The Use and Management of Sealed Radioactive Sources

A sealed radioactive source (SRS) is defined as "radioactive material that is either permanently sealed in a capsule or closely bonded and in a solid form".[1] The capsule or material of a sealed source is strong enough to maintain leak tightness under the conditions of use for which the source was designed and also under foreseeable mishaps. This document summarizes the uses as well as the safe and effective management and disposal of SRSs.

A. Introduction

Sealed radioactive sources are widely used for beneficial purposes throughout the world in industry and in medicine. In industry, common uses include non-destructive testing, radiation sterilization of health care products, modification of polymeric materials, on-line process control systems, elemental analysis of raw materials, mineral resource evaluation, food irradiation and smoke detection. In medicine, SRSs are commonly used in teletherapy and brachytherapy for the treatment of malignant diseases and for blood irradiation. Some well known examples of such sources are: cobalt-60 sources for teletherapy, brachytherapy, food irradiation, sterilizing health care products, and measuring thicknesses, densities and other important properties in industrial processes; iridium-192 sources for industrial radiography and brachytherapy; americium-241 sources for smoke detectors; and caesium-137 sources for brachytherapy and blood irradiation.

The activity of these sources ranges from tens of kilobecquerels (kBq) (1 Bq = 2.7 x 10^{-11} curies (Ci)) in sources used for calibration purposes to hundreds of terabecquerels (TBq) in industrial irradiators and sources used in radiation therapy. The radioactive isotopes employed in SRSs are used in a variety of chemical and physical forms: metallic or oxide, impregnated into ceramics or electroplated onto other support metals as thin films or deposits. The radioactive isotopes are then encapsulated in inert metallic capsules to produce the SRSs proper. These are finally enclosed in various devices that can channel a direct radiation beam at the target material or target tissues while shielding operational personnel from unwanted exposure.

The life cycle of sealed radioactive sources, from the radioactive source production to its eventual disposal is represented in Fig. VI-1. Once sealed sources become disused (e.g. once they cannot accomplish their intended purpose anymore due to radioactive decay), if they are not managed safely and securely, they may leak, become abandoned or be lost, stolen or misused by unauthorized persons, causing radiation incidents or accidents. The IAEA defines a 'disused source' as "a radioactive source that is no longer used, and is not intended to be used, for the practice for which an authorization has been granted"[2]. 'Spent sources' (a sub-set of disused sources) are those that are "no longer suitable for [their] intended purposes as a result of radioactive decay" [3]. The term 'disused source' (or DSRS, disused sealed radioactive source) is used as defined above throughout this document.

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[1] *IAEA Net Enabled Waste Management Database glossary*, http://newmdb.iaea.org/help.aspx?HTopicId=23&GLetter=S

[2] *IAEA Safety Glossary: 2007 Edition* (IAEA, Vienna, 2007) , http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf

[3] *IAEA Safety Glossary: 2007 Edition* (IAEA, Vienna, 2007) , http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf

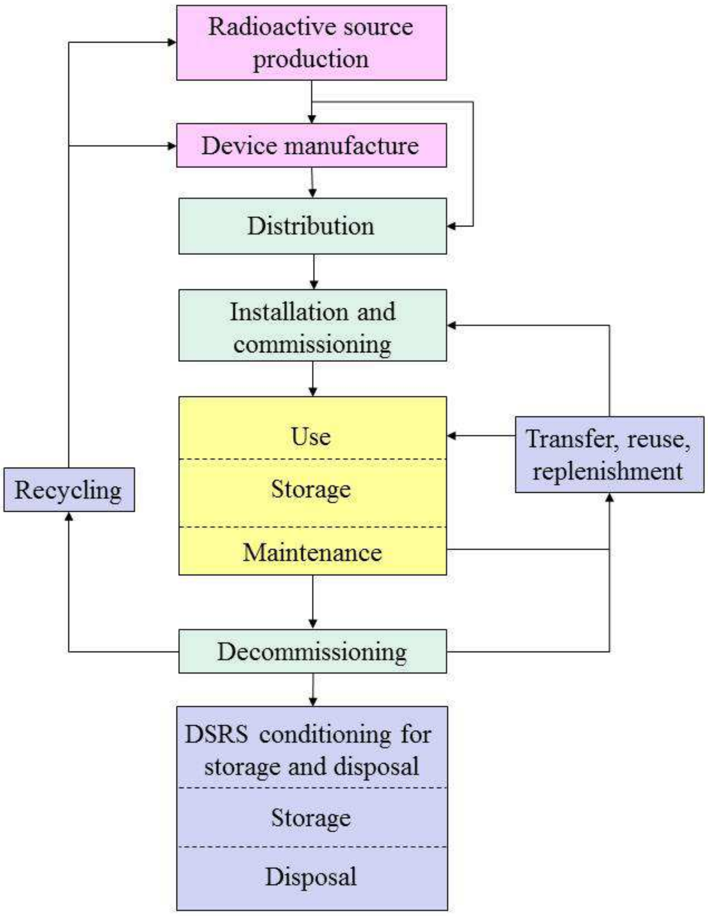

FIG. VI-1. Life cycle of sealed radioactive sources.

Some of the challenges involved in the industrial and medical use of high activity sources, mainly cobalt-60 sources, include the existence of a limited number of suppliers, security concerns and frequent transport delays. Furthermore, in light of the widespread use of radioactive sources around the world and their long half-lives, the safe management and disposal of DSRS needs to be ensured.

Partly as a result of these challenges, there has been a shift from the use of radioactive sources to electron accelerators in industrial applications, and to X-rays in research and development (R&D) work in radiation chemistry and biology. This shift away from cobalt-60 based teletherapy can also be observed in radiation medicine and is a consequence of the proven superiority of linear accelerator (linac)-based radiation therapy. Nonetheless, cobalt-60 sources are still preferred for many applications, and there is a continuing need for new sources to either replace or to replenish disused sources in existing cobalt-60 based systems.

B. Uses

B.1. Industrial applications

B.1.1. Radiation processing

Radiation sources are used in industrial applications to help modify the physical, chemical and biological properties of the irradiated materials, forming the basis of radiation processing. The principal applications of radiation processing today are: sterilizing health care products; irradiating food products (for disinfection, hygiene, sterilization, to kill pests, to extend shelf life or inhibit sprouting); disinfecting wastewater; modifying materials for polymer-based products such as cables, tubes, tapes, hydrogels and tyre belts; and colouring gemstones. Radiation processing adds value to products and its use is increasing with industrialization and economic development worldwide.

One of the major applications of radiation processing based on cobalt-60 sources remains the sterilization of health care products, established over five decades ago as an alternative to ethylene oxide and steam-based technology. About 85% of the 200 or so commercial industrial gamma facilities currently operating worldwide are used to sterilize health care products, and even more are being planned and built. The IAEA's Database of Gamma and Electron Beam Irradiation Facilities[4] lists most of them.

Cobalt-60, with a half-life of 5.27 years, and caesium-137, with a half-life of 30.1 years, are the best gamma radiation sources because of the relatively high energy of their gamma rays and their fairly long half-lives. Caesium-137, however, is used only in small self-contained dry-storage irradiators, primarily to irradiate blood and sterilize insects. All other industrial radiation processing facilities use cobalt-60.

[4] See http://www-nds.iaea.org/iacs_facilities/datasets/foreword_home.php

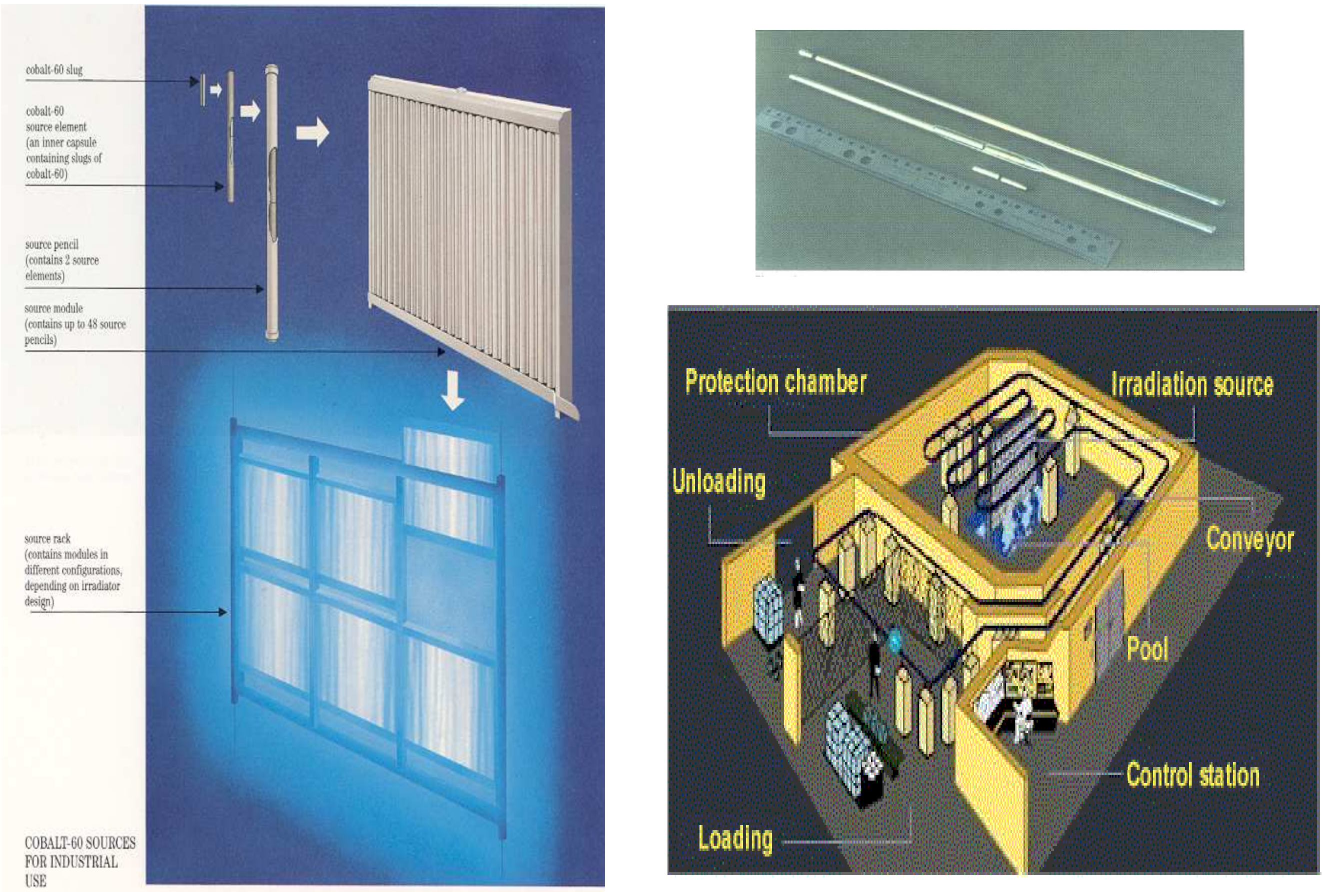

FIG. VI-2. Slugs (small cylinders) of cobalt-60 are arranged in source elements, source pencils and source modules to make up a typical cobalt source rack. The picture on the bottom right illustrates a typical cobalt-60 gamma radiation facility.

Figure VI-2 shows a typical cobalt-60 source rack. It is generally made up of modules, each containing up to 48 source pencils. Each source pencil has two source elements each, i.e. thin cylinders containing slugs of cobalt-60. With a half-life of 5.27 years, the strength of a cobalt-60 source decreases by about 12% per year. Additional pencils of cobalt-60 are added periodically to the source rack to maintain its required source strength. At the end of their useful life, typically 20 years, cobalt-60 pencils are removed and generally returned to the supplier for re-use, recycling or disposal. After about 50 years, 99.9% of the cobalt-60 contained in the pencils decays into non-radioactive nickel. Depending on its original value, the remaining 0.1% radioactivity may still pose a considerable radiological risk.

However, the acute supply shortage of cobalt-60 in recent years has been a major impediment to the construction of new cobalt-60 irradiation facilities. It is also an important concern for functioning irradiation units, as these will need the cobalt-60 isotope for replenishing the decayed activity from time to time. The re-use of cobalt-60 sources has found strong support not only thanks to this shortage but also to the current economy. Manufacturers and suppliers are increasingly exploring options to collect used cobalt-60 sources from medical facilities and appropriately modify them in order to re-qualify them for use in industrial facilities which need much less intense sources.

B.1.2. Industrial process management

Sealed radioactive sources were first utilized in industry over forty years ago and are now widely used to control and troubleshoot industrial processes, as summarized in Table VI-1.

TABLE VI-1. SEALED RADIOACTIVE SOURCES IN INDUSTRIAL PROCESS MANAGEMENT

Radionuclide	**Half-life**	**Typical radiations used (Energies in MeV)**	**Major applications**	**Physical or chemical form**	**Typical activity (TBq [Ci])**
Americium-241	432.2 y	α (5.49, 5.44)	Smoke detector Radioisotope thermoelectric generator	Pressed powder (americium oxide)	0.5–0.8 [13–22]
Americium-241/ Beryllium	432.2 y	n (4.4 $_{average}$)	Well logging in oil exploration Borehole logging and elemental analysis in mineral exploration Thickness gauging for light alloys, glass, plastics, and rubber	Mixture of americium oxide and beryllium metal	100–740 [3–20]
Californium-252	2.645 y	α (6.22)	Well logging in oil exploration Moisture gauge	Metal oxide	0.0004 [0.011]
Caesium-137 (Barium-137m)	30.17 y	γ (0.662)	Gamma irradiators Level gauge Calibrators/check sources	Pressed powder (caesium chloride)	75 [2000] 50 [1400] 15 [400] 0.00004 [0.001]
Cobalt-60	5.27 y	γ (1.17, 1.33)	Gamma irradiators Industrial gamma radiography	Metal slugs Metal pellets	150k [4 million] 500[14 000] 4 [100]
Iridium-192	74 d	γ (0.380 $_{average}$)	Industrial gamma radiography	Metal pellets	4 [100]
Plutonium-238	87.7 y	α (5.59)	Radioisotope thermoelectric generator Radioisotope heater unit	Metal oxide	10 [270] 8 [200]
Selenium-75	119.8 d	γ (0.280 $_{average}$)	Industrial gamma radiography	Metal compound	3 [75]
Strontium-90 (Yttrium-90)	28.9 y	β (0.546)	Radioisotope thermoelectric generator	Metal oxide	750 [20 000]

In smoke detectors, the first item in Table VI-1, the very small americium-241 alpha source ionizes air in a chamber in the absence of smoke. When smoke enters the chamber and reduces the air ionization, tripping the current, the alarm is triggered. Other items in the Table reflect the several hundred thousand nucleonic control systems and nucleonic gauges installed in industrial processes and plants around the world. Each nucleonic control system or nucleonic gauge incorporates one or more SRSs of alpha, beta, gamma, neutron or X-ray radiation arranged in a fixed geometrical relationship with one or more radiation detectors.

Nucleonic control systems are used:

- in on-line industrial processes to measure densities, thicknesses, levels and concentrations and to carry out elemental analysis,
- in off-line processes to do bulk sampling of coal and other minerals,
- in in-situ well logging associated with mining coal and minerals,
- in laboratories to analyse e.g. the moisture of coal ash samples, and
- in portable devices used in industrial facilities for on-site measurements of material thicknesses, blockages, corrosion, densities and moisture.

Industrial sectors that make substantial use of nucleonic control systems and nucleonic gauges are oil and gas, mining and mineral ore processing, environmental monitoring, paper and plastics, cement and civil engineering. Figure VI-3 shows a nucleonic gauge used to measure the thickness of paper.

FIG. VI-3. Thickness gauge used in paper production. Typical sources include: ^{90}Sr (370 MBq (10 mCi) to 3.7 GBq (100 mCi)); ^{85}Kr (370 MBq (10 mCi) to 18.5 GBq (500 mCi)); ^{147}Pm (3.7 GBq (100 mCi) to 18.5 GBq (500 mCi)).

B.1.3. Non-destructive testing using radioactive sources

Sealed radioactive sources are used in gamma radiography for non-destructive testing (NDT). Gamma radiography is similar to medical X-ray radiography, where the attenuation of the X-rays is used to obtain a picture of the internal structures of the human body. However, industrial radiography involves imaging the inner mechanisms of machines and structures which are much denser than the human body, and high energy radiation is necessary for the radiographic examination of these. In industrial radiography, therefore, instead of using an electrically powered high-voltage X-ray generator to create the image, a radioactive source producing gamma rays is used. Gamma radiography provides a suitable alternative to X-ray radiography, particularly in situations where there is no convenient power supply for an X-ray generator or where work is conducted in confined spaces or in the field. Gamma radiography sources (mostly iridium-192, cobalt-60 and selenium-75 sources) are typically placed in a sealed protective metal casing in a transportable device, known as a projector or camera. The projector is positioned using a remote cable handling system and the gamma rays then pass through the specimen being radiographed onto a film to provide an image. The system is commonly used for NDT during construction projects such as buildings and pipelines, including the checking of structural welds.

The best SRSs for gamma radiography are small, have sufficient gamma ray energy to penetrate the thickness of the specimen being tested, have sufficiently long half-lives and high specific activity. They are used for radiography of welds, castings, forgings, plastics, composite materials, concrete etc. The industries in which their use is widespread include chemicals, petroleum, oil and gas, automobiles, aerospace, power generation (both nuclear and non-nuclear), civil engineering, welding, general engineering fabrication plants, and maintenance operations in many industrial processing plants.

B.1.4. Materials analysis

When an element absorbs radiation of a known energy, it emits a unique spectrum of secondary X-rays. This is called X-ray fluorescence (XRF). Analysis of the spectrum allows an accurate determination of the composition of the material. The initial radiation can come from an SRS. However, it is important that the radiation from the source matches the absorption range of the element to be determined. As the atomic number of the element increases, the radiation from the source must also be more energetic. Hence, different isotopes are used to detect different elements. An SRS used for materials analysis is contained in a shielded device with a shutter that can be opened to allow collimated beams of radiation to be directed onto the material being analysed. The shutter is locked when the device is not in use. The detector is normally contained within the same unit as the source with associated electronics to analyse the spectrum of secondary X-rays and identify the material.

Typical applications of such devices, which can be portable, include alloy analysis for checking stock, sorting scrap and checking components; the analysis of material excavated in mining operations from pits or from cores, as well as of chippings and slurries from drilling operations; the analysis of electroplating solutions; general laboratory chemical analysis; wood pulp and slurry analysis; agriculture; oil exploration and production; and the determination of lead levels in old paint to establish the level of personal protection required to remove it. The typical maximum activity levels used for different radioisotopes are 1.85 GBq (50 mCi) for americium-241; 3.7 GBq (100 mCi) for californium-244; 1.85 GBq (50 mCi) for cadmium-109; and 740 MBq (20 mCi) for iron-55.

B.2. Medical applications

Sealed radioactive sources are also widely used to treat diseases. The most common uses are teletherapy, brachytherapy and blood irradiation.

In teletherapy, cobalt-60 is the most commonly used radioisotope-based radiation source in treating cancers. There are more than 2400 cobalt-60 teletherapy units around the world. Teletherapy is based on the fact that radiation kills fast growing cells, like cancer cells, more quickly than slower growing healthy cells. In teletherapy (Fig. VI-4), the dose of radiation is delivered to a well-defined area of the body that is affected by the disease.

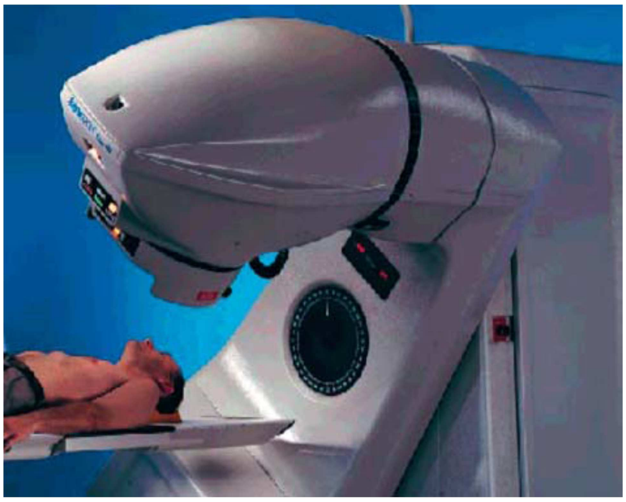

FIG. VI-4. Cobalt-60 unit used for teletherapy (Typical source activity: up to 370 TBq (10 kCi) ^{60}Co).

The sources used in teletherapy need to be changed regularly. The preferred option is to return disused sources to their suppliers, but if this is not possible, the sources should be transferred to an authorized waste management organization for storage and disposal.

Another common medical use of SRSs is brachytherapy. In brachytherapy, the radioactive source is in direct contact with the patient, inserted into a tumour either directly by a surgical team or remotely using special equipment. The IAEA's Directory of Radiotherapy Centres[5] lists more than 200 high dose rate (HDR) cobalt-60 units, 900 HDR iridium-192 units and more than 1300 low dose rate (LDR) units worldwide.

There are two main types of brachytherapy treatment that use sealed sources: 'intracavitary', in which the sources are placed in body cavities close to the tumour, and 'interstitial', in which the sources are implanted within the tumour. Intracavitary treatments are always temporary and of short duration,

[5] See http://www-naweb.iaea.org/nahu/dirac/default.asp.

while interstitial treatments may be temporary or permanent. The advantage of brachytherapy treatments over external beam radiotherapy is the improved localized delivery of the dose to the target of interest. The disadvantage is that brachytherapy can only be used if the tumour is localized and relatively small. In a typical radiotherapy department, about 10–20% of all radiotherapy patients are treated with brachytherapy.

Brachytherapy uses both gamma sources and beta sources. The radioisotopes used for gamma sources are iodine-125, palladium-103, iridium-192, caesium-137, cobalt-60 and gold-198. Those used for beta sources are xenon-133, phosphorus-32, tungsten-188/rhenium-188, strontium-90/yttrium-90 and ruthenium-106/rhodium-106.

Brachytherapy gamma sources are available in various forms, including needles, tubes, seeds, wires and pellets. Usually they are doubly encapsulated both to provide adequate shielding against alpha and beta radiation, which is also emitted from the source, and to prevent leakage of the radioactive material.

Brachytherapy sources that are implanted permanently in a tumour never need to be replaced, but other sources used in brachytherapy do need to be replaced regularly. As with the sources used in teletherapy, the preferred option is to return the source to the supplier. If this is not possible, the sources should be transferred to an authorized waste management organization for storage and disposal.

A final medical use of SRSs is for blood irradiation to prevent complications associated with blood transfusions, such as transfusion-associated graft-versus-host disease (TA-GVHD). Dedicated blood irradiators (Fig. VI-5) contain gamma-emitting sources with long half-lives, e.g. caesium-137.

FIG. VI-5. Blood irradiator unit (typical source activity: up to 250 TBq (7 kCi) ^{137}Cs;up to 25 TBq (7 kCi) ^{60}Co).

As discussed above, there are a wide variety of SRSs, varying in the type as well as the strength of the radioisotope used. Thus, SRSs may range from very small, low-activity, short-lived sources to very large and heavy long-lived sources that need to be highly shielded. This means that there will be disused sources of varied sizes, strengths and longevities which need to be disposed of in an appropriate manner. Therefore, managing disused SRSs is an issue of significant and continuing importance.

C. Management of Disused Sealed Radioactive Sources

Most countries that have adequate regulatory infrastructures keep national or institutional records of SRSs in use, as well as of disused sealed radioactive sources (DSRS), and have adequate capabilities to ensure the safety and security of their sources. However, many countries are using SRSs in medicine, industry and agriculture without having effective regulatory systems and technical capabilities to manage the resulting DSRS. Consequently, there is no reliable information on the number of DSRS in these countries and a multi-year project has been proposed at the IAEA to develop a method to collect reliable data for a worldwide estimate.

C.1. Predisposal management of DSRS

Because poorly controlled DSRS have caused serious, even fatal radiation accidents, the IAEA has, almost since its inception, been involved in improving their control. Through its technical cooperation programme, the IAEA helps interested Member States to build up their regulatory and technical capabilities. It has helped nearly 50 countries to package and store old radium sources safely and securely and has successfully recovered thousands of sources. From 2007 to 2009, 5082 sources were recovered and safely stored in national storage facilities in the countries in which they were recovered and 202 sources were repatriated to their countries of origin. Thirty-eight of the sources were recovered using the mobile hot cell (MHC), a technology that was conceived by the IAEA and developed by the Nuclear Energy Corporation of South Africa (Necsa), under contract to the IAEA (see Fig. VI-6). The MHC is used to remove high activity DSRS from devices in the field. It is designed for gamma-emitting sources up to the equivalent of 37 TBq (1000 Ci) of cobalt-60, but has also met all necessary requirements during a test with a cobalt source of over 74 TBq (2000 Ci).

FIG. VI-6. The mobile hot cell in operation in Uruguay.

The MHC was introduced in 2009 and has been used in Sudan, the United Republic of Tanzania and, in 2010, in Uruguay. In Sudan and the United Republic of Tanzania, the sources that were extracted, characterized and safely packaged using the MHC were then safely stored in national facilities in those countries. In Uruguay, the sources were packaged into transport containers for repatriation to their countries of origin.

Most countries with advanced nuclear programmes and operating radioactive waste storage and/or disposal facilities have implemented disused source recovery programmes.[6] Countries without disposal facilities would prefer to repatriate all high activity DSRSs back to their countries of origin. However, this option is not always available. In some cases, the countries of origin are not willing to take back DSRSs, the fees charged are too high, there is a lack of transport containers, there is insufficient infrastructure or there are transport problems because some shippers and ports are reluctant or unwilling to handle DSRSs. The IAEA is working to address all these constraints and many countries are supporting this effort through the voluntary contribution of expertise and resources.

C.2. Disposal options for DSRS

Proven long-term storage technologies are available for DSRSs. However, numerous factors may severely disrupt storage records and storage systems and final disposal of DSRS is a way to avoid this risk.

The disposal of DSRS in engineered near surface repositories is technically viable and has been applied in some countries where the quantity of other types of low and intermediate level radioactive waste justified establishing such facilities. However, even in many of these countries, the disposal of DSRS has been halted due to changes in regulatory practices and DSRS have accumulated in storage facilities. In countries without long-lived radioactive waste other than DSRS, the volume of DSRS is too small for such disposal facilities to be economically justifiable, and none has yet been built.

An alternative option for small scale disposal is the use of boreholes[7]. Over the past few years, the IAEA, in conjunction with African Member States, has developed a borehole disposal concept (BDC) that is appropriate for the relatively small amounts and activity levels of the sources that one can realistically expect to find in some developing countries, as well as for their limited resources. The BDC is illustrated in Fig. VI-7. It comprises a borehole with a diameter of 150 to 260 mm that is drilled to a depth of between 30 and 100 metres. The depth of the borehole would be dependent on a site-specific safety assessment. This disposal system is intended to both isolate the waste from the accessible environment and mitigate the consequences of any accident that releases radionuclides. The generic long-term safety analyses that have been conducted have demonstrated that a high degree of safety can be achieved by the BDC for a variety of scenarios and inventories of radioactive sources[8].

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[6] Examples of such domestic programmes are the Off-site Source Recovery Programme (OSRP) (http://osrp.lanl.gov/) in the United States of America and the disused source management programme implemented by the public utility group for the management of high activity disused sources (GIP sources HA) and the French Atomic energy Commission (CEA) in France.

[7] Examples of borehole disposal include the former Soviet Union's disposal of sources in shallow boreholes and the USA's disposal, during the 1980s, of sources at the Nevada Test Site in wide diameter boreholes 36 metres deep. Boreholes have also been used in Australia at the Mt. Walton East facility and in South Africa for high activity sources.

[8] The Nuclear Energy Corporation of South Africa (Necsa), contracted by the IAEA, has carried out related project development and demonstration activities since 1996. The project has looked into the technical feasibility, safety and economic viability of the BDC under the social, economic, environmental and infrastructural conditions currently prevalent in Africa.

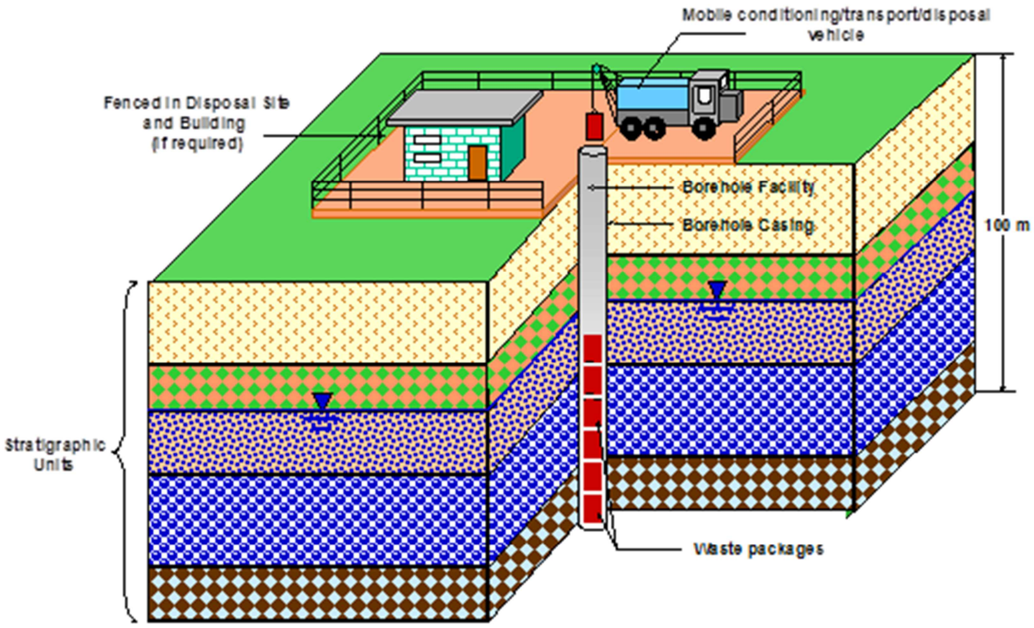

FIG. VI-7. The borehole disposal concept.

D. Conclusion

The widespread use of SRSs worldwide in industry and medicine provides major benefits to human society. However, the use of radioactive materials should be planned and addressed in a holistic manner by all stakeholders involved in any part of the life cycle of SRSs. While it is important to harness the power of radiation for various beneficial applications, it is also imperative, for safety reasons, to make the necessary arrangements to manage the entire life cycle of the SRSs thus used.

Users should identify appropriate routes for the disposal of DSRSs before they acquire and use radioactive sources. In many countries, the identification of a source management strategy is an essential prerequisite for receiving regulatory authorization to start operating a facility that uses radioactive sources.

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