing, need to be conducted in controlled areas designed for this purpose (hot cells, glove boxes, etc.). Alternative procedures, according to prevailing conditions, can be developed but should comply with the same safety requirements. All procedures need to be tested and approved prior to implementation.

Conditioned disused sources should exhibit acceptable surface dose rates for transport and storage purposes. If the conditioning operating area or facility is situated at a distance from the store (as usually is the case), the facility needs to be equipped with suitable hoisting, transfer, and transport equipment with due regard to safety and maintenance requirements.

10.5. SELECTION OF A CONDITIONING METHOD

10.5.1. Selection criteria

There are many technical and non-technical factors that influence the choice of a conditioning method [52]. The following technical parameters and some other factors need to be taken into account while planning a conditioning operation for disused sources:

— Source characteristics (type of ionizing radiation, activity, half-life, chemical toxicity);
— Chemical and physical form of the radioactive material;
— The number and physical size of disused sources; and the physical condition of the sources;
— Compliance with regulations (e.g. acceptance requirements for storage and/or disposal, radiation protection and safety requirements);
— Storage period, storage conditions and location of a storage/disposal facility;
— Heat generation either due to source material and/or conditioning method;
— Proven conditioning technologies;
— Cost and resources (equipment, manpower and materials required for conditioning).

The relative importance of the aforementioned factors will depend on the particular situation in the country.

10.5.2. Selection of materials for waste packages

The selection of materials used for conditioning is very important as a source capsule could experience damage, resulting from external environmental conditions or chemical or physical attack from inside and outside.

The conditioning process needs to take into account the various potential problems, thereby minimizing the possibility of leakage.

The sealed source and its container should be compatible. Depending on the source characteristics and the method of handling, transport and storage, the container may also need to provide shielding for direct radiation. In selecting materials for the container and its outer surface finish, consideration should be given to the ease of decontamination. If a container is not initially designed to meet the relevant acceptance criteria for transport, storage or disposal, an additional container or an overpack will be necessary to meet the acceptance criteria. Care should be taken to consider the compatibility of the DSRS package and the overpack with respect to the waste acceptance criteria.

Improper conditioning could result in the release into the environment of the radioactive material in a disused source in the form of:

- Gaseous products (e.g. radon);
- Liquids (aqueous solutions, leachates, etc.);
- Solid particles (powder, aerosols, etc.).

Encapsulation material is selected to provide assurance that appropriate and effective containment of the radioactive material is available. In addition, the barrier materials selected should be durable and be able to withstand mechanical stresses and other environmental effects.

Therefore, the selection of the materials suitable for such barriers needs to take into consideration:

- Mechanical strength;
- Material degradation (the lifetime of a barrier should at least exceed the expected storage period in the storage area or the optimal time period covered by the quality assurance plan);
- Radiation effects in the barrier material;
- Corrosion and fire resistance;
- Impermeability to water and humidity;
- Radioactive decay products, especially in gaseous form;
- Source security.

10.6. CONDITIONING METHODS

The general management strategy for disused sources has been described in Section 6. It was stated that in the event that no recycle/reuse or return to the supplier/manufacturer options exist and that a disposal site is available, then the disused sources need to be disposed of in accordance with the applicable requirements as radioactive waste. If none of the previous options are practicable, then the disused sources will need to be placed into storage until a suitable disposal option becomes available. DSRSs should be conditioned to produce a package in compliance with relevant acceptance requirements.

10.6.1. Disused sources with short lived radionuclides

In case of well or pipe type storage (see Section 9.5.1), the DSRSs with short lived radionuclides were inserted into a stainless steel drawer (diameter 37 mm, length 500 mm), which had two appropriate shielding plugs at the ends. Then the drawer was sealed by TIG welding system and tested for leakage by the bubble test method. For loading of the drawer to the storage pipes, a bottom loading shielded transport container was used and the drawer could be lowered and raised into the storage position by remote handling. Prior to the loading procedure, the transport container is aligned to the pipe using a dummy drawer (Fig. 81). The sources are kept in a number of relatively small volume containers, with a few sources in each container. Recovery of an individual container is relatively straightforward.

FIG. 81. An inner rotating part of a B(U) type loading/unloading container.

Usually one container is able to keep two or three active and one dummy drawer in a rotating part. The advantage of this method is that it can be used as a standard drawer for different sizes of DSRSs. The activity of one drawer depends on the shielding provided by the transport container. The facilities of this type have been designed for both low activity and high activity DSRSs.

In India, the source containers, designed for disposal, are emplaced into tile holes. A tile hole is a cylindrical, concrete lined, steel container with an open top and is about 4 m deep. The outer surface is covered with concrete and treated with waterproofing material. The void space in the tile hole is filled with cement grout. The tile hole is sealed at the top with concrete and subsequently waterproofed. A schematic of a typical tile hole is shown in Fig. 82.

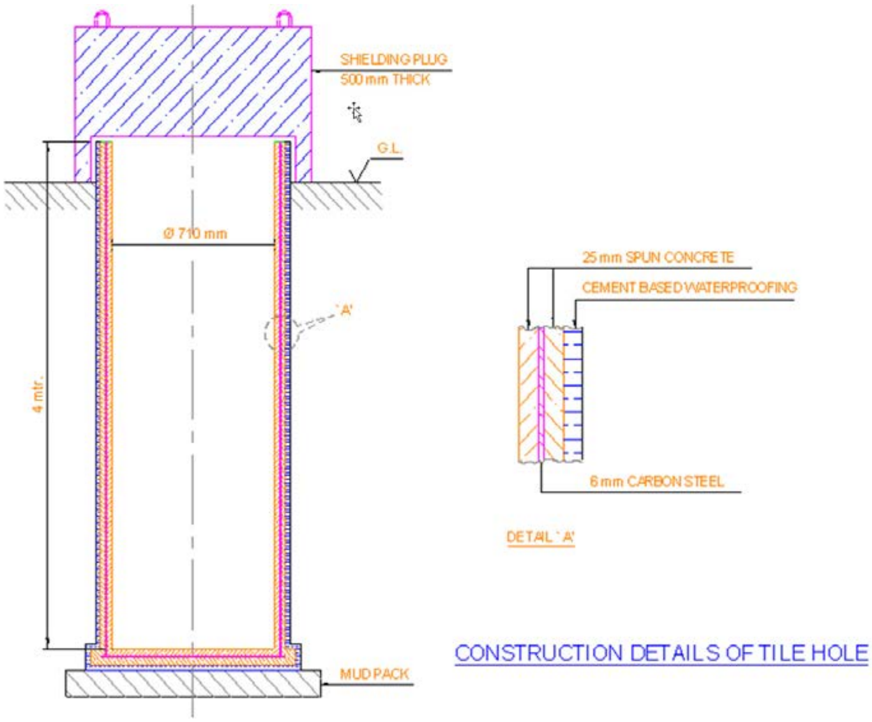


FIG. 82. A schematic of a typical tile hole.

10.6.2. Disused sources with long lived radionuclides

The most common long lived radioisotopes contained in sealed radioactive sources (LLDSRSs) are ^{238}Pu, ^{239}Pu, ^{237}Np, ^{241}Am, ^{226}Ra (alpha emitters) and ^{14}C and ^{63}Ni (beta emitters). Smoke detectors, lightning conductors and static electricity eliminators are examples of LLDSRSs, which can be handled without shielding. On the other hand, ^{226}Ra and ^{137}Cs brachytherapy sources need lead barriers to be manipulated safely.

10.6.2.1. Radium and other LLDSRSs

There is a well proven method for the conditioning of radium brachytherapy sources (Figs 83–86) and other long lived disused sources for storage, which includes their encapsulation in capsules (to facilitate their retrieval from storage for final disposal in a geological repository), emplacement of the welded capsules inside in a lead container for shielding (in case of long term storage followed by transportation), and emplacement of the container into a 200 L mild steel drum with a concrete lining [16, 18]. The concrete is used mainly for physical protection and security of the sources. Such packages typically have a minimum weight of about 350 kg and their handling and transportation require mechanical equipment, e.g. a forklift truck. Conditioning in this manner provides a barrier against loss of containment of radioactive materials as well as prevents unauthorized removal of the source because of the bulk, weight and robust nature of the package.

The capsule used for encapsulation of long lived sources is a stainless steel tube with a lid welded to one end of the tube (Fig. 83). A number of capsules need to be prepared in this manner in advance to ensure that sufficient number are available for encapsulation of all available sources. After placing the source inside the stainless steel capsule, the second lid is welded to the other end.

FIG. 83. Typical stainless steel capsules.

FIG. 84. Encapsulation of radium sources.

FIG. 85. Lead shields for long term storage.

FIG. 86. Radium package before closure.

Some slightly different and specific methods for conditioning of radium and other long lived sources have been developed and applied in the Russian Federation and in some countries of the former USSR and in Eastern Europe [65].

All relevant information on the conditioned inventory — radioisotope, date of conditioning, number of capsules, total activity, etc. — need to be recorded by multiple means (e.g. hard copy, electronic files, engraved metal plates attached to the packages) and retained by the competent authority.

10.6.2.2. Smoke detectors

Smoke detectors represent a special case in this category, since individual units are often exempted from regulatory control, and therefore, disposal in general landfill is allowed for single sources. However, due to the large number of these devices distributed within a country and the long half-life of the sources, it is becoming a preferred practice to collect, remove (Fig. 87) and consolidate the sources for conditioning and subsequent long term storage [18].

A suitable conditioning option for the collected sources could be their emplacement in stainless steel cans, followed by welding. In many countries, there is a concentration limit of 4000 Bq/g for alpha emitters in individual radioactive waste packages for disposal in near surface repositories [66]. While welding the individual stainless steel can be a preferred method to retard or remove the potential for release of radon or other daughter products from the stored container, future disposal or storage facilities might require visual verification of each source identity prior to shipment, thus other means of internal container closure should be considered. In one Member State, the ^{241}Am foils removed from smoke detectors have been packaged into cans, similar to paint cans, that are then loaded into the standard 200 L drum for storage pending disposal.

FIG. 87. Hundreds of sources removed from smoke detectors.

10.6.2.3. Lightning conductors

Lightning conductors are normally of big size with a small sealed source inside of the device. It is practical to dismantle the lightning conductor and remove the source from it (Figs 41, 88). The dismantling procedure mainly depends on the contamination level of the different parts of the device and the technical feasibility to remove the radioactive parts (foils or pellets) without giving rise to secondary waste. In order to avoid the contamination of the environment, the closed plastic bag with all its content (parts of the device, sources, consumables, etc.) is transferred to a glove box. The bag is opened after closing the glove box.

FIG. 88. ^{226}Ra and ^{241}Am plates removed from lightning conductors.

The sources (foils, strips or ceramic discs) removed from the lighting rod's body could be welded in stainless capsules in a way described above for radium.

10.6.3. Neutron sources

The major difference in neutron source conditioning is the need for attenuators that will reduce the dose rates from neutrons in addition to the gamma dose. In practice, neutron sources, including Am–Be, Ra–Be, Pu–Be are typically put into special form capsules, as described earlier, and then placed in either an S100 or S300 pipe overpacks described below. It is important to remember that neutron sources do not all use beryllium as the neutron emitter. Although beryllium is the most common element used in conjunction with the alpha emitting nuclide, other elements such as lithium, boron, fluorine and others have been employed. Californium-252 was also used in neutron sources. This nuclide, which decays by spontaneous fission, has a much higher neutron emission rate than any of the neutron sources employing alpha–neutron reactions for the neutron emission.

For neutron sources contained in devices, device manufacturer or user instructions should be followed for removal of the neutron source. If the instructions are not available, then devices can be packaged for transport intact or a method for preparation or obtaining dismantling procedures needs to be selected. Under no cases should sources be removed from devices without specific instructions or procedures from the device manufacturer or other knowledgeable source.

Neutron sources can be conditioned using S-300 or S-100 models of the pipe overpack container. This is an accepted disposal container at an operating disposal facility that accepts neutron sources, and is further certified for use as a transport container under the IAEA Transport Regulations.

The pipe overpack container utilizes high density polyethylene neutron shielding inside a stainless steel pipe, which reduces the external neutron dose equivalent rates per unit activity in the container. This allows container loading with higher activity content while maintaining compliance with external dose rate limitations for both packaging and disposal. This container is commercially available and has international certification as a Type A package.

The S300 pipe overpack consists of a 30 cm diameter pipe component positioned within a 200 L drum by means of fibreboard/plywood fillers and internal neutron shielding materials. The overall height of the pipe component is 70 cm with a 32 cm outside diameter. The pipe component overpacked in a 200 L drum weighs 195 kg. The pipe component body, lid and bolt flange are constructed of stainless steel. A butyl rubber or ethylene propylene O-ring is required for pipe component closure.

The S-100 container (Fig. 89) consists of a 15 cm diameter pipe component positioned within a 200 L drum by means of neutron shielding materials. The overall height of the pipe component is 70 cm with a 17 cm outside diameter. The pipe component overpacked in a 200 L drum weighs 220 kg. The pipe component body, lid and bolt flange are constructed of stainless steel.

Performance or procurement details are available from the US Department of Energy.

FIG. 89. The S100 pipe overpack container.

10.6.4. High activity disused sources

There are not many options for conditioning of high activity disused sources [16]. Handling and conditioning of such sources requires hot cells and remote/slave manipulators, source removal from devices is not practical.

10.6.4.1. Removal of source holder from equipment

This option is considered as a temporary measure or a measure only to be taken in special circumstances. For example, if a shielded facility is not available for removing sources from source holders, and the source holder is too large to be placed in a suitable container, there may be no other alternative but to select this option. In this case, conditioning is limited to removal of the source holder (teletherapy head, research irradiator, etc.) from the equipment followed by its transport to the storage facility. Numerous teletherapy heads, and research irradiators, due to construction and source characteristics have been conditioned in this way. All devices/source holders should be marked, labelled, and controlled to ensure both safe and secure storage.

10.6.4.2. Packaging of source holder in storage container

The use of concrete lined drums, or steel or concrete boxes for conditioning of high activity sources in source holders, is a common practice. The source holder can be placed in a standard container (Fig. 90). Typically, a 100 L drum will be set inside a 200 L drum using concrete, or for larger items, 200 L drums may be cemented into larger overpacks. Concrete or steel boxes have the advantage over drums in the sense that they can be more easily stacked, and have a much larger volume and load (Fig. 91).

FIG. 90. A teletherapy head before being conditioned inside a metal drum.

FIG. 91. Teletherapy units before and after being conditioned inside metallic boxes.

In order to ensure retrievability of the source holder for reconditioning and future disposal, the source holder is placed in a ‘void’ inside the container, but not entombed in solid concrete. This method provides sufficient shielding, retains the weight of the package, reduces the potential for unauthorized removal, and yet allows for removal of the source holder without the need for chipping of poured concrete when additional disposition paths become available.

10.6.4.3. Packaging of source removed from its holder

The source can be removed from the source holder and placed a suitable container. Removal of the source from its holder is carried out in a properly equipped hot cell (e.g. with master slave manipulators). The dismantling operation will reduce the volume both for storage and subsequent disposal. This is advantageous option if the inventory of sources is large. The design of the storage container is to be determined by the source characteristics and transport requirements. The hot cell needs to be fitted with a shielded door large enough to permit a shielded storage container to be introduced into the cell. The hot cell needs to be checked for contamination before the source is introduced. The lifting equipment in the hot cell is required, in particular, for the dismantling of older source holders, where the source was not intended to be removed.

The empty source holder should be checked for contamination and, if clean, it can be reused, recycled or disposed of. If the source holder is contaminated, it has to be decontaminated to reach acceptable levels. Special consideration is needed, if the source holder is made of depleted uranium.

A shielded storage container may be designed to accommodate a number of disused sources. When the container is full, it may be placed in a concrete lined drum, similar to that in the encapsulation option described above, to provide some additional shielding. Alternatively, an unshielded storage container may be designed to accommodate a number of sources, which could be placed in shielded storage (e.g. a well type store).

All high activity sources placed in storage, no matter if in shielded or unshielded configurations, should be secured to prevent intruders from removing sources from the containers or removing the entire container from the shielded storage location.

10.7. THE IAEA MOBILE HOT CELL FACILITY

The IAEA has developed and maintains a Mobile Hot Cell Facility (Figs 92–94) for use in conditioning disused high activity sealed sources. Since 2004, the IAEA has assisted Member States in both Africa and Latin America in the removal of sources from medical teletherapy heads, irradiators, and in removal of isolated sources from varied shielded configurations.

The design capabilities include transfer of sources to a shielded storage container or to transportation containers, as appropriate, for movement of the source inventory to national storage, repatriation or disposal. The Hot Cell Facility is transported in two ISO containers, and includes all tools, equipment and materials anticipated for the recovery mission, requiring only the addition of power, local labor, and sand from local sources for shielding.

FIG. 92. The IAEA Mobile Hot Cell — fully assembled and ready for use.

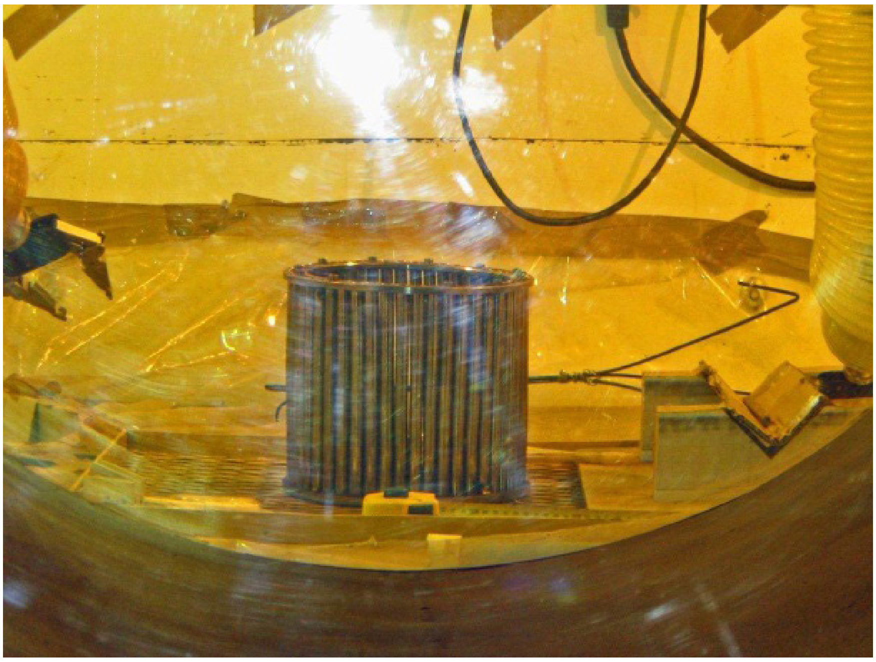


FIG. 93. The source basket from a research irradiator viewed through the window of the IAEA Mobile Hot Cell Facility.

FIG. 94. The long term storage shield fully attached to the transfer port on the IAEA Mobile Hot Cell Facility.

The use of this capability is restricted, due to time, labour and expense, to applications at sites where many high activity sources are located, no suitable remote handling capabilities exist, and the availability of secured storage facilities is limited or non-existent. Once selected as the optimum method for conditioning of a given inventory, the IAEA enters into contracts with the Member State and its operating contractor to plan and execute conditioning operations. The contractor then transports the Hot Cell Facility and the appropriate containers to the site selected by the Member State, travels to the site and assembles the Hot Cell Facility using local labour and materials as much as possible, and conditions sources from the devices assembled at the work site. Upon completion of the mission, the Member State would optimally be left with no sources, but in reality it is more likely that the Member State would assume responsibility for storage of the long term storage container in the national store that contains the remaining inventory of sources that could not be transported for long term disposition such as disposal or repatriation.

The long term storage shield is similar in concept to many 'transfer flasks' used in industry to transport new sources for refuelling teletherapy heads. It has the capacity for receiving four individual source drawers, each of which can contain multiple sources from teletherapy heads or irradiators. Initial design and safety analysis for the LTSS assumed a capacity of 370 GBq (10 000 Ci) of ^{60}Co. It can be used as a transfer flask, for storage of sources, or can be transported in a certified overpack meeting Type B package requirements.

The IAEA is continuing its efforts, in conjunction with Member States, to further develop transportation capabilities of the long term storage shield in order to certify a Type B container for transportation of the shield.

10.8. LESSONS LEARNED

10.8.1. Short lived sources

In the past, embedding of sources in concrete i.e. the enclosure of the source in Type A package was frequently used [15]. The source in its shielding was placed in the center of a mild steel 200 L drum with concrete lining, welded bars, filled with cement mortar and closed with a lid. At present, this method is considered neither practical nor economical. In absence of a disposal route and non-availability of WAC for disposal the source might need reconditioning that is linked with the necessity of retrieval of the source from concrete. This operation would be costly and unsafe. If future disposal requirements will allow disposing of the package as it is, it will lead to higher cost of disposal taking into account the size and weight of the packages. Hence, the availability of the original information on the conditioned source as well as the technical procedures used for the conditioning process is very important. There is a clear trend in conditioning to use reversible methods as much as practical.

10.8.2. Long lived sources

Conditioning of Ra, Am, Am–Be, Ra–Be and other long lived disused sources for storage include stages for their encapsulation in stainless steel capsules. This method provides a small volume of encapsulated sources and facilitates the retrieval of such capsules from the packages for final disposal in deep geological repositories. In case of Ra sources, the leak testing of the encapsulation has to be demonstrated. Suitable leak test methods are described in ISO Standard 9978 [22]. The vacuum bubble test is the preferred method.

In the past, some manufacturers used glass or quartz ampoules for encapsulation of radium [18]. The probability of leaking radon gas from such ampoule is higher than in case of welded stainless steel capsules. Additional encapsulation of such ampoules in steel or brass containers is necessary to reduce this risk and protect the ampoules from mechanical stresses and other environmental effects.

For the conditioning of other long lived DSRSs such as ^{226}Ra–Be, ^{241}Am–Be, ^{252}Cf that emit neutron radiation, hydrogenous materials (e.g. high density polyethylene, wax) should be included in the shielding design of the package prepared for storage.

10.8.3. High activity sources

Operations related to the removal of a high activity (Category 1–2) source from its holder, placing it in another container and some other operations required during conditioning of high activity sources require a hot cell and very qualified personnel. The lack of approved containers, hot cells and manpower makes the conditioning of such sources difficult or impossible in many Member States with limited nuclear applications. In practice, virtually no country disposes of high activity sources due to the lack of a geological repository. That means that conditioning of such sources is limited to the preparation of sources for long term storage only [17].

Under such circumstances, only possible resolution of these problems will be receiving international assistance, for instance from the IAEA which provides services for conditioning and repatriation of high activity sources from the country (see Section 10.7).

A special in situ conditioning technique has been developed in the Russian Federation to improve the safety of long term storage of bare high activity sources removed from devices and transferred into stainless steel containers stored in shallow bore holes at radon type repositories. The technique involves gradual filling up the storage container with a low melting point metal alloy [67].

11. TRANSPORTATION

The method, by which a disused source is transported from the user's premises to a central or regional storage/disposal facility, depends, among other factors, on the physical condition, type and activity of source, the type of device, the availability of suitable transport packages, the handling capability of the receiving facility and the requirements for conditioning and storage.

11.1. TRANSPORT REGULATIONS

Any transportation of radioactive material on public roads needs to be carried out in accordance with applicable national transport regulations. Member States usually comply with the IAEA Transport Regulations [47]. The regulatory body is consulted prior to the actual transportation of the sources. If there is no established authority with adequate expertise available in the country, assistance from the IAEA may be sought.

If the source contains the activity less than A_1/A_2 values, as set out in the IAEA Transport Regulations [47], it can be transported in Type A transport packages. Type A package may be a box, drum, or similar receptacle, or even be a tank, freight container, or intermediate bulk container containing an activity up to A_2 or up to A_1, if the contents meet the technical definition of 'special form radioactive material':

"Special form radioactive material shall mean either an indispersible solid radioactive material or a sealed capsule containing radioactive material".

For 'special form radioactive material', A_1 value applies (or A_2 value if it is not special form).For example, for some typical isotopes, those values are[8]:

— Cobalt (^{60}Co): A1 = A2 = 0.4 TBq (~11 Ci);
— Caesium (^{137}Cs)[9] A1 = 2 TBq (~54 Ci), A2 = 0.6 TBq (~16 Ci);
— Iridium (^{192}Ir): A1 = 1 TBq (~27 Ci), A2 = 0.5 TBq (~14 Ci);
— Strontium (^{90}Sr): A1 = 0.2 TBq (~5.6 Ci), A2 = 0.1 TBq (~2.7 Ci);
— Americium (^{241}Am): A1 = 10 TBq (~270 Ci), A2 = 1×10^{-3} TBq (~2.7×10^{-2} Ci);
— Californium (^{252}Cf): A1 = 0.05 TBq (~1.4 Ci), A2 = 3×10^{-3} TBq (~8×10^{-2} Ci).

It may be expected that many sources meet the requirements for classification as 'special form radioactive material', especially the sources manufactured according to current standards. These include dimensional limits, an impact test, a percussion test, a bending test and a heat test. Beyond the technical features, 'special form radioactive material' is a legal category affecting the selection of a transportation option. A source can be considered, as 'special form radioactive material', only if a valid 'Special Form Radioactive Material Certificate' is available.

If the amount of activity in the package exceeds A_1 or A_2 values, a Type B package is required. For detailed specification of tests and other criteria for a type A or type B transport package, the IAEA Transport Regulations can be consulted [47].

Type A and Type B packages are required to be durable and legibly marked on the outside and affixed with the appropriate category label. Category labels (includes the ionizing radiation symbol) are affixed on two opposite sides of the package and are visible and clear from any obstructions (Fig. 59). Warning signs on the transport markings and labels need to be in the language required by the national transportation regulations, as appropriate. Road vehicles, as well as large freight containers, are placarded with appropriate warning signs, affixed to each side wall and each end wall (Fig. 95):

> "Disused sources for which conformity with the other provisions of the Transport Regulations is impracticable shall not be transported except under *special arrangement*. Provided the competent authority is satisfied that conformity with the other provisions of these Regulations is impracticable and that the requisite standards of safety established by these Regulations have been demonstrated through means alternative to the other provisions, the competent authority *may approve* special arrangement *transport operations for single or a*

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[8] The curie values are approximate and quoted here for those who are more familiar with them.

[9] A_1 and A_2 values include contribution from daughter nuclides with half-lives less than 10 days.

planned series of multiple consignments*. The overall level of safety in transport shall be at least equivalent to that which would be provided if all the applicable requirements had been met.* For consignments of this type, multilateral approval shall be required" [47].

FIG. 95. Placarding of vehicles used for transporting SRSs.

11.2. TRANSPORT OPTIONS

There are two possible options for the transport of disused sources, namely the source transported in the original source holder and with the source holder removed (Fig. 96).

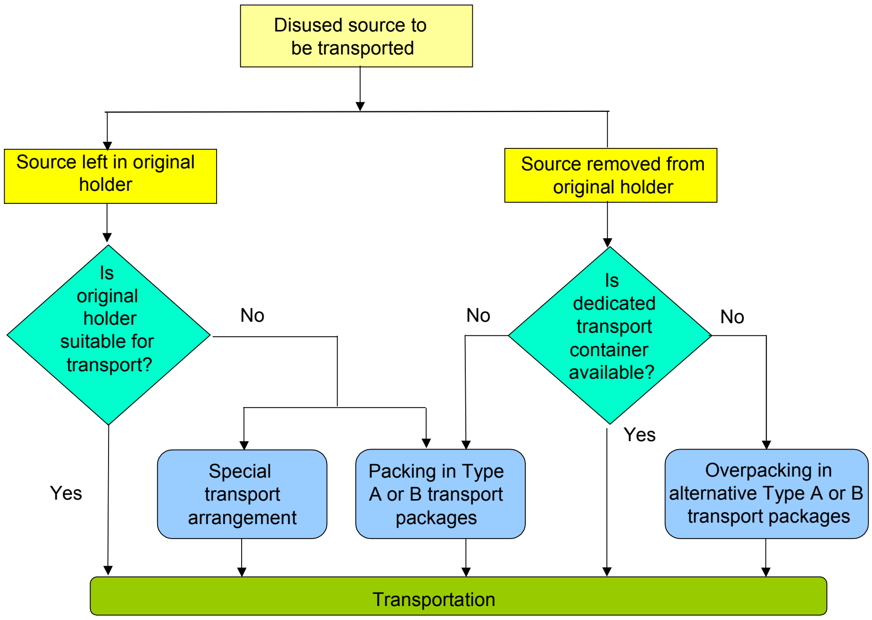

FIG. 96. Possible options for the transport of disused sealed sources.

The following subsections discuss the various possibilities for the transport of disused sources. While the various options are discussed here in some detail, the regulatory approval of the option(s) selected by the user is still a prerequisite.

11.2.1. Source left in original holder

There are two possible options for this situation.

11.2.1.1. Transport in the original source holder

In some cases, the source holder can be qualified as a Type A or a Type B transport package subject to compliance with current transport regulations. This approach is certainly safe, convenient and cost effective for the user, as it minimizes the radiation dose in handling, avoids the need for a transport package. It can also be convenient from the point of view of the receiving facility, as radiation dose is minimized, as long as the waste acceptance criteria for the disposal facility do not require the source to be removed from its holder. Even if the source needs to be removed from its holder prior to long term storage or disposal, it is likely that the receiving facility will be better equipped to undertake this operation than the user. Examples of original radioactive source holders used as transport packages are shown in Fig. 97.

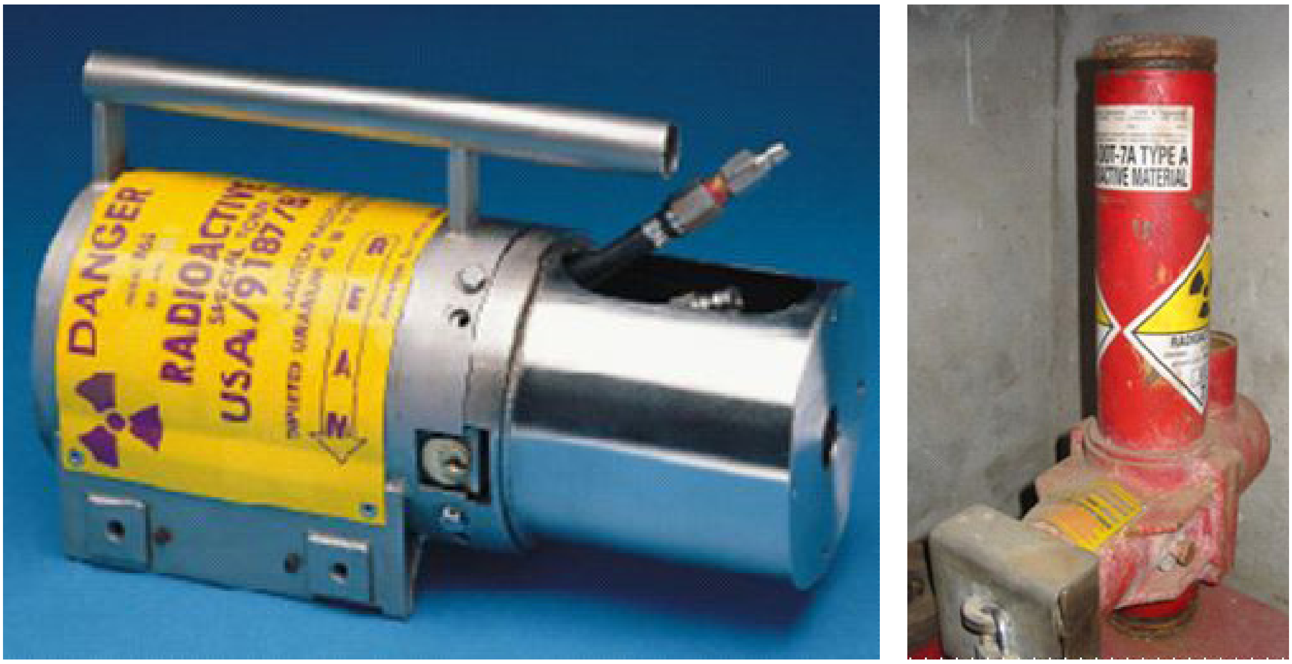

FIG. 97. Examples of an original radioactive source holder used as a transport package.

If the original source holder does not qualify as a transport package, and transportation is necessary, then approval may be granted under Special Arrangement conditions. As an alternative to a Special Arrangement Certificate, the competent authority involved needs to consider renewing the original transport certificate for a short period to allow the transport of the disused source. International assistance may be required to identify and evaluate the acceptable parameters to allow transport. Each step in source transport will need to be considered on a case-by-case basis.

This method was often used in the past for transportation of small industrial radiography sources, weighing perhaps only 20 to 30 kg (Fig. 98). However, this method may no longer be applicable, particularly for high activity sources. If this approach is to be adopted, it is important to ensure that all safety mechanisms are functioning correctly, e.g. shutter securing mechanism.

FIG. 98. For small sources, depending on the source size, geometry and activity, a special container should be used for transport.

11.2.1.2. Transport of the source left in its holder in an approved transport package

If it is not possible or practical to remove a disused source from its holder at the user's site, then it may be necessary to transport it in an approved transport package with sufficient cavity size to hold the source holder. This is particularly feasible for smaller source holders with total weights of up to approximately 500 kg and activities within Type A limits. A number of Type A package designs exist, which should be suitable for transporting such sources. A typical example of a steel drum overpack is shown in Fig. 99. Source holders may be transported in this kind of container, as long as they have suitable integral shielding and are held tightly inside the package during transit.

FIG. 99. A Type A transport package with large internal volume and load capacity (approximately 300 kg).

The transport of the source holders containing activities exceeding A_1/A_2 values may require large and complex Type B transport packages (Fig. 100). These packages are rather expensive and for some countries, with a relatively small number of Category 1 and 2 sources, there is a strong argument for international cooperation. Obviously, this option would require some discussion and agreement to address the issue of transboundary movement of radioactive material.

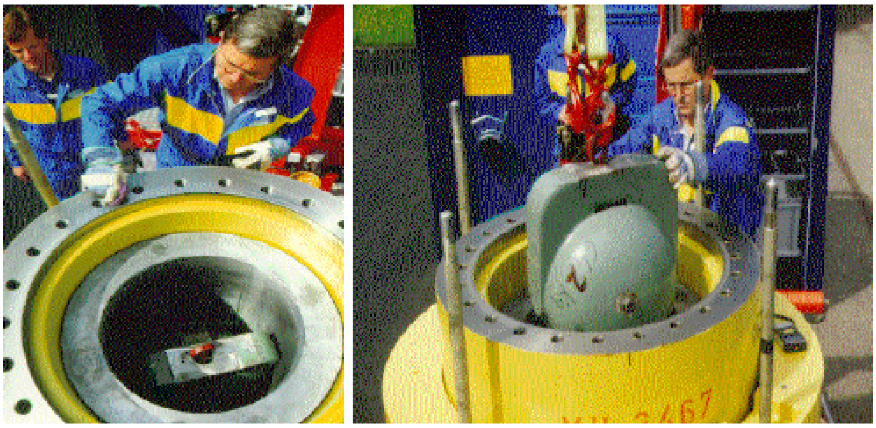

FIG. 100. Type B transport package for Category 1 sources.

In the event that no suitable transport package is available in a Member State, it may be possible to apply to the competent authority for a special arrangement, which may, for instance, allow reusing the original transport package. This option may provide a less expensive solution and needs to be given due consideration by the competent authorities in Member States to facilitate the removal and proper storage of disused sources.

11.2.2. Source removed from original holder

Category 1 and 2 sources are usually associated with high exposure dose delivered even during short exposure times. Any attempt to remove the source from the original source holder needs to be undertaken only when absolutely necessary. For safety reasons, a robust infrastructure (e.g. hot cell facility) and technical/administrative requirements need to be in place (see Section 6). Extensive radiation protection experience is necessary for radiation workers planning to undertake such an operation. The removed high activity source will be placed in a Type B package. Figure 101 shows an example of a suitable Type B package.

FIG. 101. An example of a Type B transport package.

11.2.2.1. Source transfer from device into dedicated transport container

Many types of source holder are designed to allow source exchange in the field. These include most modern industrial radiography and ^{60}Co teletherapy units. For industrial radiography units, the process of removal of the source from its holder into a relatively small, shielded container is simple. An example of a transport package designed for dedicated use with an industrial radiography source is shown in Fig. 102.

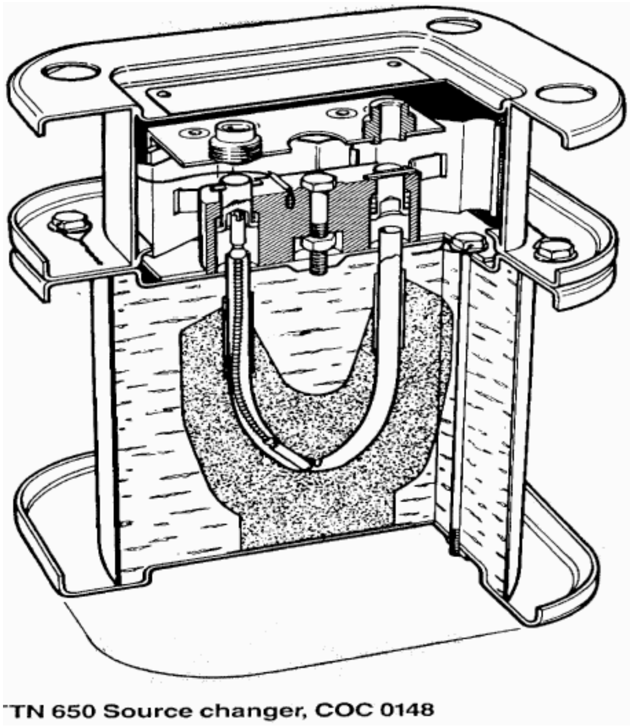

FIG. 102. An industrial radiography source transport package (Type B, 8.8 TBq ^{192}Ir).

For teletherapy units, a large dedicated transport flask is connected to the teletherapy head, and the source is pushed or pulled from the head into the transport flask. The tight fit between the teletherapy head and the transport packages ensures minimal radiation dose to the workers. This type of transfer/transport package is generally owned by the manufacturer/supplier. Figure 103 illustrates the source exchange operation in a teletherapy unit.

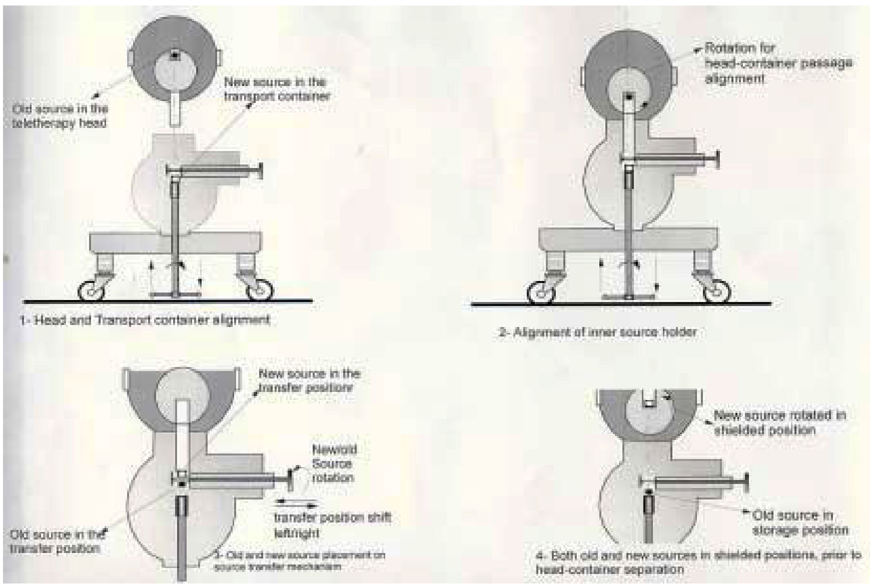

FIG. 103. A schematic diagram illustrating source exchange in a teletherapy unit.

11.2.2.2. Source transfer from device into generic transport package

For many of the older teletherapy units and older high activity industrial radiography units, the dedicated source transport packages are not available, or transfer in the field is not appropriate due to the design. If no dedicated source transport package is available, it may still be possible to transfer the source into a suitable alternative transport package. Indeed, this may be essential if the receiving facility is unable to handle the source inside its holder (e.g. due to size), or if no transport package exists for transportation of the entire unit (source inside holder, see below).

Where transfer of the source out of its holder into a shielded transport package is proposed, there are a number of highly versatile transport packages available. The transfer of the source requires an appropriate facility and well trained personnel. Figure 104 shows a series of containers with different shielding thickness. These can be nested inside each other to give a range of Type A and B formats with total a shielding thickness of up to 150 mm. This package design offers a large internal cavity and considerable flexibility.

FIG. 104. ^{137}Cs shielded inner container being loaded into a Type B package, following removal of ^{137}Cs sources from a research irradiator.

Generic transport packages, such as the one described above, are not designed for the specific purpose of transferring a source from a particular design source holder. Therefore, it will be necessary to develop a custom engineered solution that allows the transfer of the source into the package with minimal radiation dose to the operators. For instance, the package may be connected directly to the source holder, or alternatively, a two stage transfer using a custom built transfer flask may be possible. Unshielded source transfer needs to be avoided in all cases involving Category 1 and 2 sources. If this approach is to be used, technical procedures need to be developed, tested and carried out by well qualified personnel.

On receipt at the storage facility, a solution will also be required to remove the source from the transport package. Often this is achieved inside a hot cell.

If there is insufficient local expertise to perform source removal, or equipment or tools are unavailable, then a supplier/manufacturer/owner of similar packages/sources, or a foreign waste management organization or international organization (e.g. IAEA), need to be contacted for assistance.

11.3. PROBLEMS ENCOUNTERED AND LESSONS LEARNED

There are many cases in which sources remain at the user's premises due to problems in identifying a suitable and economical method for transporting the sources to the supplier/manufacturer, another user, a conditioning facility, a storage facility at a CRWMO, or a disposal facility in accordance with relevant international transport regulations [48]. Some main reasons for the delay of transportation of a disused source from the user's site are the following:

- — Inadequate financing;
- — Licensing difficulties;
- — Absence of source certificates or source information;
- — Absence of Special Form Radioactive Material certificates;
- — Absence of a suitable certified transport container.

It is important that competent authorities and licensee collaborate to find solutions to these problems to safely transport disused sources.

11.3.1. Inadequate financing

At present, it is often expensive to transport disused sources internationally because the original transport package is not available or its certificate has expired. Once the equipment has been purchased and delivered, a facility might not provide for the cost of ownership transfer of the source when the equipment is eventually retired. The reason may be that the facility owners do not have a budgetary mechanism for accruing for a cost that will be realized only well into the future (perhaps decades) and for which the value can only be estimated. Another reason could be because the facility assumes that it can cover the ownership transfer cost out of its operating budget or as a condition of purchase of new equipment. This can lead to financial pressure when the time for ownership transfer arises, with the corresponding temptation to use less expensive options. These alternatives could result in a higher likelihood of loss of control of the spent or disused source.

11.3.2. Difficulties in licensing

In some countries, it is necessary to obtain a license for the transportation of radioactive material. As a consequence when sources are being transported across several borders it is necessary to employ a local company or a driver native to the country where this regulation is in effect. This adds significant administrative effort and costs.

11.3.3. Absence of source certificate or source information

The source certificate or source information is needed to decide whether a source can be transported in an available package. The source certificate or source information can be used to determine if the source activity and physical dimensions are compatible with the available transport package. If the source certificate or source information is not available, the following options may be considered:

(a) A new source certificate or information can be provided by the manufacturer or supplier;
(b) The source must be characterized to determine its activity, isotope and containment integrity.

11.3.4. Absence of Special Form Radioactive Material Certificate

In many cases, Special Form Radioactive Material certificates may no longer be valid for disused sources. This is usually the case when the capsule design is obsolete or the source manufacturer is no longer in business and, therefore, no longer in a position to extend the validity of the certificate. The expiry of the Special Form Radioactive Material Certificate does not imply that the radioactive source no longer meets the 'special form radioactive material' technical requirements. The source may still comply with the containment requirements for the Type B packages and, therefore, safely transported. It is important that the competent authority and the licensee work together to find a feasible solution to facilitate the transport of the sealed radioactive source. This could consist of renewing the Special Form Certificate for a short period, amending the transportation certificate to include the radioactive source as non-special form, or issuing a Special Arrangement license.

11.3.5. Inadequacy of an original transport package

Even if the source certificate and Special Form Certificate are available, the transport package in which the source or device was originally delivered may no longer comply with the current transport regulations. In most cases, the transport package is still in good condition; however, the Competent Authority Approval Certificate is no longer valid. An example of this problem is old teletherapy heads, which were delivered complete with their sources in simple overpacks (Fig. 105).

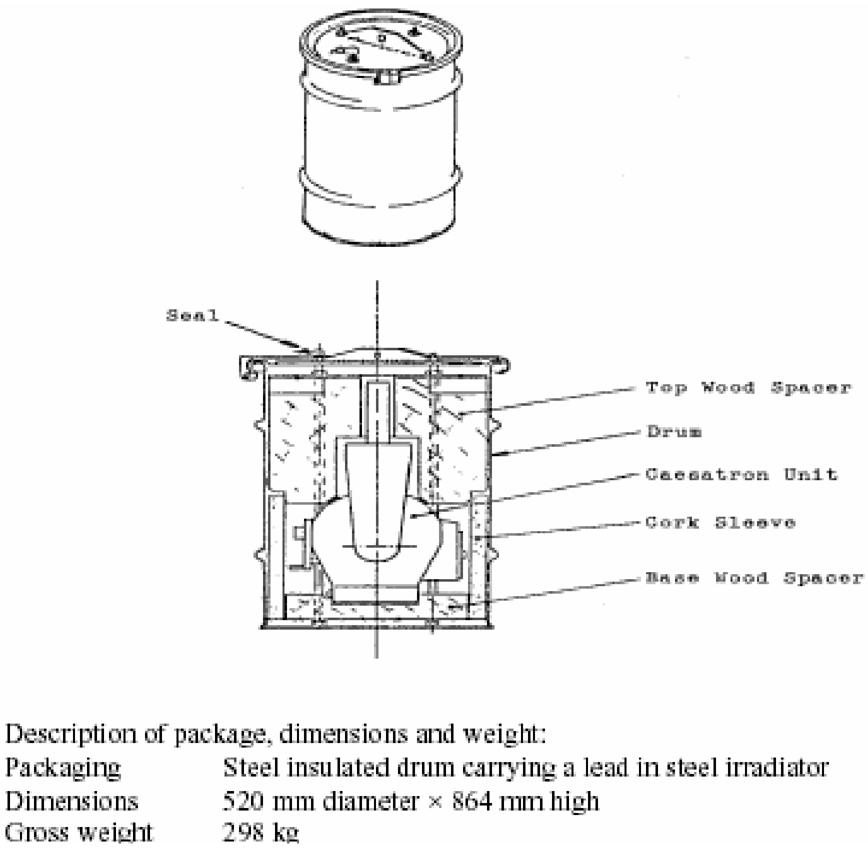

FIG. 105. A transport package for an old ^{137}Cs teletherapy unit that does not comply with current standards.

Sometimes, an appropriate transport container is not available or the design of the source holder and drawing with descriptions of the source removal order is unknown (lost). In such cases, the reloading of DSRSs is impossible and transportation can only be carried out under Special Arrangements. For example, the body of an irradiator (with some safety upgrades) can be used for the transportation and interim storage of DSRSs (see Fig. 106). This transport requires approval and control by the national regulatory authorities.

FIG. 106. An irradiator loaded with ^{137}Cs DSRSs ready for transport to the disposal facility.

12. DISPOSAL

DSRSs for which no recycling or repatriation options exist should be declared as waste and needs to be disposed of in a disposal facility in compliance with relevant international legal instruments, safety standards, and good practices, to provide for their safe, long term management. Development of a disposal facility requires relevant infrastructure including a national waste management policy and corresponding strategy for implementation [50], a regulatory framework, and the financial, human and technical resources needed for such a development. In the event the DSRSs cannot readily be disposed in already existing or planned facilities, a dedicated disposal solution must be developed and the corresponding infrastructure needs to be provided. In such a context, the implementation of a suitable disposal route for DSRSs continues to be a subject of concern at the international level, especially in Member States with limited resources [68–71].

Section 2.1 outlines some important factors to consider when deciding on a suitable disposal option. The inventory of sources and the corresponding characteristics of the radionuclides considered for disposal should be assessed. Disposal needs should be evaluated consistent with safety requirements pertaining to the disposal of radioactive waste [72]. In this regard, the activity concentration typical for many DSRSs is given particular attention, together with other considerations such as activity overall and half-lives. Disposal options should be considered in the context of the broader national context of current and future plans related to the use of nuclear technology, research and/or nuclear power generation. DSRSs declared as waste are typically conditioned into waste packages, and their properties and characteristics may influence and need to be designed to ensure acceptability of disposal in a given facility. Finally, WAC provide a management tool to verify whether a given inventory of packaged DSRSs can be accepted for disposal in a given facility, whether an additional, focused safety assessment needs to be conducted, or whether an alternative disposal route needs to be developed.

In principle, a suitable disposal solution can be provided for all DSRSs declared as waste. The options available include near surface disposal facilities, geological disposal facilities, as well as dedicated borehole disposal facilities. A brief overview for these is provided in Section 2.2. Indeed, significant progress has been made in the disposal of low and intermediate level waste, and disposal facilities accepting these waste types have been operating for several decades. In addition, several countries have submitted or are nearing submission of a license application for the construction of a geologic disposal facility destined to receive intermediate level waste, high level waste and/or spent fuel declared as waste. Finally, the borehole disposal concept has been given due consideration and is proposed as a disposal facility dedicated to receiving DSRSs declared as waste. The available experience and lessons learnt with these types of disposal facilities is briefly reviewed in Section 2.3.

12.1. FACTORS INFLUENCING THE CHOICE OF DISPOSAL OPTIONS

The disposal of the inventory of DSRSs declared as waste could either be done together with other radioactive waste in already existing or planned disposal facilities, or in a disposal facility specifically designed and dedicated for the disposal that inventory. Furthermore, a dedicated disposal solution might under certain conditions be co-sited with an already existing facility, or the design of an existing facility be adapted in parts as a prerequisite for the acceptance of DSRSs declared as waste in that facility.

The most appropriate solution for a Member State will depend on several factors, particularly the DSRS inventory and the associated disposal needs, as well as the inventory of radioactive waste that might be expected from other activities, and for which disposal facilities may already be planned for or exist.

Irrespective of the context, disposal needs should be evaluated consistent with safety requirements pertaining to the disposal of radioactive waste. In a first analysis, DSRSs must be associated to a class of waste to understand the associated disposal needs. SRSs, however, are categorized according to the risk posed by the source when out of control. This is different from the waste classes developed to assist strategic decisions on disposal development, and the radiological properties of the sources need to be evaluated to decide on a suitable disposal option. Therefore, to make informed choices, the IAEA Waste Classification System should be understood, the radiological properties of DSRSs evaluated and matched to this system, and suitable disposal options selected to provide for safe and efficient disposal.

12.1.1. The IAEA waste classification system

To understand what disposal option might be suitable, one first needs to consider the waste classes to which DSRSs declared as waste need to be attributed. If a disused sealed source is declared as radioactive waste, all safety principles relevant to waste [28] apply. The IAEA has developed an internationally accepted waste classification system which allows radioactive waste, including DSRSs, to be grouped into the following six classes according to the activity and half-lives of radionuclides [66]:

(1) Exempt waste (EW): Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes as described in Ref. [59].
(2) Very short lived waste (VSLW): Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. This class includes waste containing primarily radionuclides with very short half-lives often used for research and medical purposes.
(3) Very low level waste (VLLW): Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Such landfill type facilities may also contain other hazardous waste. Concentrations of longer lived radionuclides in VLLW are generally very limited.
(4) Low level waste (LLW): Waste that is above clearance levels, but with limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. This class covers a very broad range of waste. LLW may include short lived radionuclides at higher levels of activity concentration, and also long lived radionuclides, but only at relatively low levels of activity concentration.
(5) Intermediate level waste (ILW): Waste that, because of its content, particularly of long lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal. ILW may contain long lived radionuclides, in particular, alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of meters to a few hundred metres.
(6) High level waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW.

These waste classes provide general guidance for the duration and robustness of containment and isolation, as well as other considerations such as related to heat dissipation, that are needed for the safe disposal of waste. They allow inferring general guidance on suitable options for a corresponding disposal facility.

12.1.2. DSRS inventory, corresponding radionuclide characteristics and waste classes

If the DSRS inventory includes several classes of waste, then different options need to be considered for their disposal, ranging from near surface to geological disposal, and including borehole type facilities of varying depths. Safety considerations allow regrouping the inventory in the disposal option suitable for the higher level waste class. However, considerations of cost, overall volume of DSRS inventory, and the possible option of making use of existing facilities for lower level waste classes may suggest disposing of the DSRS inventory in several, suitable disposal facilities.

The analysis of disposal needs can only be carried out if the inventory of DSRSs declared as waste is known. DSRSs exhibit a high degree of variability in their physical and radiological characteristics, such as radionuclide content, half-lives, total activities and activity concentration. These characteristics determine the waste class they should be assigned to, consistent with the classification presented in the previous section, and thus the duration and robustness of containment and isolation expected from the selected disposal option. There is no exact correspondence between source categories 1 through 5 and the waste class they will eventually belong to. Obviously, sources containing radionuclides with higher activities and longer half-lives require a greater degree of containment and isolation and may need to be considered ILW. Others may qualify as VLLW.

Some preliminary guidance can be provided based on the analysis of common DSRSs and associated radionuclide properties. Data on the radionuclides used in SRSs for various applications are summarized in Ref. [23]. Table 8 is based on the data presented in Ref. [23] and by way of example contains the half-lives and the range of activities of some radionuclides being used in SRSs.

TABLE 8. THE HALF-LIVES AND THE RANGE OF ACTIVITIES OF SELECTED RADIONUCLIDES USED IN SRSs FOR VARIOUS APPLICATIONS

Main radionuclide	Half-life	Minimum activity for nuclide (Bq)	Maximum activity for nuclide (Bq)	Application
^{3}H	12.3 a	1.9E + 09	1.1E + 10	Military, industrial applications, gaseous light emitting devices, targets for neutron tubes
^{60}Co	5.3 a	9.3E + 09	5.6E + 17	Irradiators, teletherapy, industrial radiography, brachytherapy, industrial gauges
^{75}Se	120 d	3.0E + 12	3.0E + 12	Industrial radiography
^{85}Kr	10.7 a	1.9E + 09	3.7E + 10	Industrial gauges, lightning rods
^{90}Sr	28.6 a	3.7E + 08	2.5E + 16	RTGs, thickness measurement, eye applicators
^{125}I	60 d	1.5E + 09	3.0E + 10	Brachytherapy
^{137}Cs	30.1 a	3.0E + 08	1.9E + 17	Irradiators, brachytherapy, industrial gauges, well logging/moisture gauges
^{169}Yb	32 d	9.3E + 10	3.7E + 11	Industrial radiography
^{170}Tm	129 d	7.4E + 11	7.4E + 12	Industrial radiography
^{192}Ir	74 d	7.4E + 08	7.4E + 12	Industrial radiography, brachytherapy
^{226}Ra	1600 a	2.6E + 05	1.9E + 09	Brachytherapy, lightning rods, smoke detectors
^{238}Pu	87.8 a	1.1E + 11	1.0E + 13	RTGs, pacemakers
^{239}Pu–Be	24 100 a	7.4E + 10	3.7E + 11	Research
^{241}Am	432 a	4.8E + 07	8.5E + 11	Industrial gauges, smoke detectors, lightning rods, bone densitometry
^{241}Am–Be	432 a	1.9E + 10	8.5E + 11	Research
^{244}Cm	18.1 a	7.4E + 09	3.7E + 10	Industrial gauges
^{252}Cf	2.6 a	1.1E + 06	4.1E + 09	Industrial gauges, oil well logging, neutron activation, medical application

It should be noted that the activity ranges provided in Table 8 refer to sources in use. When becoming disused, the source activities are at or below the indicated minimum activity, and further decrease according to their half-lives. By way of example, a DSRS inventory having specific source properties may be suitable for the following disposal options:

— Radioactive sources containing levels of activity below clearance levels, as might be the case e.g. for smoke detectors and provided this option is foreseen by national regulation, may be disposed of in landfills, consistent with the management option for exempt waste.

— Radioactive sources of low to medium activity with very short half-lives (typically less than about 100 days) will decay to clearance levels in a few years. From a waste management point of view such sources can be safely allowed to decay in a storage facility, consistent with the management option for VSLW.
— Radioactive sources containing very low levels of activity, even though they may contain very long lived radionuclides such as ^{14}C (half-life = 5700 a), ^{36}Cl (half-life = 300 000 a) and ^{129}I (half-life = 17 million a), such as may be used e.g. for the calibration of instruments, might be acceptable at near-surface, landfill type disposal facilities, consistent with the management of VLLW.
— Radioactive sources with short half-lives (up to about 30 years, such as ^{60}Co, ^{90}Sr and ^{137}Cs) can generally be disposed of at near surface facilities provided that their activity will decrease to limits set by the safety analysis during planned duration of the institutional control and provided that any criteria on activity density are respected, consistent with the management option for LLW. For a rough estimate, this is relevant to sources decreasing activity to clearance levels within 300 years and not exceeding specific activities defined in the safety case.
— High activity sources of short half-life, as well as sources containing long lived radionuclides, such as ^{238}Pu and ^{226}Ra, may require geological disposal providing for long term safety, consistent with the management option for ILW.

All of the above are examples referring to disposal facilities developed for the management of radioactive waste in general. If a specific disposal facility dedicated for DSRSs is to be developed, borehole disposal may be the most efficient option providing for a suitable degree of protection [73]. Depending on its siting and depth of emplacement, it could in principle provide for the level of isolation and containment consistent with LLW, as well as ILW. Such a borehole could be sited as a stand-alone facility or co-sited with another disposal facility.

Quantitative aspects, e.g. values of allowable activity content for each significant radionuclide as well as values for local concentration of activities and thermal output will be specified on the basis of safety assessments for the actual disposal facility. These in turn refer to the safety scenarios used for the assessments, including considerations of radionuclide release and transfer to the accessible environment and likelihood of inadvertent intrusion. These can then be specified as part of WAC, as a management tool assisting the decision whether given radioactive waste can be safely disposed of in this facility.

12.1.3. DSRS disposal options in the context of the national radioactive waste inventory

When selecting a suitable disposal option for the DSRS inventory declared as waste, this should be done consistently with the broader picture of the national socio-political and regulatory context and take into account: (i) radioactive waste inventory; (ii) site characteristics; and (iii) disposal facility design. This national context is illustrated in Fig. 107.

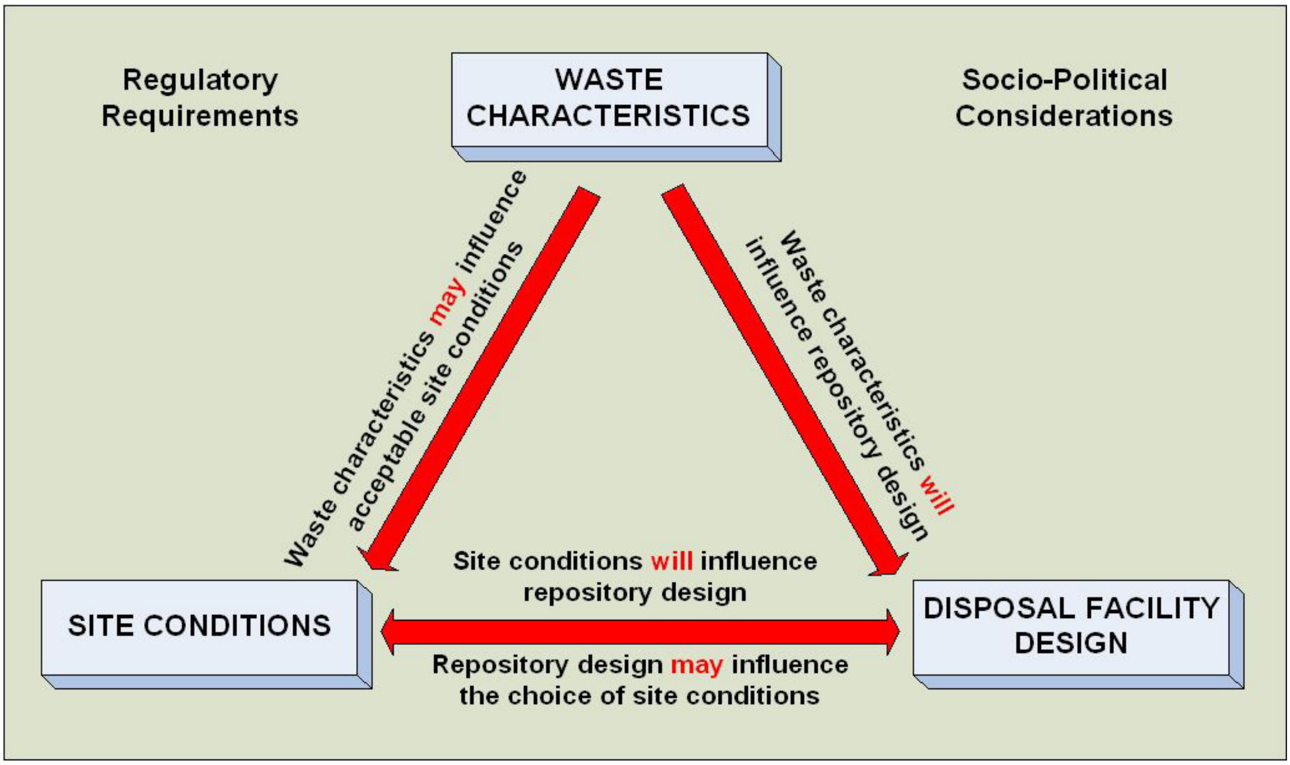

FIG. 107. Characteristics of the entire waste inventory as an influence on repository design.

For small radioactive waste management programmes, consisting essentially or exclusively of DSRSs declared as waste, the development of one or several dedicated disposal facilities is called for. A well studied solution capable of providing for efficient and safe disposal of small volumes of radioactive waste is the borehole disposal concept [73]. If gaining initial experience with implementing the borehole disposal concept is necessary, then a suitable option might be to first dispose of DSRSs identified to be LLW in a dedicated borehole disposal facility, and in a later, second step dispose of those DSRSs identified to be ILW in a separate borehole disposal facilities providing for more robust isolation and containment. If on the other hand, experience could already be gained with a prior implementation of the borehole disposal concept, effectively demonstrating its robustness, then it might be preferable to select the disposal option suitable for ILW and co-dispose DSRSs qualifying as LLW in that same borehole.

How to adapt disposal of DSRSs declared as waste to the wider radioactive waste management infrastructure, for instance to already existing or planned disposal facilities destined to receive VLLW or LLW, needs to be considered as well.

For radioactive waste management programmes having to contend with a larger inventory, e.g. of LLW and DSRSs, several options can be considered. The inventory of DSRSs declared as waste acceptable for disposal in a near surface disposal facility for LLW could be conditioned in a suitable waste package and disposed of as other LLW. Special attention may need to be paid to the combination of activity concentration and half-life, which may be higher in DSRSs than in other LLW. This may or may not be consistent with the WAC for landfill type or near surface disposal facilities. If it is not, one may evaluate the option of storing some of the DSRS inventory, until the natural decay reduces the activity concentration to a level consistent with the WAC. If this does not provide a reasonable option, meaning that the safe disposal calls for a higher level of containment and isolation then provided by the near-surface disposal, available and efficient option may be borehole disposal at proper depth and with adequate engineered barriers. This could then be co-sited, or not, with the existing near surface facility, depending on site properties and other considerations.

If, in addition to operating a near surface disposal facility, the radioactive waste management programme needs to develop solutions for disposal of ILW or HLW, then DSRS unacceptable for disposal in the existing facility could be kept in long term storage until a geological repository is commissioned.

12.1.4. Conditioning DSRSs for disposal — the waste package

A radioactive device contains one or more radionuclides of known radioactivity and chemical form, sealed in a special capsule providing primary containment. In most cases, the radioactive sources will need to be further conditioned and packaged prior to disposal to contribute to the robustness of their long term containment (see Section 10), and to adapt the waste package to the disposal facility. A radioactive source package for disposal can contain more than one type of source and may comprise additional containment layers and any matrix material added to improve its overall safety performance. This effectively provides an engineered barrier for isolation and containment, and should be designed consistent with and suitable for the chosen disposal option.

The design requirements for a disposal package are discussed in detail in Ref. [48]. The package might be designed to contribute to the containment of the radioactive sources by preventing or limiting the release of radionuclides into the geosphere. Two approaches can be applied to ensure longevity of the containment: Use of corrosion resistant materials, or use of a thick walled container that would require a sufficiently long time to corrode. In both cases the materials selected for packaging, as well as the effects of the physical and geochemical environment in the disposal zone, play an important role. Typically, the external layer of the package may consist of metal, concrete or composite materials. The matrix (backfill) in which the radioactive sources are immobilized may also have a significant effect on the properties of the package and can strongly influence its required performance.

Chemical, microbiological or radiolytic processes may take place within the radioactive source package, giving rise to gas, heat and/or corrosion, depending on the radionuclide, its activity and the characteristics of the package materials. Potential gas generation issues should be addressed at an early stage in the development of a disposal concept and the design of the disposal units [74–77].

The maximum activity that will be accepted in a package must be determined from operational and post-closure safety assessments. In some cases the packaging may reduce external radiation levels sufficiently to allow for handling and transport. Shielding is not, however, an issue after the package is disposed of, and special considerations for storage and transport may apply if the disposal package does not provide adequate shielding.

If the disposal is to take place in disposal units with limiting dimensions, such as in boreholes, the outer dimensions of the disposal package should be adapted to this. Further technical, e.g. handling requirements may further constrain package design.

Considerations of regrouping and packaging DSRSs into a waste package, and the corresponding waste package design, should be carried out consistently with the preferred disposal option for the DSRS inventory. In particular, the activity concentration in a given waste package may be a criteria determining whether it is accepted for disposal in a near-surface facility. More generally, waste package design and their waste content refer to the WAC of the disposal facility and thus also to the safety scenarios that were assessed when applying and receiving a license to emplace waste in that facility.

12.1.5. Disposal WAC

During the operation of a radioactive waste disposal facility, acceptance for disposal of a given inventory of DSRS, conditioned in waste packages is decided by comparing waste and waste package properties to WAC. WACs are a management tool allowing verification whether such a disposal is compliant with the safety assessments, administrative and operational needs of the disposal facility [74, 75]. In practice, WAC for DSRSs, as for other types of radioactive waste, need to be defined in such a manner that the results of the operational and post-closure safety assessments are consistent with the applicable safety requirements (e.g. dose and/or risk constraints or targets). While generic WAC can in principle be defined prior to a given facility being sited, designed and the corresponding safety assessment performed — these generic WAC would then become a design requirement for that facility — the actual WAC can only be established based on a complete safety assessment and require the authorization of the national safety authority. Note that in addition to WAC defined with reference to safety assessment results, additional WAC refer to technical criteria defined with reference to the facility design, e.g. package dimensions and weight limits, or refer to administrative criteria, e.g. to ensure waste identification and tracking.

If disposal is planned in a near surface repository, a particularly important factor is the anticipated duration of institutional controls, which contribute to the determination of the acceptable content and concentration of longer lived radionuclides in the inventory for disposal. Another important consideration is the activity concentration of the DSRSs declared as waste, and the scenarios used to assess the long term safety of their disposal in a near-surface facility.

DSRSs will be disposed of either in existing facilities or in newly developed ones. In the former case, WAC approved by a regulatory body for the existing facility will determine which DSRSs can be readily accepted for disposal. In the event DSRSs declared as waste constitute a waste stream not originally planned for at that facility, and their characteristics are not consistent with the WAC, then their acceptability for disposal must be justified by a targeted safety assessment, and approved by the regulatory authority. For disposal solutions specifically designed to accommodate DSRS declared as waste, such as in a borehole disposal facility, the safety assessment and WAC should be consistent to allow disposal of the inventory considered. Meeting WAC implies that disposal of these DSRS is consistent with the safety assessment and that the borehole disposal facility will provide for the containment and isolation needed to protect man and the environment.

12.2. DISPOSAL OPTIONS

With the exception of DSRSs qualifying as exempt waste or VSLW, DSRSs declared as waste need to be disposed of in an adequate disposal facility. Disposal options for disused sources and factors affecting the selection of an appropriate option for the various types of sources are discussed in IAEA Technical Reports Series No. 436 [48]. They have been introduced above and already existing and operating disposal solutions are briefly described in the following sections.

12.2.1. Near surface disposal

Near surface disposal facilities have been developed and are in operation for many decades, to dispose of VLLW and LLW, including DSRSs declared as waste in the corresponding waste class and having properties consistent with WAC. Non-engineered trenches are in operation and may only be suitable for sources which will have decayed to safe levels during the institutional control period. The objective is to ensure that after this period any radioactive sources in the repository do not constitute hot spots of activity that could present a hazard if the site is inadvertently excavated or intruded into. Therefore, activity concentration may be a limiting criterion requiring careful consideration and possibly preventing some DSRSs and/or waste disposal packages regrouping several DSRSs to be accepted in certain near -surface facilities.

Large scale (typically thousands of cubic metre capacity) near surface engineered vault repositories (Fig. 108) have similar containment objectives and are also used primarily for VLLW and LLW. Much of this waste arises from the operation of nuclear power plants. The design and function of near surface repositories are described in Refs [78–81]. Such disposal facilities may not, however, provide for significantly greater acceptance of DSRSs, as compared with trenchtype disposal. Indeed, in those cases where the engineered barriers do not provide better protection from and/or reduce the risk of post-institutional intrusion, the scenario evaluating the consequences of intrusion at the emplacement location of DSRSs may be the dominant factor conditioning the corresponding WAC. This is the case when DSRS properties, their packaging and/or disposal strategy are likely to present activity hot spots.

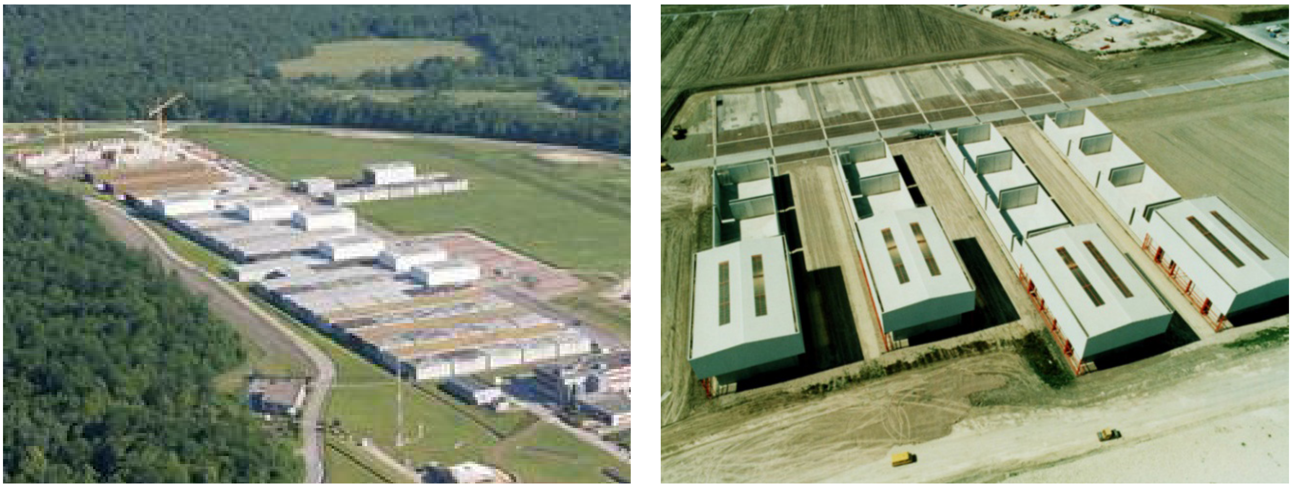

FIG. 108. Centre de l'Aube LLW, engineered near surface disposal facility in France (courtesy of ANDRA).

While this is well understood, the safety case and the characteristics of some of the DSRS inventory have nevertheless allowed several countries operating near-surface engineered type repositories to conclude that given a suitable disposal strategy, part of the DSRS inventory comply with the WAC of those facilities (e.g. Slovakia, France and Spain).

Near surface disposal for LLW includes those facilities sited in a mined, subsurface facility too close to the surface to provide for the long term passive safety features required for the disposal of certain ILW and HLW. Some Member States, e.g. Sweden, Finland, and Norway, have developed disposal facilities for radioactive waste in large rock cavities at depths of several tens of metres, generally in hard crystalline rocks such as granite, to dispose of LLW. The containment provided by such repositories often comprises massive concrete vaults or silos, with additional engineered barriers such as clay backfills and buffers. This provides a suitable disposal option for some higher activity DSRSs, given due consideration to adequate packaging and activity concentrations that suit the characteristics of the host rock and the engineered barrier system of the repository.

The Richard repository in the Czech Republic is situated in an abandoned mine excavated in limestone, and is licensed to receive LLW. The repository consists of a main access tunnel, excavated almost horizontally into the hillside for several hundred metres. A number of chambers leading off the main access tunnel are used for the disposal of conditioned waste in 200 L steel drums. Short lived and low activity sources have been disposed in those chambers. The Richard repository did not accept Am–Be, Pu–Be sources or others that exceed the specified activity limits for a waste drum [82]. However, these sources are stored at the facility in special designed containers, pending their conditioning and subsequent disposal in an appropriate geological repository.

If no repositories are available or are likely to become available in the near future for the radioactive waste other than DSRSs, provision can be made for the disposal of DSRSs in near surface disposal facilities specifically designed to accommodate the generally small volume of radioactive sources. These disposal facilities designed specifically for DSRSs would have varying levels of engineered containment matched to the characteristics of the radioactive sources they are to hold [48]. Such purpose designed near surface disposal facilities may not be suitable for the disposal of the entire inventory, in particular of high activity DSRSs and decisions would have to be made on the basis of safety assessments, amongst other factors.

In India, the Bhabha Atomic Research Centre operates two such facilities for the disposal of sealed sources: the Radioactive Solid Waste Management Site (RSMS) at Trombay and the Centralized Waste Management Facility (CWMF) at Kalpakkam. Both facilities have been operational for many years. The sources destined for disposal are segregated into similar source groups. Volume reduction is applied, if needed. Leaking sources are resealed and smaller sources are put into a stainless steel container and sealed with welding. ^{137}Cs, ^{60}Co, ^{192}Ir and other beta and gamma sources of half-life less than 30 years are being routinely disposed of.

12.2.2. Geological disposal

Mined repositories, comprising caverns or tunnels with varying types of engineered barriers are being developed in many countries that have nuclear power industry waste to manage. In addition, disused mines and/or caverns can also be considered for geological disposal. In both cases, their suitability would have to be demonstrated through a safety case and comply with the prescribed regulatory process. Depending on their siting and design, or due to political decisions, certain geological disposal facilities may be limited to receiving LLW or ILW, while others may be suitable for the disposal of HLW and spent fuel declared as waste. Irrespective of this, the containment provided by all such repositories [83] would be more than adequate for the disposal of all types of radioactive sources, so that countries having access to a geological repository may consider storing all radioactive sources for eventual disposal, provided that legal and regulatory requirements on repository inventory allow it. Indeed, some countries have strict constraints on the types of waste that can be placed in specific repositories, applied for policy reasons and not necessarily justified by safety and performance considerations.

At present, there are no geological disposal facilities for the disposal of HLW or spent nuclear fuel declared as waste in operation. However, geological facilities exist that do or have accepted other classes of radioactive waste and more are expected within the next decade. For example, the Waste Isolation Pilot Plant (WIPP) is located in the Chihuahuan Desert, outside Carlsbad, New Mexico, USA. It began disposal operations in March 1999. The repository is situated in bedded salt formations at a depth of 650 metres. The facility was licensed for disposal of transuranic waste derived from the government defense programme. The facility is also licensed to accept, for disposal, all conditioned DSRSs, containing ^{241}Am, ^{238}Pu and ^{239}Pu, manufactured in the USA.

Another repository, the geological disposal facility sited in a former salt mine in Morsleben, Germany, was used for disposal of LILW, including some DSRSs. However, the type of isotopes and activity levels accepted for disposal were strictly limited [82]. At present, Morsleben is undergoing licensing for sealing and closure.

12.2.3. Shaft and borehole disposal

Disused radioactive sources that are not acceptable for disposal in near surface repositories, because their initial specific activity exceeds acceptance criteria or because they will not decay sufficiently within the period of institutional control, may be suitable for disposal at greater depth in appropriately sited and designed disposal facilities. In Member States with negligible nuclear programmes or where resource availability is limited, disposal of disused radioactive sources in shafts and boreholes is a promising option. The borehole disposal of DSRSs entails the emplacement of solid or solidified radioactive waste in an engineered facility comprising a borehole of relatively narrow diameter drilled directly from the surface. Other concepts consider disposal in wider diameter shafts. Borehole and shaft disposal facilities may cover a range of designs with depths ranging from a few tens of metres up to several hundred metres. Their diameters can vary from a few tens of centimetres up to more than one metre [84–86]. The borehole or shaft may have a casing and the sources would normally be contained within an engineered package that is surrounded by backfill material (Fig. 109).

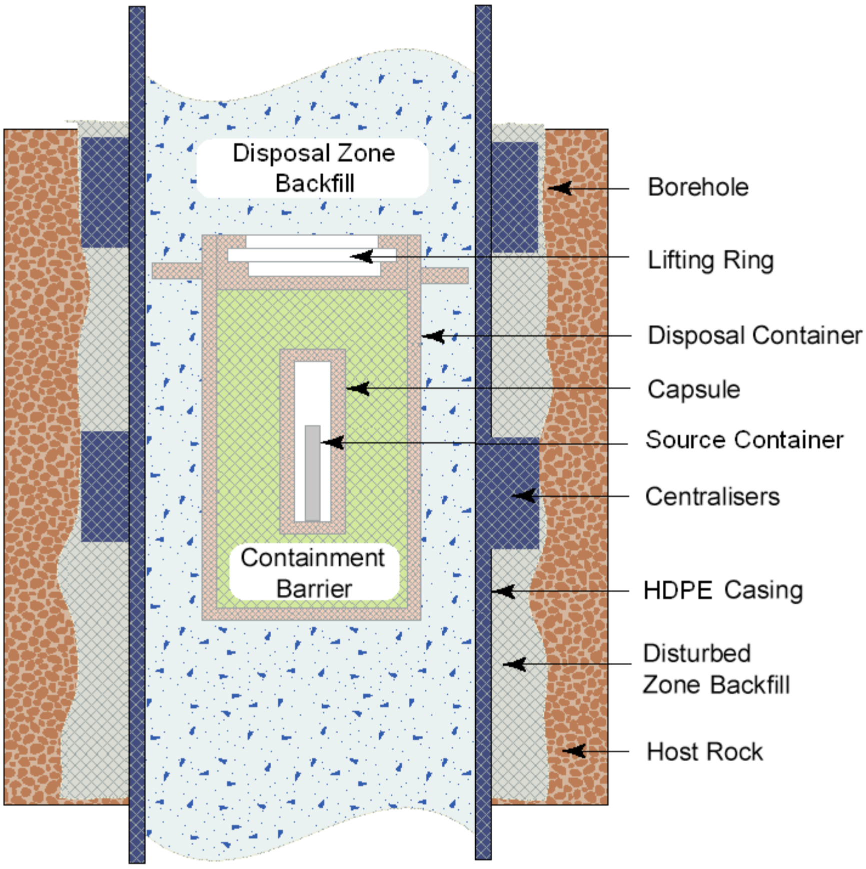

FIG. 109. A schematic illustration of possible components of a borehole disposal system.

A disposal facility may consist of a single borehole or a group of boreholes that may or may not be located in conjunction with other nuclear facilities. The limited radionuclide inventory intrinsically limits the potential hazards to people and the environment. Borehole disposal facilities have a number of favourable characteristics of potential benefit from a waste safety and economic point of view, namely they:

— Provide long term isolation from humans and the environment for small volumes of high specific activity radioactive waste in high integrity waste packages;
— Provide direct and cost effective access to a suitable geological horizon, using readily available technology;
— Require limited land area and limited infrastructure;
— Require short periods of construction, operation and closure;
— Have a low probability of human intrusion and future disruptive events due to the small footprint of the borehole and the ability to select a suitable depth. `

The natural and engineered barriers can be designed to provide for long term safety by means of multiple safety functions that are not unduly dependent on each other. This can be achieved by ensuring that the functions of the engineered and natural barriers depend on diverse physical and chemical processes and are assured by quality management procedures. In this way, the overall safety of the system should not be strongly dependent on the performance of any one component. More details about borehole disposal are given in Ref. [48].

Borehole facilities have been used in a number of countries for storage and disposal of radioactive waste. A brief review of these facilities is presented in Ref. [81].

For example, disposal of DSRSs in shafts or boreholes excavated in arid environments in the unsaturated zone has been implemented in the Greater Confinement Disposal Facility, Nevada Test Site in the USA and at Mt. Walton East in Australia [87, 88].

As a further example, the borehole facility for DSRSs in the Russian Federation is a stainless steel cylindrical vessel with a diameter of 400 mm and height of 1500 mm, emplaced at a depth of 4 m in a reinforced, concrete well (Fig. 110). A clay–cement mixture is used to backfill the initial construction hole in the ground around the concrete wall of the facility and acts as an impermeable seal. The design of the facility considers the maximum allowable temperature generated by the sources (around 230°C). To satisfy this requirement, the maximum load in the facility may not exceed 1.85 PBq (50 000 Ci). “The capacity of the borehole facilities has been increased to 6.7 PBq (180 000 Ci) when in-situ conditioning with metal matrix was used.”

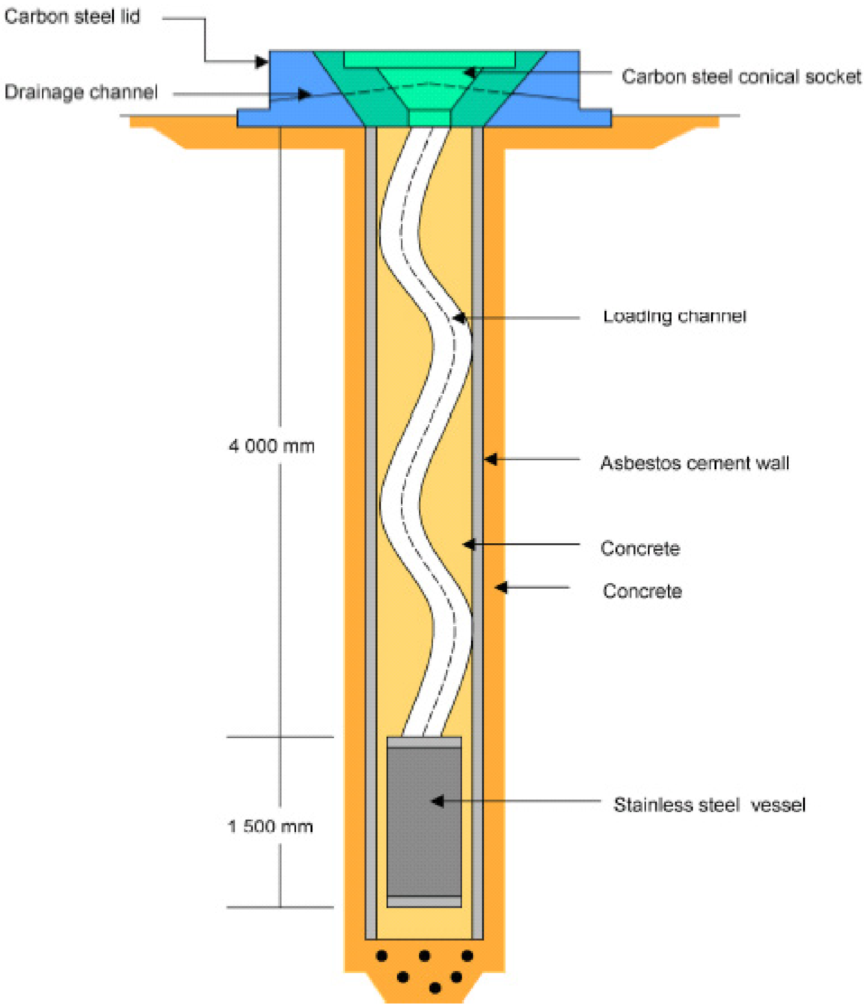

FIG. 110. The design of a ‘radon type’ borehole repository in the Russian Federation.

New borehole disposal facilities are currently being planned as an extension of a conventional near surface disposal facility, either already in operation or in a planning stage [89, 90]. Also, the IAEA in collaboration with Necsa of South Africa has developed a borehole disposal concept design specifically for the safe disposal of DSRSs [73, 85, 86].

The borehole disposal concept (shown schematically in Fig. 111) entails the emplacement of DSRSs in an engineered facility bored or drilled and operated directly from the surface. Borehole disposal is envisaged mainly as a small scale activity that can be carried out without a large programme of scientific and site investigation.

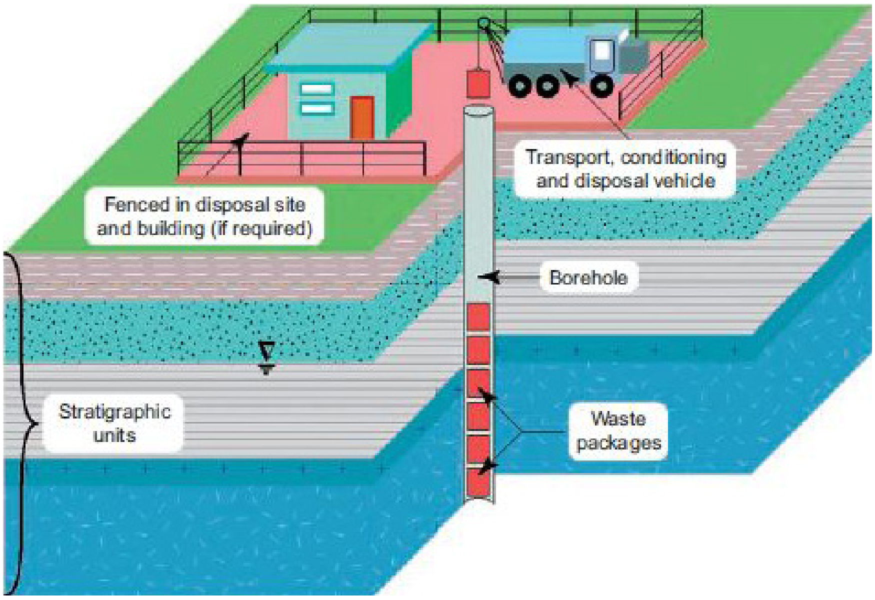

FIG. 111. Schematic layout of a borehole disposal concept and facility.

From a safety requirements perspective, borehole disposal is not different from either near surface disposal or geological disposal of radioactive waste. Indeed, because the range of depths accessed by borehole disposal approaches the depths normally associated with both near surface disposal and geological disposal, consideration is given to elements of both. As for near surface disposal and geological disposal, a combination of natural barriers and engineered barriers contribute to safety for borehole disposal. In combination, these barriers are designed to contain radioactive material until it has decayed to insignificant levels, and to provide sufficient isolation and containment to ensure an adequate level of protection for people and the environment [91]. Guidance on how the predisposal activities may be organized to deliver the required operational and post-closure safety (i.e. how the protection requirements and associated criteria specified may be satisfied) for a new borehole disposal facility is provided in Ref. [91].

12.3. PROBLEMS ENCOUNTERED AND LESSONS LEARNED

12.3.1. Near surface disposal

Many Member States have developed near surface disposal facilities for VLLW and LLW. However, the specific characteristics of many DSRS do not comply with the WAC established for the existing facilities already in operation. These characteristics include:

- Levels of activity: The basic property of Category 1 and 2 DSRSs is the residual high activity.
- High specific activity: A considerable number of higher activity sources exceed the specific activity limits for waste acceptable in near surface disposal facilities because it could give rise to unacceptable radiation doses in the event of inadvertent human intrusion.
- Physical and chemical characteristics: Although robust construction is employed in the manufacture of sealed sources, they are not indestructible. The chemical form of the radioactive contents determines the degree of dispersability and potential for radionuclide migration.
- Heat and dose: The high specific activity of a Category 1 source may cause localized, elevated local temperatures, which may result in decreasing isolation capability of one or more barriers.
- Gas generation: Potential gas generation due to radiolysis, radioactive decay products and corrosion need to be considered.

A number of unconditioned DSRSs mixed with other waste have been disposed of in near surface facilities having unsuitable site characteristics, which caused serious safety concerns due to the high activity and long lived nature of the sources disposed of. These concerns have invariably resulted in relevant authorities considering the retrieval and recovery of high activity and long lived DSRSs from such facilities in several countries, such as Estonia, Hungary and Lithuania, as part of their repository upgrading programmes [82].

In Latvia, DSRSs have been disposed of at the Radon facility at Baldone during the period from the 1960s to the early 1990s. Since then, DSRS disposal is no longer permitted and they are now being retrieved and transferred to a new interim storage vault. Future actions regarding DSRSs, already disposed of, and those in storage, will depend on the outcome of a safety assessment to determine whether any remedial action is required.

Between 1963 and 1988, DSRSs have been disposed of in Lithuania at the Maišiagala near surface repository. The repository has recently been reclassified as a storage facility and an upgrading project was implemented in years 2004–2006. The disposed waste is planned to be retrieved as soon as geological disposal becomes available.

Safety cases for many near surface disposal facilities assume a period of institutional control (typically a few tens to hundreds of years) during which inadvertent human intrusion is assumed to be unlikely. However, even within this period and particularly for longer time frames, during which the high activity and long lived sources will not decay sufficiently, it is conceivable that the institutional control will no longer be fully in place, and thus inadvertent human intrusion and associated radiation hazard to humans cannot be ruled out.

12.3.2. Geological disposal

The cost of construction of a geological disposal facility is high. It would be difficult to justify the construction of such repositories in countries having only a few long lived DSRSs. Possible solutions are the design of a suitable borehole facility, or considerations of sharing disposal responsibilities at a regional scale. The latter raises questions associated with the option for multinational repositories, as is further discussed e.g. in Ref. [92].

12.3.3. Borehole disposal

The borehole disposal concept developed by the IAEA specifically for disused radioactive sources [73, 91] could potentially provide a cost effective and safe disposal option, particularly for countries with a limited nuclear infrastructure. It holds out particular promise for countries that have just DSRSs and no other disposal facilities available for radioactive waste disposal.

Some safety concerns associated with the radon type borehole disposal have been mitigated by the in situ conditioning of bare sources using low melting point metal alloy and introducing retrievability in the design [93]. However, this practice planned earlier as disposal, is now considered as storage.

The Russian Federation has also developed a new container design for long lived radioactive sources, which enables the retrieval of DSRSs underground for transport to final disposal. This repository container has an underground reservoir for storing sources with the volume 106 dm^3. It is designed to store DSRSs with total radioactivity of 3.7×10^{14} Bq (10 kCi).

The disposal facility at Novi Han in Bulgaria has accepted DSRSs for disposal. The operational license for the facility was suspended in 1994 due to safety issues. Subsequently, a major upgrading programme was initiated to improve repository safety [82].

Another example of the borehole disposal of disused sealed sources is the Püspökszilágy repository in Hungary, situated about 40 km north of Budapest on the ridge of a hill. The waste has been disposed of in a number of different near surface disposal units (vaults and boreholes) with engineered barriers. The long lived DSRSs emplaced in boreholes were initially intended for disposal, but the approach has been reconsidered as being in storage, and awaiting retrieval, prior to disposal in a geological repository.

13. SAFETY CASE AND SAFETY ASSESSMENT

The IAEA's Safety Requirements [62, 72] requires, inter alia, that a safety case be developed together with supporting safety assessment. The safety case is the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility. Safety assessment, an integral part of the safety case, is driven by a systematic assessment of radiation hazards and is an important component of the safety case. The latter involves quantification of radiation dose and radiation risks that may arise for comparison with dose and risk criteria, and provides an understanding of the behaviour of the facility under normal conditions and disturbing events, considering the time frames over which the radioactive waste remains hazardous. The safety case and supporting safety assessment provide the basis for demonstration of safety and for licensing. They will evolve with the development of the facility, and will assist and guide decisions on siting, design and operations. The safety case will also be the main basis on which dialogue with interested parties will be conducted and on which confidence in the safety of the facility will be developed. IAEA Safety Guides [94, 95] provide guidance and recommendations on meeting the safety requirements for the safety case and supporting safety assessment for the predisposal management and disposal of radioactive waste.

Safety assessment as defined in Ref. [1] is the "assessment of all aspects of a practice, that are relevant to protection and safety; for an authorized facility this includes siting, design and operation of the facility". Safety assessment plays an important role throughout the lifetime of the facility or activity whenever decisions on safety issues are made by the designers, the constructors, the manufacturers, the operating organization or the regulatory body. The initial development and use of the safety assessment provides the framework for the acquisition of the necessary information to demonstrate compliance with the relevant safety requirements, and for the development and maintenance of the safety assessment over the lifetime of the facility or activity.

Safety assessments are required to be prepared for facilities and activities used for the management of disused sealed sources as a particular waste stream, including decommissioning activities, to demonstrate that the basis for safety is adequate and, more specifically, that such facilities and activities will be in compliance with the safety requirements established by the regulatory body [96]. The safety assessment should also demonstrate that the packages for DSRSs will sufficiently confine the radionuclides in normal operations and in postulated incidents and accidents.

13.1. SAFETY ASSESSMENT PRINCIPLES

The IAEA Fundamental Safety Principles publication [28] states that the "fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation". This objective applies to all facilities and activities dealing with the management of DSRSs, and has to be achieved for all stages in their lifetime without unduly limiting the application of technology.

Stages in the lifetime of a facility or activity where a safety assessment is carried out, updated and used by the designers, the operating organization and the regulatory body include [96]:

(a) Site evaluation for the facility or activity;
(b) Development of the design;
(c) Construction of the facility or implementation of the activity;
(d) Commissioning of the facility or activity;
(e) Commencement of operation of the facility or conduct of the activity;
(f) Normal operation of the facility or normal conduct of the activity;
(g) Modification of the design or operation;
(h) Periodic safety reviews;
(i) Life extension of the facility beyond its original design life;
(j) Changes in ownership or management of the facility;
(k) Decommissioning and dismantling of a facility;
(l) Closure of a repository for the disposal of radioactive waste and the post-closure phase;
(m) Remediation of a site and release from regulatory control.

For many facilities and activities, environmental impact assessments and non-radiological risk assessments will be required before construction or implementation can commence. The assessments of these aspects will, in general, have many commonalities with the safety assessment that is carried out to address associated radiation risks. These different assessments may be combined to save resources and to increase the credibility and acceptability of their results.

The Fundamental Safety Principles [28] include ten principles that apply in achieving the fundamental safety objective. This leads, inter alia, to the requirement for a safety assessment to be carried out. The interrelationship of the Fundamental Safety Principles and safety assessment is discussed in detail in Ref. [96], which also establishes the generally applicable requirements to be fulfilled in safety assessment for facilities and activities, with special attention paid to defence in depth, quantitative analyses and the application of a graded approach to the ranges of facilities and of activities that are addressed. That publication also addresses the independent verification of the safety assessment that needs to be carried out by the originators and users of the safety assessment. This publication is intended to provide a consistent and coherent basis for safety assessment across all facilities and activities, which will facilitate the transfer of good practices between organizations conducting safety assessments and will assist in

The safety assessment needs to consider internal process related events (internal fire, dropped waste packages, failure of waste package containment, ventilation failure, power failure, etc.) and external hazards (e.g. aircraft crashes, transport accidents away from the facility, earthquakes, tornados and external fires).

13.2. SAFETY ASSESSMENT PROCESS

The main elements of the process for safety assessment and verification are shown in Fig. 112 [96]. This requires that a systematic evaluation of all features of the facility or activity relevant to safety be carried out, and includes:

(a) Preparation for the safety assessment, in terms of assembling the expertise, tools and information required to carry out the work;
(b) Identification of the possible radiation risks resulting from normal operation, anticipated operational occurrences or accident conditions;
(c) Identification and assessment of a comprehensive set of safety functions;
(d) Assessment of the site characteristics that relate to possible radiation risks;
(e) Assessment of the provisions for radiological protection;
(f) Assessment of engineering aspects to determine whether the safety requirements for design relevant to the facility or activity have been met;
(g) Assessment of human factor related aspects of the design and operation of the facility or the planning and conduct of the activity;
(h) Assessment of safety in the longer term, which is of particular concern when ageing effects might develop and might affect safety margins, decommissioning and dismantling of facilities, and closure of repositories for radioactive waste.

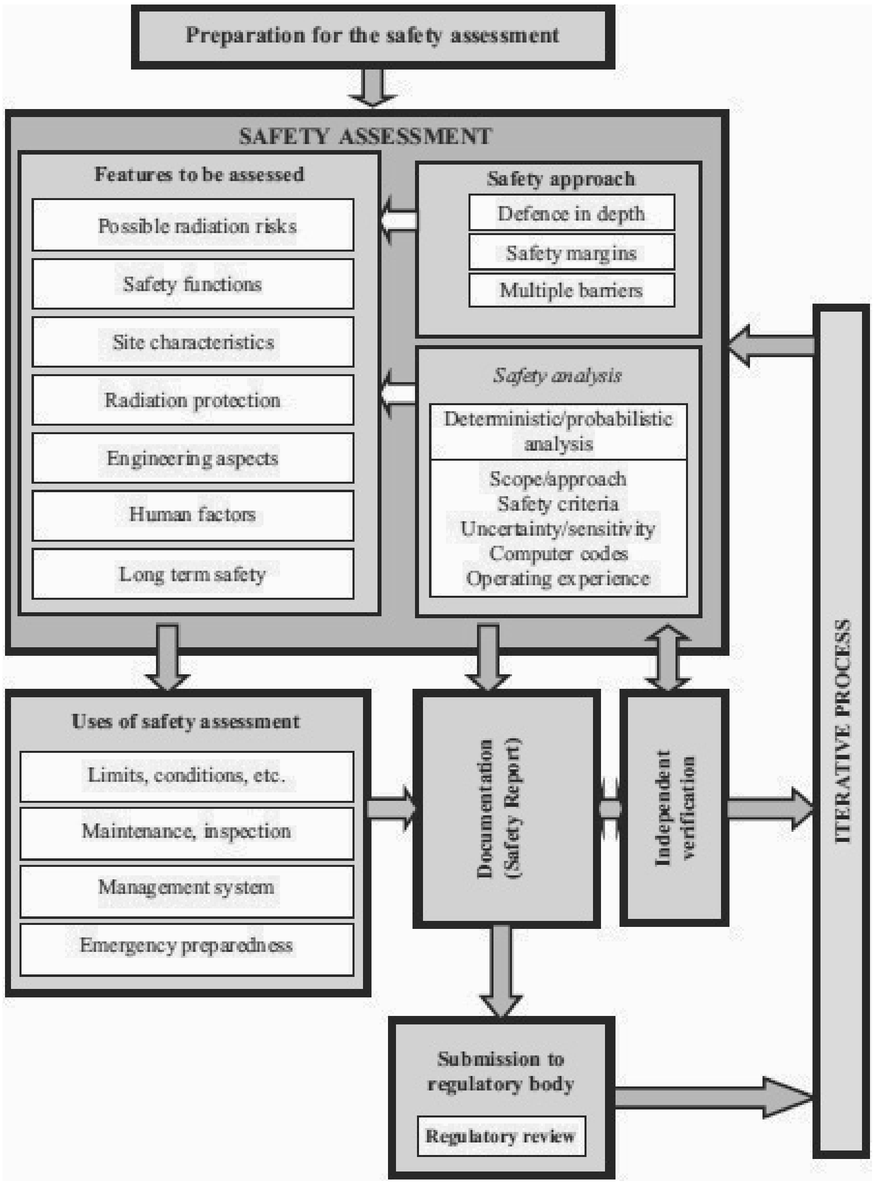

FIG. 112. Overview of the safety assessment process [96].

A safety assessment should be conducted with due regard to all relevant regulations and safety guidelines pertinent to the potential hazards at each stage of the waste management. The safety assessment should cover all of the operations and inherent hazards associated with every aspect of the management of radioactive waste at the facility. Safety assessments may also be required for practices for waste management off the site, including the transport of the waste.

The process of safety assessment for facilities and activities is repeated in whole or in part as necessary later in the conduct of operations in order to take into account changed circumstances (such as the application of new standards or scientific and technological developments), the feedback of operating experience, modifications and the effects of ageing. For operations that continue over long periods of time, assessments are reviewed and repeated as necessary. Continuation of such operations is subject to these reassessments demonstrating to the satisfaction of the regulatory body that the safety measures remain adequate.

In the case of a repository for radioactive waste in significant quantities, radiation risks have to be considered for the post-closure phase. Radiation risks following closure of the repository may arise from gradual processes, such as the degradation of barriers, and from discrete events that could affect isolation of the waste, such as inadvertent human intrusion or abrupt changes in geological conditions.

The full range of characteristics of the waste that are anticipated should be considered and the impacts and environmental effects of normal operations of the facility and potential accident conditions should be evaluated in the safety assessments. This will entail identifying the environmental pathways for radionuclides to humans and the potential exposures. Values for acceptable levels for all liquid and gaseous effluents that may be routinely discharged to the environment from the facility should be derived on the basis of the potential exposures. The adequacy of equipment used to monitor and control the levels of such discharges should also be assessed. The safety assessments should be reviewed from time to time and updated as necessary on the basis of the information gathered by monitoring the workplace and the environment.

Recommendations on preparing a safety assessment for near surface disposal of radioactive waste are provided in Ref. [97]. An overview of post-closure safety assessment and the development of a safety case for borehole disposal facilities are given in Ref. [86, 98]. Recommendations for the development and review of safety assessments for decommissioning activities are provided in Ref. [99].

14. CONCLUSIONS

The report provides a review of various management steps applied to disused radioactive sources with the intention to give practical guidance to Member States for the handling, conditioning, transporting, and storing of any kind of DSRSs arising from medical, industrial, research and other nuclear applications. These guidelines, while in compliance with the basic safety standards and relevant safety requirements, are only one way to fulfill these requirements. The reader is expected to consider actual conditions and prevailing situations to make his procedures and actual guidelines effective according to his conditions and available infrastructure.

Conclusions derived from this report can be summarized as follows:

(a) The applications and characteristics of SRSs used in medicine, industry and research are extremely diverse. A large number of portable sealed sources, most of them small and of low activity, are used in industry and medicine. Consequently, it is not surprising that, in spite of inventory keeping and controls, some sources are lost. The construction of most sealed sources is quite robust, so the accidents involving lost sources are usually due to human error. High activity sources are not readily movable but they present a high risk of overexposure if not properly managed.

(b) Sources must be fully characterized in radiological, chemical and physical terms as a precursor to effective management. There is a challenge in the identification and characterization of undocumented SRSs. The Reference Manual on Identification of Radioactive Sources and Devices, prepared by the IAEA [21], could be an effective tool for the identification of sealed sources and associated devices.

(c) All activities relating to the use and management of disused sources should be included within the regulatory system. A key management control issue is to identify exactly when a source becomes disused. This is simple if a source is being replaced or a facility closes. However, the process is often more gradual (e.g. as a research source is used less regularly). It is at this stage that sources are at most risk of loss. Regulatory schemes should differentiate between used/disused sources. One way is to require regular inventory reporting to the regulator by the user, with separate listing of used/disused sources. This may not be sufficient to deal with sources which gradually drift into disuse. A second option might therefore be to report the date each source was last used. A time limit may then be set, beyond which failure to use the source renders it automatically 'disused'.

(d) A modern management system, covering handling, packaging, training, auditing, safety assessment, the relevant regulatory requirements and record keeping, should be implemented for all steps and components of a DSRS management strategy.

(e) Depending upon the situation, disused sources may be either returned to the supplier, or transferred to another user, or disposed of in the country in which they were used, or disposed of in a third country willing to accept them. Unfortunately, disused sources are often discarded. Sometimes discarded sources give rise to accidents. Such accidents, which occur even in Member States with adequate legislative and regulatory frameworks, have resulted in people being irradiated, with fatal consequences in some cases. It is therefore essential that the regulatory body be provided with the means necessary for effectively controlling all major sources in the Member State. It is also essential that the regulatory body maintain effective communication with the holders of licenses for these sources.

(f) The return of DSRSs to the supplier, as envisaged in the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Ref. [13], Article 28), is, in principle, a good solution. In practice, however, there may be difficulties due to the Member State's legislation and/or financial burdens for instance the supplier may go out of business or the manufacturer of the sources may not exist.

(g) Storage of disused sources at user facilities is not ideal from the safety and security points of view. Disused sources in operational storage are at some risk of being lost from control. Central storage of disused sources reduces the likelihood of losing control. The time in user's storage should be minimized and specific attention should be paid by the user and the regulator to access control, security, maintenance of adequate records, individual responsibilities and routine checks (e.g. leak tests).

(h) Any segregation required depends on the storage facility and on the final disposal route. The segregation of potentially recyclable or reusable material is advised. Most segregation policies are on the basis of dose rate (an important factor in storage), isotope/half-life and activity (important factors in disposal).

(i) Due to some characteristics of disused sources (high specific activity, high activity, long half-life, etc.) many sources cannot be disposed of in the near surface facilities. Since deep geological repository is not yet available the only management option is long term storage. A promising solution could be disposal in boreholes; this concept is under development now. Until the situation changes, most efforts should be placed on the adequate preparation of the sources of concern for storage by proper conditioning and the provision of safe storage facilities for conditioned sources. Centralized waste processing facilities serving a number of users can be cost effective management option.

(j) Waste operators should implement conditioning of disused sources that are the most cost effective to procure and operate, and which satisfy all local and national requirements. Process selection, especially in developing Member States, should be based on relatively simple, robust technology that is readily available and maintainable and is adequate to deal with disused sources. The use of stainless steel capsules followed by lid welding can be recommended for conditioning of long lived sources in view of further retrieval and reconditioning of sources for disposal.

(k) Dismantling may be required where volume is a premium. Dismantling should only be done in suitably contained and shielded facilities by suitably qualified and experienced personnel. If such facilities and experience are not available, mobile systems and expert teams can be acquired from abroad commercially or through bilateral or international assistance programmes.

(l) The disposal route should be identified prior to purchase of a source and if possible, commercial arrangements agreed at the same time. While this approach is becoming standard, many historical sources do not have available interim storage/disposal routes in many countries. Return to a manufacturer is generally preferred to sending to a central interim store. Where possible, reuse or recycling should be considered, but it is unlikely that such routes can be identified at time of purchase. Return to the manufacturer may give access to recycling possibilities.

(m) All transfers of disused sources to the central storage/disposal facility should be carried out in accordance with appropriate quality management procedures. A Source Disposal Certificate should be issued to the consignor by the operator of the central facility to confirm transfer of liability.

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ABBREVIATIONS

ALARA	as low as reasonably achievable
BSS	International Basic Safety Standards — Radiation Protection and Safety of Radiation Sources
CRWMOO	central radioactive waste management operating organization
DSRS	disused sealed radioactive source
EW	exempt waste
GVHD	graft versus host disease
HDR	high dose rate
HLW	high level waste
ISO	International Organization for Standardization
ILW	intermediate level waste
LSC	liquid scintillation counting
LDR	low dose rate
LLW	low level waste
LLDSRS	long lived disused sealed radioactive sources
MSM	master slave manipulator
NDA	non-destructive assay
QA	quality assurance
RAIS	Regulatory Authority Information System
RMC	radioactive material coordinator
RTGs	radioisotope thermoelectric generators
RWMP	radioactive waste management registry
RWL	recommended working life
SRS	sealed radioactive source
VSLW	very short lived waste
WAC	waste acceptance criteria

Annex

RISKS ASSOCIATED WITH DISUSED SOURCES

In this annex, hazards, in particular radiological hazards associated with DSRSs, are discussed.

The most severe accidents with disused sources have occurred when the sources ended up in the hands of non-professionals who were unaware that they were dealing with radioactive material, since equipment or source holders containing disused sources may look like normal scrap (see Fig. A–1). Loss of control over DSRSs can also lead to risk of loss, theft or misappropriation of the source. A new dimension to the potential hazard of disused sources is the possibility that they may be intentionally stolen for malicious use or illicit trafficking.

Past accidents have demonstrated that radiation, due to its nature and history, has a unique ability to trigger fear and anxiety in the general population. The quantity of radioactive material required to cause economic consequences does not need to be large; even a small amount could trigger huge psychological impacts. Implementation of appropriate security measures can reduce the probability of such situations occurring.

A–1. FEATURES INFLUENCING THE HAZARDS ASSOCIATED WITH DISUSED SOURCES

In the case of DSRSs, the consequences of an accident could include of one or more of the following [A–1]:

— Internal and/or external contamination of individuals and associated radiation injuries (e.g. erythema, tissue damage, amputation and even death) due to excessive exposure of individuals;
— Contamination of material or the environment due to the breaching of the encapsulation and dispersion of the radioactive content of the SRS (destruction of the encapsulation, melting down with scrap, etc.);
— Economic losses due to medical treatment, accident related radiation surveillance, decontamination, dismantling, waste management and disposal, as well as costs due to loss of production capacity, monetary compensation to over exposed individuals, social expenses and the loss of use of the source itself.

In general terms, risk is the chance or probability that a person will be harmed or experience an adverse health effect if exposed to a hazard, and is a function of probability (likelihood that a certain event will occur) and consequence (extent of detrimental effects). The risks associated with exposure to DSRSs are affected by the characteristics of the source, the environment in which the source is affected, and the actions of the persons involved. Radioactive sources containing long lived radionuclides, such as ^{241}Am or ^{226}Ra, will still be potentially dangerous after thousands of years. Conversely, short lived radioisotopes become safe in a far shorter time. The decay of ten half-lives decreases the activity by a factor of about 1000. A teletherapy source with an initial activity of 100 TBq ^{60}Co will decay to a safer level after 100 years, while a ^{137}Cs source of the same activity requires 600 years and an ^{192}Ir radiography source only four years, to decay to the same level of activity.

The consequences of an accident involving exposure to an SRS are directly proportional to its activity [A–2]. For a alpha or beta emitting source, the damage caused by the handling of a kBq source would be undetectable, but a similar source of TBq strength could have fatal implications (note this assumes beta and/or gamma sources only).

FIG. A–1. Out of service equipment containing disused sources.

A–2. EFFECTS OF IONIZING RADIATION

The impact of any radiation exposure depends on the type of radiation associated with the source. When ionizing radiation imparts energy to living tissue, damage is likely to occur. The higher the intensity of incident radiation, the greater is the extent of damage. It is, therefore, the transfer or deposition of energy in living tissue that determines the extent of the damage to the tissue and, hence, the injury. The ionization of tissue can also take place as a direct consequence, as is the case with alpha and beta radiation, or indirectly, as is the case with gamma rays and neutrons. While alpha radiation has a high specific ionization characteristic, its penetration is very limited.

Gamma radiation and neutron beam ionization characteristics depend on their energy. Neutron sources (e.g. Am–Be, Ra–Be, Pu–Be) require particularly careful handling as neutrons emitted by these sources represent a more dangerous type of radiation. Moreover, when absorbed by the surrounding medium, neutrons can induce artificial radioactivity.

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 humans. 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. The IAEA source categorization system [A–3] is based on the deterministic effects.

Category 1 sources, if not safely managed or protected securely, are likely to cause permanent injury to a person during handling, or alternatively, from contact with the sources for more than a few minutes. It would probably be fatal to be in close proximity of unshielded radioactive material for a period of a few minutes to an hour.

Category 2 sources, if not safely managed or protected securely, could cause permanent injury to a person during handling, or alternatively, from contact with the sources for a short period of time (minutes to hours). It could possibly be fatal to be in close proximity of unshielded radioactive material for a period of hours to days.

Category 3 sources, if not safely managed or protected securely, could cause permanent injury to a person during handling, or alternatively, from contact with the sources for several hours. It is very unlikely that any person in close proximity will be exposed for more than a couple of hours at such short distances.

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 $2–4 \times 10^{-2}$ per Sv, while for severe hereditary effects the risk is smaller, about 10^{-2} per Sv. A fuller discussion of the effects of ionizing radiation on man and the environment is given in Refs. [A–4–A–8].

Time, distance, and shielding are the key elements of radiation protection and minimizing exposure. The radiological risk is linked with the same elements. Radiation exposure may cause more harm if people are exposed for longer times, at closer proximity, and with less shielding material between the source and the subject. These factors make it difficult to do grave harm to large numbers of people because it is difficult to put many people in close proximity to a source for a long time, and even the human body itself provides some shielding, so that a crowd somewhat shields a radioactive source. A single source, even a large one, might not have major or lasting psychosocial or economic impacts.

In the event of a damaged source, the effect on the environment may be contamination of buildings and of the general area. The high specific activity of the radioactive material in sealed sources means that the spread of as little as microgram quantities of its contents into the environment can generate a significant risk to man, thereby restricting the use of potentially contaminated buildings and areas. The cost of decontamination can be very high. Accidents with disused sources have already resulted in extensive contamination of the environment and high costs for the associated decontamination work.

A–3. TOXIC HAZARDS OF RADIOACTIVE SOURCES

Poisoning large numbers of people by radionuclides contained in sealed sources to achieve near-term health impacts would be difficult because in food, for example, the radioactive material must be fairly highly concentrated to have a deterministic effect on any individual. Bacteria are much more effective at causing harm. So to affect many people requires a very large amount of material. Soluble radioactive material could be introduced into water reservoirs, but almost any plausible number of radioactive sources would become too dilute to have much health impact. The material could be introduced closer to the point of consumption, but then the number of people affected would be low. It is possible that a poisoning attack could trigger some mistrust of the food or water supply, but because food-borne and water-borne illness outbreaks occur with some frequency, they are somewhat familiar. It is also possible that if a reservoir were contaminated with radioactive material, consumers would insist on cleaning up the reservoir, even if the radioactive material had no safety implications for the water in people’s homes. Such cleanup could be costly, but such an attack would no longer be about poisoning; it would be a use-denial type radiological dispersal attack.

A–4. ROLE OF THE SOURCE DESIGN

Many applications of radioactive sources require the activity to be concentrated into a very small volume *(point source)* or to approximate the geometry of a line *(line source).* The volume of radioactive material is usually in the order of a cubic centimetre or a few cubic millimetres, which ensures very small dimensions for the source, even though the overall volume increases as a result of encapsulation.

The material used for encapsulation is usually stainless steel, but sometimes platinum, titanium, aluminium or other materials are used as well. Gold, brass, silver and even glass capsules have been used in early ^{226}Ra sources. Precious metals, used for encapsulating radium sources, have been stolen for their monetary value and have become a cause for many accidents.

Old sources (especially old radium sources) were manufactured to standards lower than would be acceptable today. The radioactive substance in these sources was either a powder or soluble salt, which is readily dispersible in the event of damage to the encapsulation.

A–5. SOME ACCIDENTS/INCIDENTS INVOLVING DISUSED SOURCES

Very often disused sources and their containers are collected by non-professionals as valuable scrap. Such situations can prove to be very dangerous. The Goiânia accident in Brazil in 1987 represents such an accident, which resulted from inadvertent abandonment of a ^{137}Cs teletherapy unit [A–9]. This occurred when a private radiotherapy institute in Goiânia moved to new premises, leaving behind a ^{137}Cs teletherapy unit without notifying the licensing authority as required under the terms of the institute's authorization. The former premises were subsequently partly demolished. As a result, the teletherapy unit became unsecure. Two people entered the premises and, not knowing what the unit was, but thinking it might have some scrap value, removed the source assembly from the radiation head of the machine. They took it home and the source capsule ruptured. Subsequently, the remnants of the source assembly were sold to a scrap yard owner. Fourteen people were seriously contaminated, four of whom died and the others survived after extensive treatment. More than 12 000 persons had to undergo thorough monitoring for radiation exposure, out of which 249 individuals were contaminated either internally or externally. Severe environmental contamination had occurred. Remediation of the contaminated area resulted in a total volume of contaminated waste of 3500 m^3. International cooperation was required to mitigate the consequences of this accident. The direct costs for the decontamination operation and for the construction of two concrete storage vaults for the waste are estimated to be $15 million.

Another accident involving disused sealed sources occurred in Georgia in 1997 [A–10] where 11 military service personnel were found to have developed radiation induced skin disease. The major cause of the accident was the improper and unauthorized abandonment of 12 ^{137}Cs radioactive sources previously used by the army.

A third example of an accident of this nature occurred in Estonia in 1994, where three people intruded into an unguarded waste disposal facility and removed a ^{137}Cs source and brought it home [A–2]. As a consequence, one person died and several other family members were contaminated, some of them having developed radiation induced skin burns.

Other accidents are associated with melting of disused sources placed in recycling metal scrap. Worldwide, there have been many cases where radioactive materials were unintentionally melted in the course of recycling metal scrap.

In one single accident in Mexico in 1983, a ^{60}Co teletherapy source was melted down in a foundry in the northern part of the country. The resulting contaminated steel bars were used for civil construction in Mexico and in the USA, giving rise to the contamination of several thousand persons and demolition of several contaminated houses. A similar accident occurred in 1998, in Europe, when a ^{137}Cs source was melted down at a metallurgical factory in southern Spain. The resulting airborne contamination spread for days until it was detected in southern France, Switzerland, Italy and southern Germany. The steel mill and two processing plants that received the incinerated material were also contaminated. These plants were ordered to be shut down by the Spanish nuclear security body until decontamination measures were implemented.

A–6. PRACTICAL STEPS TO MINIMIZE RISK

The infrastructure components that are related to risk reduction related to the DSRS management, at the waste operator level, can be summarized as follows [A–1]:

— Full familiarity with the design and characteristics of the sources brought to the facility for conditioning or storage. This implies good documentation and technical description of all types of sources imported into the country.
— Trained and experienced staff (initial and periodical training including radiation protection, operating procedures, practical aspects of health care and safety, source characteristics, regulatory requirements, management control procedures, requirements for documentation).

— Licensing (including fulfillment of all requirements of the competent authority).
— Management system (including i.e. written procedures, surveillance, security measures, emergency planning).
— Regular auditing (internal and/or external).

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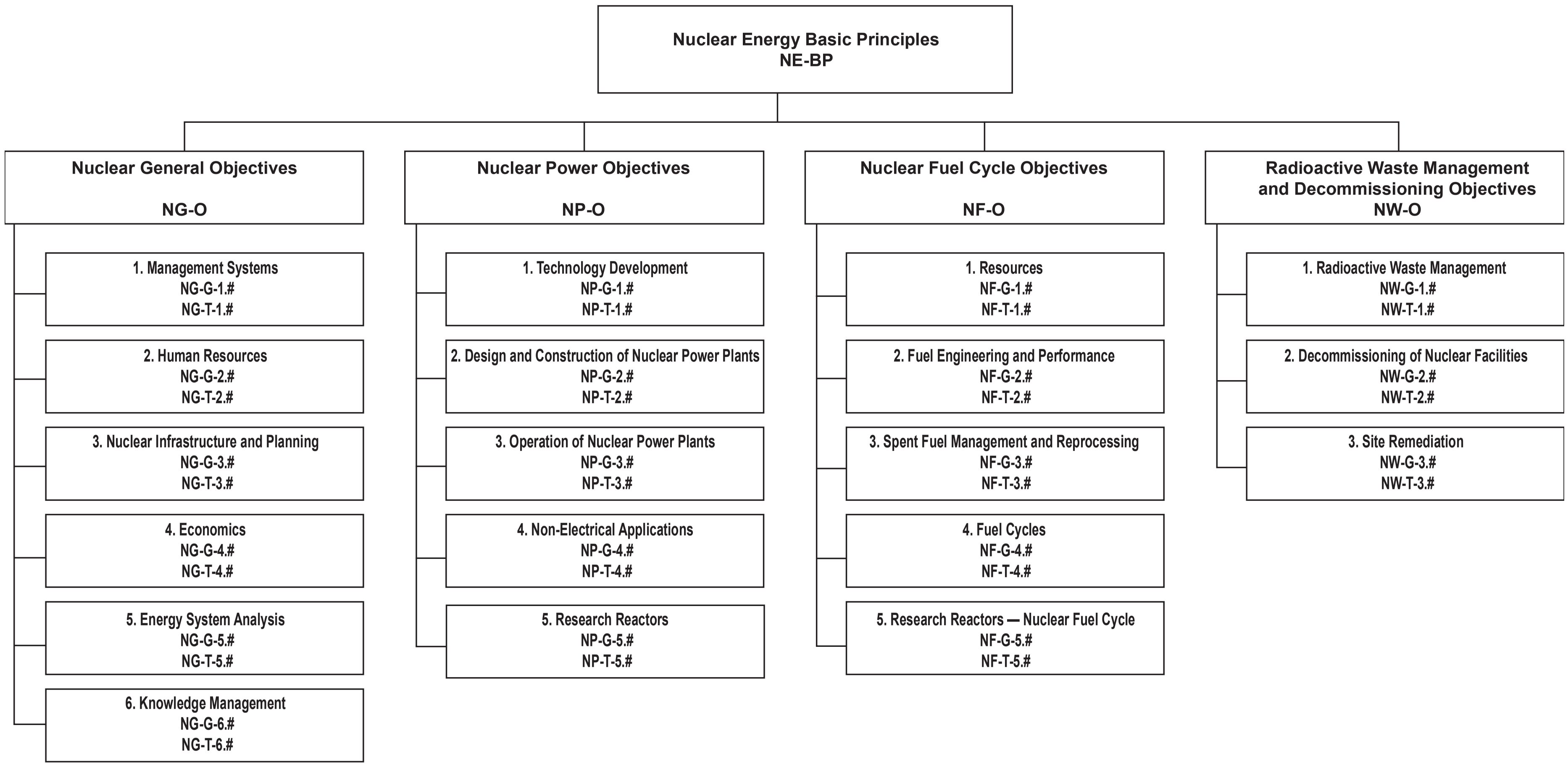

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