IAEA-TECDOC-1690

Review of Sealed Source Designs and Manufacturing Techniques Affecting Disused Source Management

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REVIEW OF SEALED SOURCE DESIGNS AND MANUFACTURING TECHNIQUES AFFECTING DISUSED SOURCE MANAGEMENT

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2012

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Printed by the IAEA in Austria
October 2012

IAEA Library Cataloguing in Publication Data

Review of sealed source designs and manufacturing
techniques affecting disused source management. –
Vienna : International Atomic Energy Agency, 2012.
p. ; 30 cm. – (IAEA-TECDOC series, ISSN
1011-4289 ; no. 1690)
ISBN 978-92-0-134310-9
Includes bibliographical references.

1. Radiation sources. 2. Radioactive substances –
Packaging. 3. Radioactive waste disposal.
I. International Atomic Energy Agency. II. Series.

IAEAL 12-00775

FOREWORD

Sealed radioactive sources are used throughout the world in medical, agricultural, industrial and research applications. When a source is no longer needed or becomes unfit for use in its application, it is considered disused. When it is declared as waste it should be properly managed and eventually sent for disposal.

Factors considered in the design of a source for its intended application may not be practical from a further management and disposal standpoint. This report presents information about the different sealed source designs and features, and examines how they affect the safe management of disused sources. It will help waste operators to understand the special features that could cause difficulties during the handling of disused sources. Sealed source manufacturers can also use this publication to improve their products, taking into account waste management issues. A review and discussion of the recommended working life for sealed radioactive sources is also presented.

This topic was first addressed in the Technical Meeting on Investigation of Radioactive Source Designs to Minimize the Consequences of Malicious Use, held in September 2004. The meeting made the recommendation that more attention be given at the source design stage to the features that affect the source management when the source is declared disused. Further international discussion on this topic took place during the international conference on Safety and Security of Radioactive Sources (Bordeaux, 2005). A risk based approach to the safety of disused sources must examine all aspects, including the design and manufacturing of the sources.

The IAEA wishes to thank the representatives of the major radioactive source manufacturers who were involved in compiling this publication through their recently established association, ISSPA (International Source Suppliers and Producers Association). 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.

EDITORIAL NOTE

CONTENTS

SUMMARY

This publication presents an investigation on the influence of the design and technical features of sealed radioactive sources (SRSs) on predisposal and disposal activities when the sources become disused. The publication also addresses whether design modifications could contribute to safer and/or more efficient management of disused sources without compromising the benefits provided by the use of the sealed sources.

This technical publication aims to collect information on the most typical design features and manufacturing techniques of sealed radioactive sources and examines how they affect the safe management of disused sealed radioactive sources (DSRS). The publication also aims to assist source designers and manufacturers by discussing design features that are important from the waste management point of view.

It has been identified that most SRS manufacturers use similar geometries and materials for their designs and apply improved and reliable manufacturing techniques e.g. double-encapsulation. These designs and manufacturing techniques have been proven over time to reduce contamination levels in fabrication and handling, and improve source integrity and longevity. The current source designs and materials ensure as well as possible that SRSs will maintain their integrity in use and when they become disused. No significant improvement options to current designs have been identified. However, some design considerations were identified as important to facilitate source retrieval, to increase the possibility of re-use and to ensure minimal contamination risk and radioactive waste generation at recycling. It was also concluded that legible identifying markings on a source are critical for DSRS management.

The publication emphasizes the need for a common understanding of the radioactive source's recommended working life (RWL) for manufacturers and regulators.

The conditions of use (COU) are important for the determination of RWL. A formal system for specification of the COU, including a description of the intended application, and transfer from the manufacturer to the user and the waste operator seems to be beneficial for recycling and waste management activities. Such information could be incorporated into the sealed source test certificate.

1 INTRODUCTION

1.1 BACKGROUND

Sealed radioactive sources are used worldwide in medicine, agriculture, industry and research, in mobile as well as stationary devices. The Radiation Protection Safety and Safety of Radiation Sources: International Basic Safety Standards [1] defines a sealed source as “radioactive source in which the radioactive material that is (a) permanently sealed in a capsule or (b) closely bounded and in a solid form”.

If a source is no longer needed (e.g. replaced by a different technique) or it becomes unfit for the intended application (e.g. the activity becomes too weak, the equipment containing the source malfunctions or becomes obsolete, the source is damaged or leaking) it is considered disused. Disused sources, if they are deemed unusable, are conditioned and disposed of at a waste disposal facility, if such a facility is available. If a disposal option is not in place the conditioned disused source should be stored under proper conditions.

The high radioactivity content of some disused sources, combined with the long half-lives of some of the radionuclides used in them, must be taken into consideration in conventional waste management schemes [2]. Other considerations are the geometry, method of sealing the source, the materials used, and the chemical and physical form of the radionuclides used in sealed source designs. These factors are considered in the design of the source for its intended application, but features that are advantageous from an application perspective may not be ideal when the source becomes disused.

1.2 OBJECTIVE

The objective of this report is to review and discuss important design considerations from a radioactive waste management perspective. It aims to provide organizations and individuals involved with SRS, from manufacturing to the management of disused SRS, with sufficient information about the different source designs and manufacturing techniques, and to examine how the different sealed source designs affect the safe management of DSRS. This report will also help radioactive waste management operators to understand the special features that can affect the safe management of DSRS.

1.3 SCOPE

The scope of this report includes the review and analysis of various designs of sealed sources and the identification of design features that make disused source management easier. The publication provides:

- A general overview on sealed radioactive sources;
- A review of the features and benefits/disadvantages of different source designs and manufacturing techniques affecting their safe handling and management during use and when they become disused;
- A review of the RWL of the sources;
- Recommendations regarding source design and manufacturing techniques for enhanced and safer management of disused sources.

The sources considered are those classified as categories 1 through 5 under the ‘Categorization of Radioactive Sources’, Safety Standards Series No. RS-G-1.9 [3], as summarized in chapter 2, page 4.

There are many different sealed source applications and designs. Not all of them could be covered in this publication.

2 OVERVIEW OF SEALED RADIOACTIVE SOURCES

SRSs are categorized into groups based on the potential for the SRS to cause deterministic health effects [3]. The physical properties of the source, the application the source is used in, shielding provided by the device, portability, security and other criteria are all used in the determination of the categories. It is important to understand these categories when considering handling and management of disused SRSs. The plain language description of the five categories of SRSs is summarized as follows [3];

Category 1 – Extremely dangerous to the person: This source if not safely managed or securely protected, would be likely to cause permanent injury to a person who handled it or who was otherwise in contact with it for more than a few minutes. It would probably be fatal to be close to this amount of unshielded radioactive material for a period in the range of a few minutes to an hour. This amount of radioactive material, if dispersed, could possibly – although it would be unlikely – permanently injure or be life threatening to persons in the immediate vicinity.

Category 2 – Very dangerous to the person: This source, if not safely managed or securely protected, could cause permanent injury to a person who handled it or who was otherwise in contact with it for a short time (minutes to hours). It could possibly be fatal to be close to this amount of unshielded radioactive material for a period of hours to days. This amount of radioactive material, if dispersed, could possibly – although it would be very unlikely – permanently injure or be life threatening to persons in the immediate vicinity.

Category 3 – Dangerous to the person. This source, if not safely managed or securely protected, could cause permanent injury to a person who handled it or who was otherwise in contact with it for some hours. It could possibly – although it would be unlikely - be fatal to be close to this amount of unshielded radioactive material for a period of days to weeks. This amount of radioactive material, if dispersed, could possibly – although it would be extremely unlikely – permanently injure or be life threatening to persons in the immediate vicinity.

Category 4 - Unlikely to be dangerous to the person. It is very unlikely that anyone would be permanently injured by this source. However, this amount of unshielded radioactive material, if not safely managed or securely protected, could possibly – although it would be unlikely – temporarily injure someone who handled it or who was otherwise in contact with it for many hours, or who was close to it for a period of many weeks. This amount of radioactive material, if dispersed, could not permanently injure persons.

Category 5 – Most unlikely to be dangerous to the person. No one could be permanently injured by this source. This amount of radioactive material, if dispersed, could not permanently injure anyone.

The main uses and characteristics of SRSs are detailed in references [2] and [4]. Table 1 shows a summary of these main applications and the main isotopes and associated half-lives used in SRSs. Table 2 lists the most common radionuclides used in SRSs and the range of activity for each radionuclide.

Tables 1 and 2 show that the most dangerous SRSs (categories 1, 2 and 3) are used at irradiators for radiation processing (consumer products, food, health-care, blood/tissue), in radioisotope thermoelectric generators (RTGs), teletherapy machines, industrial radiography, high-dose brachytherapy, well logging and in some industrial gauges. Several different radionuclides are used with varying half-lives and energy levels. The highest activity radionuclides in this group (^{60}Co, ^{90}Sr and ^{137}Cs) have half-lives between 5 to 30 years. These radionuclides require a greater degree of isolation on disposal. From the transportation point of view radioactive sources are usually designed and manufactured to meet the requirements for ‘special form radioactive material’ [5].

In contrast, some less dangerous SRSs (categories 4 and 5) contain radionuclides with long half-lives, such as: ^{226}Ra at 1600 years and ^{239}Pu-Be at 24 100 years. Although the activity of these sources is lower, they will still pose a potential long-term waste management issue. Therefore, regardless of the category of the source, each radioactive source needs particular attention depending on the isotope, half-life, and the activity.

TABLE 1. APPLICATIONS OF SRSs, RADIOISOTOPES AND HALF-LIVES [2, 3, 6]

Application	Main radionuclide	Half-life	Assigned category based on usual initial activity
RTGs	^{90}Sr	28.6a	1
	^{238}Pu	87.8a	1
Irradiators	^{60}Co	5.3a	1
	^{137}Cs	30.1a	1
Teletherapy	^{60}Co	5.3a	1
	^{137}Cs	30.1a	1
Industrial radiography	^{60}Co	5.3a	2
	^{192}Ir	74d	2
	^{75}Se	120d	2
	^{169}Yb	32d	2
	^{170}Tm	129d	2
Brachytherapy (high/med dose rate)	^{60}Co	5.3a	2
	^{137}Cs	30.1a	2
	^{192}Ir	74d	2
Well logging/moisture gauges	^{241}Am-Be	432a	3
	^{137}Cs	30.1a	3
	^{252}Cf	2.6a	3
Industrial gauges	^{60}Co	5.3a	3
	^{137}Cs	30.1a	3/4
	^{252}Cf	2.6a	3/4
	^{85}Kr	10.7a	4
	^{241}Am	432a	3/4
	^{244}Cm	18.1a	4
	^{147}Pm	2.6a	4
Research	^{241}Am-Be	432a	3/4
	^{239}Pu-Be	24,100a	2-5
Brachytherapy (low dose rate)	^{137}Cs	30.1a	4
	^{226}Ra	1,600a	4
	^{192}Ir	74d	4
	^{125}I	60d	4
	^{90}Sr	28.6a	5
	^{106}Ru/Rh	368d	5
Bone densitometry	^{109}Cd	464d	4
	^{153}Gd	242d	4
	^{125}I	60d	4
	^{241}Am	432a	4
X ray fluorescence analyzers	^{55}Fe	2.7a	5
	^{109}Cd	464d	5
	^{57}Co	271d	5
Electron capture detectors	^{63}Ni	96a	5
	^{3}H	12.4a	5
Lightning conductors	^{241}Am	432a	5
	^{60}Co	5.3a	5
	^{154}Eu	8.6a	5
	^{152}Eu	13.5a	5
	^{226}Ra	1600a	5
	^{3}H	12.4a	5
Instrument calibration	Many varieties	-	5
Mossbauer spectrometry	^{57}Co	271d	5
Pacemakers	^{238}Pu	87.8a	no longer manufactured
Static eliminators	^{210}Po	138d	4
	^{241}Am	432a	4

TABLE 2. COMMONLY USED RADIOISOTOPES AND ACTIVITIES IN SRSs (HALF-LIFE > 0.1 YEAR) [2]

Radionuclide	Half life	Minimum activity (Bq)	Maximum activity (Bq) *
^{60}Co	5.3a	9.3E+09	5.6E+17
^{137}Cs	30.1a	3.0E+08	1.9E+17
^{90}Sr	28.6a	3.7E+08	2.5E+16
^{238}Pu	87.8a	1.1E+11	1.0E+13
^{170}Tm	129d	7.4E+11	7.4E+12
^{192}Ir	74d	7.4E+08	7.4E+12
^{75}Se	120d	3.0E+12	3.0E+12
^{3}H	12.4a	1.9E+09	1.1E+12
^{241}Am	432d	4.8E+07	8.5E+11
^{239}Pu-Be	24,100a	7.4E+10	3.7E+11
^{244}Cm	18.1a	7.4E+09	3.7E+10
^{85}Kr	10.7a	1.9E+09	3.7E+10
^{125}I	60d	1.5E+09	3.0E+10
^{109}Cd	464d	7.4E+08	5.6E+09
^{153}Gd	242d	7.4E+08	5.6E+09
^{55}Fe	2.7a	1.1E+08	5.0E+09
^{252}Cf	2.6a	1.1E+06	4.1E+09
^{147}Pm	2.6a	1.9E+09	1.9E+09
^{226}Ra	1,600a	2.6E+05	1.9E+09
^{57}Co	271d	5.6E+08	1.5E+09
^{63}Ni	96a	1.9E+08	7.4E+08
^{106}Ru/Rh	368d	8.1E+06	2.2E+07

* Maximum activity is sometimes achieved by a set of sources

Other sources not listed in the table, such as ^{14}C and ^{129}I sources used in instrument calibration, have extremely long half-lives (5700 years and 17E+06 years, respectively), but their activity is very low. In such situations, the categorization can be considered by national authorities case by case by calculating the A/D ratio and then considering other factors as appropriate.

The main applications of SRSs listed in Table 1 are further discussed in the following sections. There are many different types of SRSs and therefore not all of them could be covered here, but the intent of this report is to cover those most frequently used in the different applications.

2.1 RADIOISOTOPE THERMOELECTRIC GENERATORS (RTGs)

An RTG is a generator that produces electricity using the heat produced from radioactive decay. The heat released by the decay of certain isotopes (typically ^{90}Sr or ^{238}Pu) is converted to electrical power by an array of thermocouples. RTGs output a few hundred Watts of power for a long period of time and are usually used on satellites or space probes, and for unmanned remote equipment or facilities where frequent maintenance and refueling are impossible. They also provide low-level, long-lasting, economical power where conventional batteries, solar cells or wind power are impractical.

The radioisotopes used must have half-lives long enough to produce power for a long time at a continuous rate, while being short enough to produce a sufficient amount of heat in decay. This is why ^{90}Sr with a half-life of 28.6 years and ^{238}Pu with a half-life of 87.8 years are usually used. The structure of the heat source for NASA's Cassini spacecraft RTG [7] is shown schematically in Figure 1. SRSs used in RTGs are all category 1 [3].

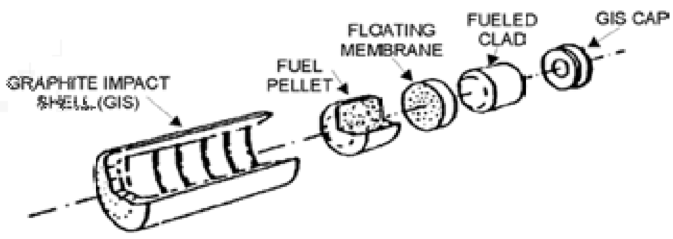

FIG. 1. Radioisotope thermoelectric generator source used in Cassini spacecraft [7].

2.2 IRRADIATORS

There are different types and sizes of irradiators, from large-scale commercial sterilization plants to appliance-size medical and research irradiators. Irradiation is used for processing a broad range of products including blood, pharmaceuticals, cosmetics, meat, vegetables and other foodstuffs, as well as the sterilization of medical disposables. Because of the requirement for providing high dose within a reasonably short period of time, the SRS used are usually very high activity. ^{60}Co and ^{137}Cs are most frequently used. Irradiator SRSs are most often double encapsulated and tested to IAEA Special Form requirements [5].

Typical irradiator sources are shown in Figure 2. As is shown, most irradiator sources are long and slender, about 1 cm diameter by 50 cm long, to provide a better dose distribution. The activity of individual irradiator sources are in the order of 500 TBq. A large irradiator includes several hundred sources for a total activity of hundreds of PBq. The IAEA safety guide SSG-8 [8] provides information on safe design and operation of gamma irradiators. Disused irradiator sources provide a challenge for disposal in that they have high activity, generate heat, there are large numbers of them, and they take many years to decay. These SRSs all belong to category 1.

2.3 TELETHERAPY

External beam radiotherapy, also called teletherapy, is used to treat cancer in patients by using ionizing radiation to destroy cancer cells in a specifically targeted area. Radiation therapy is most commonly used to shrink a cancerous tumor to make chemotherapy or surgery more effective. The SRS is contained in a radiation-shielded head, at some distance from the patient, usually about one meter. The SRS is moved to an opening, or a shielded shutter is opened, to allow a collimated beam of radiation to reach the patient at a predetermined location.

A typical teletherapy source is shown in Figure 3. They are generally a few centimeters in diameter and a few centimeters long. These sources are usually of very high activity in order to minimize the exposure time for the patient, yet provide effective and efficient treatment. The end 'windows' of the sources are usually thinner than the rest of the encapsulation to maximize the delivered dose. ^{60}Co and ^{137}Cs are the isotopes most frequently used. SRSs used in teletherapy are most often double encapsulated and tested to IAEA Special Form requirements [5]. These SRSs are all category 1.

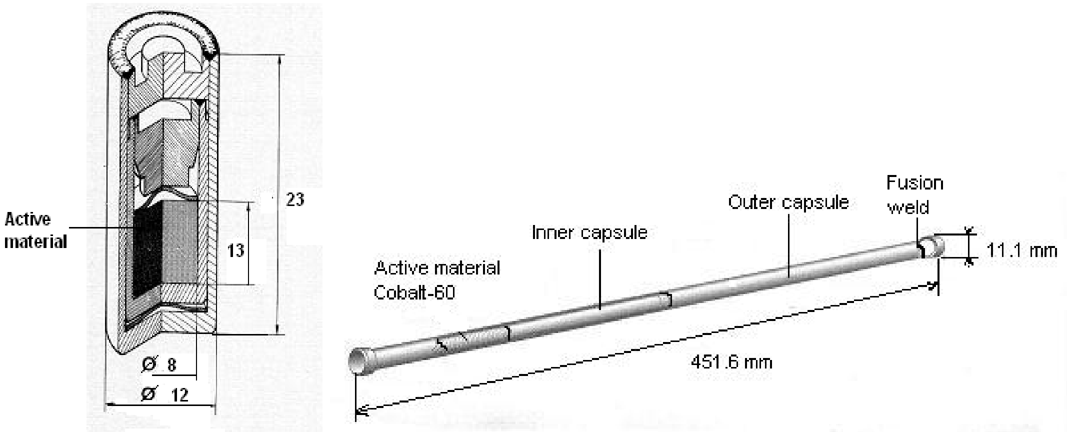

FIG. 2. Typical irradiator sources.

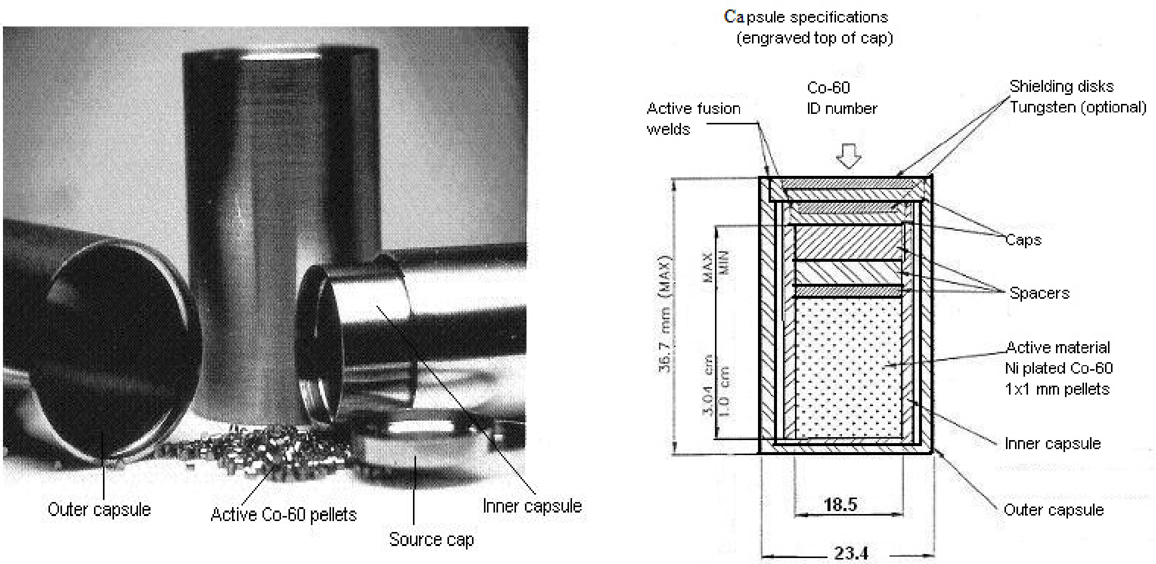

FIG. 3. Typical teletherapy source.

2.4 INDUSTRIAL RADIOGRAPHY

Industrial radiography is the process of performing nondestructive testing (NDT) or inspection of materials or components using radiation emitted from a SRS. It is used in a number of industrial applications such as oil and gas and construction. It is especially useful for visualization of cracks, corrosion or pitting, and to control the integrity of welded structures. The radiation penetrates the object to be inspected and exposes a film, which is then developed to reveal any discontinuities or irregularities in the object. Radiation safety aspects in industrial radiography are covered in the IAEA safety guide SSG-11 [9].

The radionuclides most commonly used for radiography are ^{192}Ir, ^{75}Se, ^{60}Co, ^{137}Cs and ^{170}Tm depending on the penetration and image quality required. A typical radiography source is shown in Figure 4. The SRS is usually attached, either by crimping, pinning or welding, to the end of a wire cable that is used to drive the SRS out to the area to be radiographed. When not in use, the SRS are contained in a shielded, portable exposure device (also known as a camera or projector) that is a licensed transport container, to be moved from place to place. These SRSs are almost all in category 2.

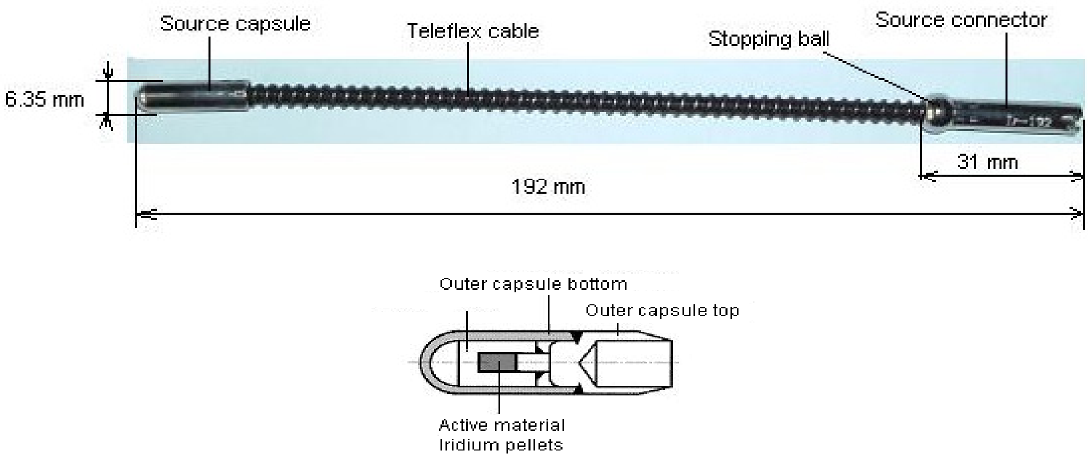

FIG. 4. Typical industrial radiography source.

2.5 BRACHYTHERAPY

Brachytherapy is a medical treatment whereby a SRS is placed within or near a cancerous tumor in a patient. The SRS is usually in the form of needles, tubes (stents), wires, or small ‘seeds’ that are placed over the surface of the tumor, within the tumor or into a body cavity near the tumor. High dose rate brachytherapy (HDR) sources are usually inserted for a short time and then removed, whereas low dose rate sources are often implanted into the patient. This treatment allows a highly localized dose of radiation to be delivered to the patient without the larger radiation exposure and longer treatment time required for teletherapy. Brachytherapy is usually an outpatient treatment that can be delivered in less than an hour.

Some typical brachytherapy sources are shown in Figure 5. Many different isotopes are used in brachytherapy, depending on the application and the dose requirements. Some of the more common isotopes are listed in Table 1. The high dose SRSs (e.g. ^{192}Ir) are mostly category 2, while the low dose SRSs (e.g. ^{125}I) are in categories 4 and 5.

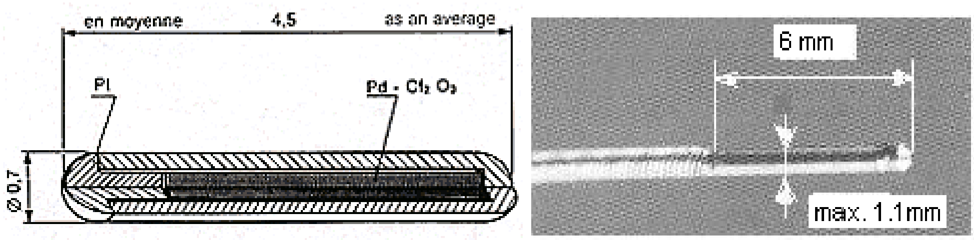

FIG. 5. Typical brachytherapy sources.

2.6 WELL LOGGING

Nuclear well logging is used to study the ground around exploratory bore-holes in the oil, gas and mining industries. The SRS is lowered into the borehole with detectors that monitor the response of the surrounding materials to the radiation. The response differs depending on the porosity, lithology or fluid properties of the materials. The purpose in most applications is to locate zones of hydrocarbons in the rock that indicate the presence of oil, gas or other geological formations.

Both neutron and gamma sources are used in well logging, with some of the more common radionuclides listed in Table 1. Figure 6 shows some typical SRSs used in well logging. These SRSs are mostly all in categories 2 and 3.

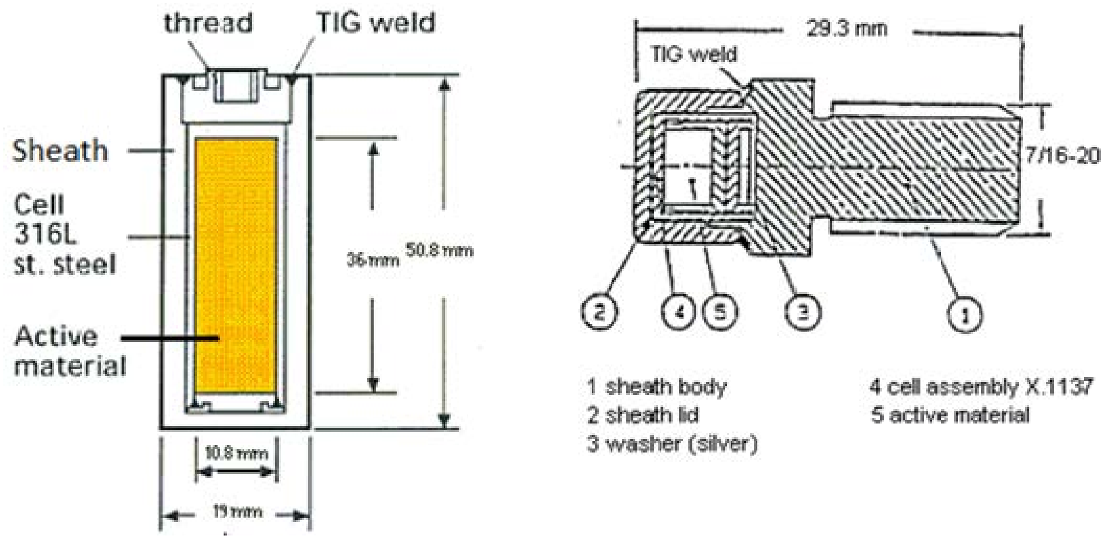

FIG. 6. Typical well logging sources.

2.7 INDUSTRIAL GAUGES

There are many different kinds of industrial gauges that use radioactive material; the most common ones are level and thickness gauges, used in process control. Other applications include density gauging, moisture gauging and some analytical procedures. A wide range of radioisotopes is used, from high-energy ^{60}Co with a half-life of 5.3 years, to low energy ^{241}Am with a half-life of 432 years. Gamma, neutron and beta sources are used. A typical industrial gauge SRS is shown in Figure 7. These gauges present one of the largest challenges in terms of disposal because of their number and wide-ranging use. These SRSs are mostly category 3 and 4.

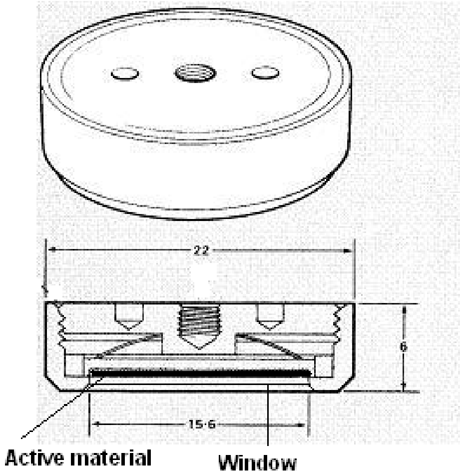

FIG. 7. Typical industrial gauge source.

2.8 RESEARCH

Radioisotopes and SRSs are used in many different branches of nuclear and general research, too numerous to list here. Virtually all of the applications listed in Table 1 are also used in research. A very small cross-section of the SRS used in research and development are shown in Figure 8. The categories of SRSs used in research applications vary widely, but as shown in the IAEA International Catalogue of Sealed Radioactive Sources and Devices (ICSRS), those sources are generally category 3 and 4.

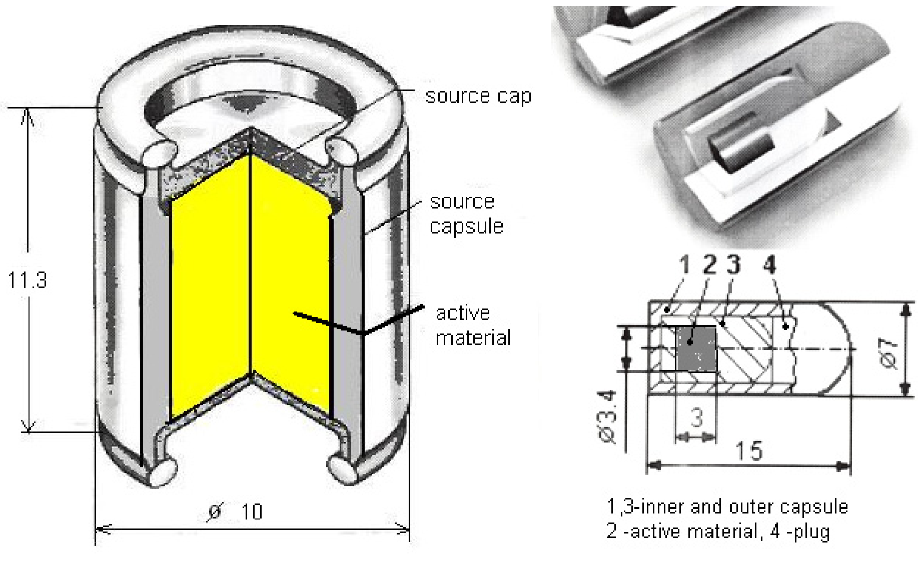

FIG. 8. Cross-section of radioactive source used for research.

2.9 BONE DENSITOMETRY

Bone densitometry is a radiological test to measure bone density. It is usually used for detecting the early stages of osteoporosis, before any symptoms occur. A typical bone densitometry SRS is shown in Figure 9. The radioisotopes (e.g. ^{109}Cd, ^{125}I, ^{153}Gd) used in bone densitometry are low gamma energy and are all unlikely to be dangerous (category 4).

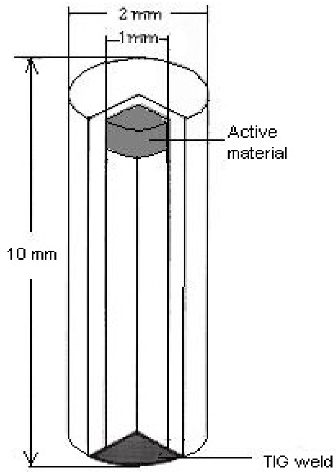

FIG. 9. Typical bone densitometry source.

2.10 X RAY FLUORESCENCE ANALYZERS

X ray fluorescence analyzers provide a quick and easy method of non-destructively determining the elemental concentrations in materials. The response signals from a material subjected to the radioactive X ray beam are analyzed and based on the energy and intensity of the emitted X rays the concentration of particular substances in the sample can be determined. A typical X ray fluorescence analyzer SRS is shown in Figure 10. The radioisotopes (e.g. ^{55}Fe, ^{109}Cd, ^{57}Co) used in this application are low energy and are all unlikely to be dangerous (category 5).

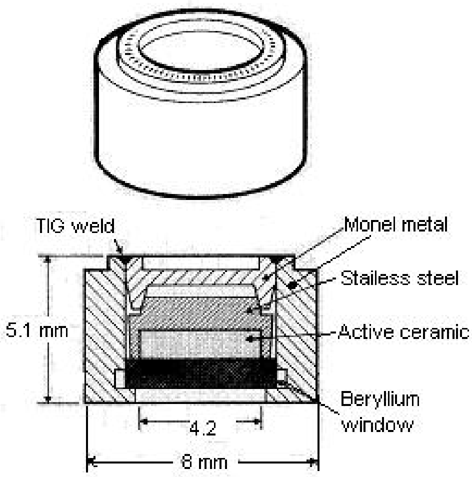

FIG. 10. Typical X ray fluorescence analyzer source.

2.11 ELECTRON CAPTURE DETECTORS

Electron capture detectors are used in gas chromatography to detect trace amounts of chemical compounds in the atmosphere and in other applications. The detector is placed in the output stream of the gas chromatograph to detect electron-absorbing components. The most commonly used beta emitting radioisotope is ^{63}Ni, which is contained on a metal foil within the detector. All of the radioisotopes used in this application are of lower energy and are all unlikely to be dangerous (category 5).

2.12 RADIOACTIVE LIGHTNING CONDUCTORS

A lightning conductor with radioactive sources ionizes the air around itself to increase air conductivity and thus to guide lightning discharge towards the lightning conductor. Typical isotopes used in this application are ^{241}Am and ^{226}Ra, both of which have extremely long half-lives, although they are lower energy and are considered category 5 SRS. In later years, and in particular in the former Yugoslavia countries, larger quantities of gamma emitting radionuclides were used for this purpose: typically $^{154/152}Eu$ at ~0.4 Curie (~15 GBq) or ^{60}Co at ~0.2 Curie (~7.5 GBq) (category 4 and 5). Occasionally ^{90}Sr, ^{85}Kr, and ^{14}C have also been used.

2.13 INSTRUMENT CALIBRATION SOURCES

Companies and institutions using radiation survey and monitoring instruments must calibrate their instruments on a routine basis. Calibration and check sources are used to ensure the functionality and accuracy of these instruments. Many different isotopes and activities, ranging from few kBq up to a few MBq are used for this purpose.

2.14 MOSSBAUER SPECTROMETRY

Mossbauer spectrometry is a spectroscopic technique based on the Mossbauer effect, whereby the exposure of a solid substance to gamma rays produces resonances that can be detected and measured. In the resulting spectra, the numbers, positions and peaks in the response are analyzed to characterize the sample. Very low energy gamma emitters, such as ^{57}Co, are required for this application, and are category 5 SRSs.

2.15 PACEMAKERS

Some implanted pacemakers are powered by ^{238}Pu batteries; although Lithium powered batteries is now the norm. The radioactive batteries used are basically a small RTG where the heat of decay is converted into electrical energy. The long half-life of ^{238}Pu makes it ideal for this application. These are very low energy sources used in the human body and have not been assigned a category.

2.16 STATIC ELIMINATORS

Radioactive static eliminators create an ionized atmosphere in close proximity to a surface that neutralizes the static charges. ^{210}Po and some other isotopes are generally used for this purpose with low activity that does not involve a significant radiological hazard.

2.17 LUMINOUS SIGNS

Radioactive self-illuminating signs contain tritium (^{3}H) or krypton (^{85}Kr) gas sealed in glass tubes. The tubes are sometimes lined with phosphor that emits light when excited by the radioactivity. Since tritium and krypton are low energy beta emitters, intact signs do not present a radiological hazard.

2.18 SMOKE DETECTORS

Smoke detectors use a small amount of ^{241}Am (a few kBq) to ionize the air around the detector. A low-level electric voltage is applied across the chamber to collect ions, producing a small electric current between two electrodes. Smoke passing between the electrodes absorbs the radiation and causes the rate of ionization of the air, and subsequently the electric current to fall, which sets off an alarm. Only a small amount of ^{241}Am is used in these detectors and ^{241}Am is a low energy alpha emitter, such that these devices are not a radiological hazard.

3 SEALED SOURCE DESIGN/MANUFACTURING FEATURES

Most commercial SRSs are manufactured and tested to international standards [5, 10, 11]. The design, materials and processes used for encapsulation are chosen to afford the greatest degree of containment, but are dependent on many factors including the condition of use (COU) and the availability and type of nuclide.

The ICSRS [12], an IAEA database containing the design features and manufacturers of SRSs, was used to delineate and compare the design/manufacturing features of the sealed sources used in the applications listed in Table 1. The key features examined are discussed in the following sections.

3.1 GEOMETRY

Most sources in the ICSRS are cylindrical and range in diameter from about 1 to 30 mm. Most are short (length < 2xdiameter). Irradiator sources are the longest (up to about 50 cm, the length of line sources for gauges and static eliminators could be more than 1 m) and have the greatest ratio of length to diameter, up to 40:1.

The cylindrical design is almost universally used as it allows the source to be sealed by a continuous weld. Also, most welding devices are designed to rotate the capsule to be welded. It would be more complicated to produce a good quality weld for a capsule of a non-cylindrical shape. Manufacturing the components for cylindrical sources (bodies and end caps where applicable) is also easier since tubes and round bars are readily available in many different sizes and materials.

A cylindrical geometry also allows the radioactive material, often pellets or powder, to be distributed uniformly inside the capsule by shaking or pressing. A non-circular geometry, with corners or edges, would make it more difficult to obtain a uniform distribution in the capsule. A more even dose distribution all around the source is also obtained with a cylindrical source.

A cylindrical source simplifies and reduces time of handling in the hot cell, as the cell operator does not have to rotate the source into a particular orientation on its axis. This is particularly important for automated welding processes.

For some applications other geometries are more appropriate, such as rectangular and ring sources used in various applications such as thickness gauges, flood sources, X ray fluorescence sources.

Many SRSs require that the activity is concentrated into a small volume to produce ‘point’ or ‘line’ sources. To achieve this, SRSs are made as small and thin as possible with radioactive material of as high a specific activity as possible [13]. Some low activity unshielded sources can be tiny metal fragments with dimensions down to a few millimeters [14]. Because of their small size, sources should be handled carefully when they are transferred to a waste disposal facility. Detailed procedures must be in place to ensure SRSs are not misplaced.

3.2 CAPSULE MATERIAL

The factors affecting the selection of capsule materials for SRSs are the same as those considered for any engineering application, with the added direct and indirect effects of radiation. For lower energy radionuclides the primary consideration is that the absorption of the radiation by the capsule material should be as low as possible. The absorption capability of materials for a specific type of radiation is characterized by the thickness of the material that absorbs half of the radiation and is called half value layer (HVL). Typical low HLV materials used as capsule material are aluminium or zirconium. For higher energy radionuclides, as the heat of decay increases, and subsequently strength and corrosion resistance becomes more important, higher HVL materials such as stainless steel, titanium and nickel base alloys are used. The selection of material for SRS encapsulation usually requires the best combination of physical and mechanical properties, corrosion and heat resistance, weldability and machinability. The material cost is normally a secondary consideration because of the much higher cost of the radioisotope. The most common materials listed in the ICSRS [12] are discussed in the following sections.

3.2.1 Stainless Steel

Over half of the encapsulations in the ICSRS use some type of stainless steel, most notably low carbon containing austenitic 300 series stainless steels. The most commonly used grade is 316 or 316L, while 304, 321 and 347 are also used. Ferritic stainless steel 416 is also used on occasion. Thin-walled tube or bored out round bar is used for the body of the capsule, while mostly round bar is used for the end caps welded to the ends of the tube.

Other encapsulation materials used for some sources include titanium and its alloys, aluminium and its alloys, and platinum. Generally these encapsulation materials are used for lower activity alpha/beta emitting sources for medical applications such as brachytherapy needles and stents.

Stainless steel provides a combination of mechanical properties, corrosion and heat resistance superior to any other metal. Austenitic stainless steel is most often used as it has the highest corrosion resistance of all the stainless steel types. The most commonly used types of stainless steel are (or have the quality like) the following [15, 16]:

- 316L – Molybdenum added to increase pitting corrosion resistance. Carbon further reduced for better welding characteristics;
- 316 – Molybdenum added to increase pitting corrosion resistance;
- 304 – Carbon lowered for better corrosion resistance. Not as good as 316 or 316L;
- 321 – Titanium added to prevent carbide precipitation (sensitization);
- 347 – Niobium and tantalum added to prevent carbide precipitation (sensitization);
- 416 – free-machining (added sulfur) version of 410 base alloy;

or stainless steels with comparable specifications as listed above.

Austenitic stainless steel is one of the best capsule materials for SRSs as it is corrosion resistant as mentioned above, but it also machines well and is easily welded, even without filler metal. They are also generally resistant to chemical or physical reactions with other materials [16]. The 316 and 316L grades are often used in the chemical and medical industries because of these properties. They are widely available in many different stock sizes and can also be specially ordered.

Stainless steel is also very ductile, which makes it ideal for SRSs, which must pass impact and bending tests to be licensed for use [10]. Being more ductile, it is less likely to fracture when impacted or bent.

Stainless steel is not ideal for some lower energy isotopes where the stainless steel would effectively provide shielding. Where very low HVL are required, other materials such as titanium or zirconium alloys are required.

Specialty steels, such as Hastelloy, have greater resistance to corrosion, but are much more expensive, harder to machine and weld, and are not as readily available.

3.2.2 Aluminium and its Alloys

Aluminium and its alloys are used in about 10% of the encapsulations in the ICSRS [12]. The aluminium is usually used for an inner encapsulation that is over-encapsulated with another material such as titanium or stainless steel. Aluminium is also used in foil form where the isotope is deposited onto it. Generally aluminium is used in lower activity sources with lower heat output because of its lower melting point, although higher resistant grades are available and are used as well.

Aluminium is used for SRSs because of its low HVL, good resistance to corrosion in certain environmental conditions, and its machinability and availability compared to other materials. Many different forms of welding can be used to seal aluminium. In most cases, reverse polarity (electrode positive) is used to prevent excessive heat buildup in the aluminium.

3.2.3 Titanium

Titanium is also used in about 10% of the encapsulations in the ICSRS [12]. Titanium alloys are used in SRSs because of its high strength to weight ratio, which allows for thin encapsulations that reduce the shielding effect on the radioisotopes encapsulated. Pure titanium is a relatively weak, ductile material. However, when alloyed with interstitial elements such as nitrogen, oxygen and iron it becomes a much stronger and useful material. The fatigue characteristics of titanium alloys are also excellent. This makes it ideal for high temperature applications where thermal cycling must be considered [17].

Titanium and its alloys are all weldable. Annealed titanium alloys are generally used for SRSs as welding of cold-worked alloys anneals the heat-affected-zone (HAZ) and negates any strength advantages produced by the cold work [18].

The machinability of titanium is similar to that of stainless steel, although the higher strength alloys are more difficult to machine. Titanium has a relatively low modulus of elasticity making it ‘springier’ than stainless steel to machine.

The corrosion resistance of titanium, much like that of aluminium and stainless steel, can be attributed to the formation of a passive oxide film. This oxide film affords protection mainly at low temperatures (less than 370°C). Titanium is not particularly oxidation resistant at higher temperatures, although its corrosion resistance exceeds that of stainless steel. The ability of titanium to passivation gives it a high degree of immunity against attack by most chlorides and acids. In fact, because titanium has a high affinity for oxygen, a scratched or damaged titanium capsule can generally re-heal itself if in the presence of oxygen [17-19].

3.2.4 Other Materials

Although the majority of SRSs are manufactured from the materials listed above, there are other materials used; such as platinum, nickel, zirconium and their alloys.

Both platinum and nickel are used for their excellent corrosion resistance. They both possess remarkable resistance to chemical attack, excellent high temperature characteristics and stable electrical properties. Platinum especially does not corrode in air at any temperature and is inert under body condition, making it excellent for applications such as stents or brachytherapy sources. The higher cost of pure platinum limits its use in higher volume applications [15].

Like aluminium, zirconium alloys are often used for encapsulating material to be irradiated in a reactor because of its low neutron cross-section. The alloy then becomes radioactive itself. Zirconium alloys also have excellent corrosion resistance, good mechanical properties and machinability [15].

Beryllium is sometimes used as a thin-window for low energy gamma sources. It has a low gamma absorption and good mechanical properties at higher temperature. The workability of beryllium, especially its low temperature brittleness, and a rather erratic corrosion resistance make it less attractive than other materials in most applications [15].

Glass is used for encapsulation of some tritium and krypton sources, most specifically in luminous signs where the encapsulation material must be transparent to light and easily formable.

Plastics (non-halogenated) which act as the source window are used to encapsulate calibration sources.

Platinum and gold were often used for encapsulation of medical ^{226}Ra sources. Americium oxide, used in smoke detectors, is uniformly sintered onto gold foil, which is further contained between layers of silver or gold by hot forging.

3.3 SEALING METHODS

Most of the sources in the ICSRS database [12] are sealed by welding. Those that are not sealed by welding are generally deposited (by electro-deposition or spray onto a foil, disc or rod made of nickel, platinum or aluminium), glued, or sealed in glass ampoules. The deposited sources are mostly lower activity alpha and beta sources in the 4 and 5 source categories. The more common methods of sealing radioactive sources are discussed in the following sections.

3.3.1 Welding

SRS are usually sealed by an autogenous weld (no filler metal) and use an automatic or semi-automatic process controlled by an operator outside a hot-cell, glove-box, or fume hood. The most common welding processes are tungsten inert gas (TIG, also called GTAW or Heliarc) welding, electron-beam welding and laser welding, of which TIG is the most common. These types of welding are ideal as they;

- Produce very high quality, superior welds;
- Allow precise control of the welding variables to limit the welding heat, which is important for welding thin materials;
- Produce low distortion as a result of the lower welding heat;
- Produce very clean welds free of slag and splatter;
- Use an inert cover-gas (argon, helium, or argon/helium mixtures) or vacuum (electron-beam) which protects the weld from oxidation.

All of the above welding processes produce high quality, smooth and attractive welds that require no post-weld cleaning or removal of slag. They can be used to weld a wide variety of materials including stainless steel, titanium and aluminium; the primary materials used in SRS. Heat input to the weld is limited. This reduces distortion in the weld and discontinuities in the material that could be susceptible to corrosion or stress fracture over the life of the source.

Most of the welded SRSs consist of a body made of a thin-walled tube or a piece of bored-out round bar, with an end cap or caps welded in place to seal the source. There are two common weld geometries; a side-weld and an end-weld, as shown in Figure 11.

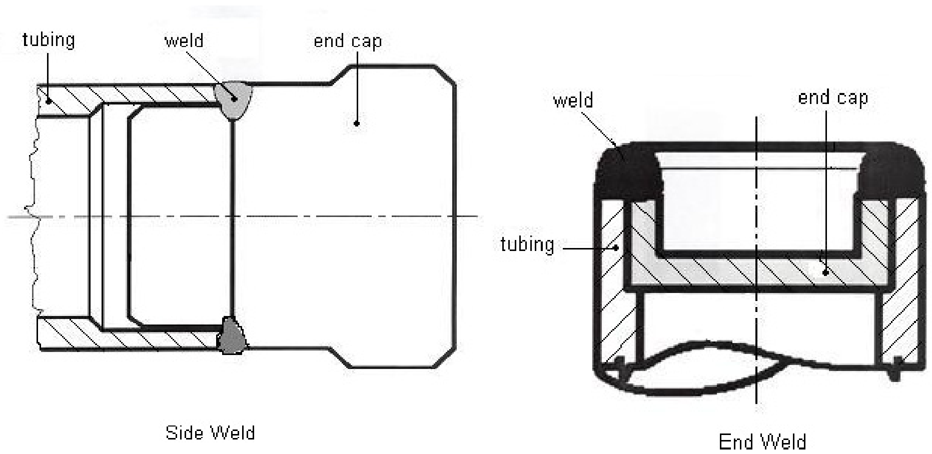

FIG. 11. Side and end weld geometries.

Generally a side-weld is used for sources such as irradiator sources that are periodically moved in and out of water, and are therefore subject to temperature changes that will cause expansion and contraction of the weld. An end-weld is more often used in dry applications such as teletherapy.

3.3.2 Material Deposition

Some sources are formed by various methods of material deposition, which can be used to deposit both the radioactive material and an encapsulating layer as thin films. Typical deposition techniques include sputtering, ion plating, spray and chemical vapor deposition. The thickness of these coatings, deposited on wires, rods, seeds and films, is in the in the range of 10 – 300 × 10^{-8} cm (10 – 300 angstrom)

3.3.3 Other sealing methods

Brazing

Brazing is used in applications where the components cannot be welded or the component materials are dissimilar.

Gluing/epoxy sealing

Gluing/epoxy sealing is used for plastic sources, especially in low activity sources. Glue is cheaper and easier for these types of sources than welding.

Sealing in glass

Glass is used to seal the radioactive material in ampoules, such as for self-luminescent light sources and Krypton inert gas gauges.

Pressure/temperature sealing

Plastics used in calibration sources are often hot-sealed under elevated pressures and temperatures.

3.4 CHEMICAL/PHYSICAL FORM OF THE RADIOACTIVE MATERIAL

Although SRSs are robustly designed and constructed, they are not indestructible. The chemical and physical form of the radioactive material is therefore an important factor to consider in disused source management. Where possible, the radioactive material is in an insoluble and non-dispersible form.

The radioisotope selected for a source depends on the application. For large-scale irradiators and teletherapy, for example, ^{60}Co is used because it emits high energy gamma radiation that is required to penetrate and deliver sufficient dose to the product or patient to be treated. ^{137}Cs is also used in many therapy applications because it is a gamma emitter, but has a lower energy than ^{60}Co and has less damaging effect on healthy tissues surrounding the treatment area. ^{192}Ir is used in many brachytherapy applications for the same reason. ^{90}Sr/^{90}Y are pure beta emitters without gamma emission and are therefore ideal for medical purposes in eye and skin treatment where tissues are sensitive and little penetration of the radiation is required [14].

The physical form of the radioactive material is important when considering encapsulation. Elemental (metallic) ^{60}Co is ideal for many applications because it has properties similar to steel. It can also be sintered and formed into many different shapes, varying from cobalt granule to larger diameter, long slugs. ^{137}Cs is only available in the form of salts (typically cesium chloride). This is preferred in many applications because cesium chloride is a fine powder and therefore, fills the full volume of the source capsule and thus provides for a more even dose distribution. However, the disadvantage of cesium chloride is its high dispersibility.

It is highly soluble in water or easily becomes airborne as fine powder in case of capsule rupture [20].

The dispersibility of the radioactive material (e.g. salts of ^{137}Cs or ^{90}Sr) can be reduced by embedding in a ceramic matrix, although this results in reduced specific activity and thus reduced effectiveness of the sealed radioactive source [2].

3.5 EFFECTS OF DECAY

Decay products of some radioisotopes can affect the integrity of the sealed source in a long-term storage or disposal facility. Gases released during radioactive decay, such as radon (^{222}Rn), helium and hydrogen could also pressurize the encapsulation and possibly rupture the sealed source [21]. The heat of decay can also present a risk in case of high activity sources. Generally, however, SRSs are designed to withstand large internal and external pressures and must be proven to maintain their integrity under worst-case gas emissions and temperatures when tested and licensed [10].

When disused SRSs are recovered, they should be examined for bulging or surface changes that would indicate if any outgassing has occurred. Generally, if no such pressurization has occurred over the useful life of the source, there is likely to be no risk when the source has decayed and is ready for disused source management. There are situations, however, where significant off-gassing will occur after the useful life of the source. The source designer and supplier must be aware of this and account for the additional pressure build up in the design of the source, or have a predetermined strategy developed and documented for disused source management [13].

3.6 TYPE OF RADIATION

The sealed source design depends mainly on the type of radiation that it emits and the dose it is required to deliver. For example, thin-windowed capsules are required for lower energy gamma and beta radiation and some sources have tungsten inserts to collimate the radiation. Also, alpha emitting sources inside smoke detectors use a sealing layer of a thickness of a few atoms to enclose the radioactive material.

Neutron sources normally contain alpha emitting radionuclides (^{226}Ra, ^{238}Pu, ^{241}Am) encapsulated together with a target material of light elements such as beryllium, boron, or lithium. The activity of the alpha sources may be up to several hundred GBq [2] to produce sufficient neutron flux as a result of the nuclear reaction between the alpha particles and the target material.

In general, sources are designed so that the radiation will not have any significant damaging effects on the capsule.

The type of radiation emitted by the source should be identified so that necessary precautions (e.g. radiation protection) can be taken when managing disused sources.

3.7 IDENTIFICATION

All SRSs must be marked with a serial number for identification as required by ISO 2919 [10]. If the source is large enough, the manufacturer and radionuclide must also be included.

The correct identifying markings, as well as the legibility and condition of the markings on the source are critical for disused source management.

Special consideration should be given to the application of the source identification for long-term legibility, especially the serial number. For example, most irradiator gamma sources have the serial number and radionuclide deeply engraved in the end cap of the source. This allows for easy identification even after several years in a wet environment where the source will become discolored and scratched from use.

It has to be emphasized here for safety reasons that any markings on sealed sources of categories 1-3 and possibly of the upper range of category 4 [3] must only be read if the source is adequately shielded, in case of high activity sources normally in a hot cell or under water using remotely controlled video camera.

3.8 NUMBER OF ENCAPSULATIONS

Single Encapsulation

Single encapsulation, (see Figs 8 and 10), represents less shielding for lower energy isotopes. A single encapsulation can be as robust as an equivalent double encapsulation, but it may be more difficult to ensure that the outer surface is contamination free.

Double Encapsulation

In case of double encapsulation the inner capsule containing the radioactive material is welded first and then over-encapsulated by an outer capsule, which adds additional robustness to the source (see Figs 3). This process is used in some applications as it allows the inner source to be loaded with the radioactive material in one hot cell, cleaned of contamination, and then passed into another cleaner hot cell for over-encapsulation. With this procedure it is easier to seal and clean the outer surface to meet regulatory limits for leakage and contamination.

4 DISCUSSION OF DESIGN/MANUFACTURING FEATURES AFFECTING DISUSED SOURCE MANAGEMENT

The following discussion looks at sealed source design and manufacturing and how it may affect the various stages of disused source management, including retrieval, re-use, recycling, conditioning, transport, storage and disposal. Table 3 lists the positive attributes and provides a comparison of the key features of design and manufacturing that affect disused source management.

4.1 CONDITIONS OF USE

The conditions of use (COU) largely dictate the design of a SRS. The design features must provide the required dose in the application. As listed in Table 3, in most cases sources are cylindrical for easy handling and a uniform dose distribution and as thin-walled as possible to maximize the dose output. Capsule materials chosen must be resistant to corrosion and chemical attack, radiation resistant and compatible with the device they are installed in and with the environment. A robust seal is mandatory to ensure the sources remain leaktight under the COU. Where necessary, encapsulations must be designed to withstand any pressure from gas emissions or known environmental effects. Many manufacturers use double encapsulations to reduce contamination levels in manufacturing as well as for added protection from the environment. As far as the COU allow, source design should maximize the life of the source to facilitate later retrieval and possible re-use or recycling. The required identification markings for SRS are specified in the ISO standards [10].

4.2 RETRIEVAL

There are three options for retrieval of a sealed source from the field: i) removing the source from the device and placing it into a transport package, ii) shipping the source in the device if the device meets the requirements for a transport package, and iii) placing the device in a licensed overpack for transport. The source design and manufacturing techniques need only be considered when the source is to be removed from the device. In all of these cases, there must be an authorized consignee to accept the shipped package.

As listed in Table 3, important factors to be considered in source design and manufacture to facilitate retrieval include ease of handling, robust construction, corrosion and chemical resistance, proper fit including the effects of thermal expansion, and material compatibility. Shorter half-life and low heat emitting radioisotopes will make the sources easier to handle, retrieve, condition, store and dispose of, but may make the source less suitable for re-use or recycling. Non-dispersible forms of the radioactive material are preferred. It is also very important to clearly define the COU, including temperature, humidity, vibration, and cycling effects to name a few. Good communication between the source designer, the device manufacturer and the user is required to ensure that the adequate COU are taken into account in the design. It is the user's responsibility to ensure that the COU are maintained throughout the useful life of the source.

Unless there is an overriding reason, device designers should always consider that the source should be removable from the device. This may require the source walls to be thicker and stronger than required by the application, but will facilitate removal since the sources will be better protected against mechanical damage. The identification markings on the source, especially the serial number should be particularly robust to remain legible when the source is recovered.

Packaging and transportation of the source can be complicated if the device is not licensed as a transport package, no licensed transport container is available, the Special Form Certificate [5] is no longer valid, the source is damaged or leaking, or in some situations where the recommended working life (RWL), discussed in section 5, has expired. In such cases special arrangements may be required to transport the source, but these are often not feasible.

4.3 RE-USE

Re-use is the transfer of a source, without any modification of the source, from one device to another or from one application to another. When reusing a source, the device designer and/or user is responsible for assessing the condition of the source and for ensuring the source meets the stated performance requirements under the conditions of the new environment and usage.

Important factors to be considered in source design and manufacture to facilitate re-use include a robust construction, corrosion and chemical resistance, and the use of longer half-life isotopes, as listed in Table 3. A double encapsulation can facilitate re-use.

4.4 RECYCLING

Recycling is the removal of the active material from a source or over-encapsulation of a disused source for manufacturing of a new source or sources. The manufacturer performing the recycling normally issues a new source certificate for the new source.

4.5 CONDITIONING AND STORAGE

Conditioning or immobilization includes producing a waste package that reduces the potential for migration or dispersion of radionuclides during handling, transport, storage and/or disposal. Conditioning may include conversion of the source to another form, enclosing the source in another capsule and, if necessary, providing an overpack [22].

Storage is the holding of the disused SRSs, preferably in conditioned form, in a facility that provides for its containment, with the intention of retrieval. Storage may be dry or wet (in a water filled pool) [23].

Disused sources are often stored at users' site although this is not a preferred option. Return of the disused source to its manufacturer/supplier, or transfer to a waste operator, are the most preferred solutions. In any case, particularly when the disused source is stored at the user's site, measures are required to maintain continuous control over the disused source.

Conditioning practices should take into account the source design and performance characteristics to minimize unintentional damage to the source during conditioning. In case this information is not available, the IAEA sealed source catalogue [12] can be used to research source characteristics.

The source designer and/or the equipment designer should consider aspects of the design that would facilitate removal of inactive parts or modification of the source assembly to minimize the volume for storage and disposal.

The waste operator should be aware of the COU and ensure sources are stored in the same or less severe conditions than the COU. Where this is not possible or the COU are not known, the storage environment should be maintained such that degradation of the source is reasonably minimized. For the majority of sources, a clean, dry environment is acceptable.

From Table 3 it is seen that the design features optimized for the application are at odds with those for disused source management. The optimal design for use is generally a thin-walled containment made of a cost-effective, easily machined material to maximize exposure dose. The ideal design for storage and disposal would use thick-walled containment capsule made of highly corrosion resistant material that would require a sufficiently long period to corrode.

So, the design of a SRS should strive to balance the needs of the application, which are paramount, and the favorable features of conditioning and disposal of the source, which are also important.

TABLE 3. COMPARISON OF SEALED SOURCE DESIGN FEATURES AFFECTING DISUSED SOURCE MANAGEMENT

Feature	Positive attributes for conditions of use	Positive attributes for retrieval	Positive attributes for re-use	Positive attributes for recycling	Positive attributes for conditioning and storage	Positive attributes for disposal
Geometry	Size, shape and fit as required for the application. Cylindrical – ease of handling in-cell, good dose distribution. As thin-walled as possible – less self-shielding, higher dose delivered and better dose distribution. Generally tight fit of internal components.	Easy to remove. Loosely attached to device. Easy to handle. Equipped with a handling location or attachment. Robust construction. Thick-walled so as not easily damaged.	Standardized size to be interchangeable between devices. Cylindrical without steps or non-uniform geometry. Robust construction.	Standardized size to be interchangeable between devices. Cylindrical without steps or non-uniform geometry. Easily dismantled. Thin-walled, defined cutting location to avoid damaging active material. Loose fit of internal components.	Cylindrical – ease of handling. Rectangular – will stack better to make more efficient use of space. Thick-walled and shielded – reduces dose to operators and greater resistance to corrosion long term. Small to make better use of space.	The geometry is considered in the conditioning phase of preparing the source for disposal.
Capsule material	Compatible with commonly used device materials that it will be in contact with. Corrosion / chemical / radiation resistant. Compatible with the environment.	Compatible with commonly used device materials with which it will be in contact. Corrosion / chemical / radiation resistant. Compatible with the environment.	Compatible with commonly used device materials with which it will be in contact. Corrosion / chemical / radiation resistant. Compatible with the environment.	Lower strength and toughness material to facilitate cutting/opening. Easy to decontaminate (smooth surface finish).	Corrosion / chemical / radiation resistant. Compatible with the environment.	The type of material is considered in the conditioning phase of preparing the source for disposal.
Sealing method	Robust seal.	Robust seal.	Robust seal.	Easily dismantled.	Robust seal. Or easily dismantled to remove the radioactive material for encapsulation in a more robust, more highly shielded vessel (screw-cap, gluing).	The sealing method is considered in the conditioning phase of preparing the source for disposal.

TABLE 3. COMPARISON OF SEALED SOURCE DESIGN FEATURES AFFECTING DISUSED SOURCE MANAGEMENT (cont'd)

Feature	Positive attributes for conditions of use	Positive attributes for retrieval	Positive attributes for re-use	Positive attributes for recycling	Positive attributes for conditioning and storage	Positive attributes for disposal
Chemical /physical form of radionuclide	Form of radionuclide best suited to application and easiest to store and handle.	Non-dispersible, if possible.	Non-dispersible, if possible.	Easily recoverable.	Non-dispersible.	The form of radio-nuclide is considered in the conditioning phase of preparing the source for disposal.
Effects of decay	Longer half-life to increase longevity of the source. Design for gas emission.	Shorter half-life (including decay products) and low heat emitters to facilitate handling. Radionuclides that do not emit pressurizing gases on decay.	Longer half-life to increase longevity of the source. Design for gas emission.	Longer half-life to increase longevity of the source. Design for gas emission.	Shorter half-life (including decay products) and low heat emitters to facilitate handling. Radionuclides that do not emit pressurizing gases on decay.	Shorter half-life reduces cost and enables cheaper disposal solutions.
Type of radiation	All types depending on application.	Low energy levels and/or non-penetrating radiation reduce exposure and require less sophisticated facilities.	All types depending on application.	All types depending on application.	Low energy levels and/or non-penetrating radiation reduce exposure and require less sophisticated facilities.	The types of radiation are considered in the conditioning phase of preparing the source for disposal.
Identification	Markings as required by ISO regulations.	Markings as required by ISO regulations. Extra clear to be legible when recovered.	Markings as required by ISO regulations. Extra clear to be legible when recovered.	Markings as required by ISO regulations. Extra clear to be legible when recovered.	Markings as required by ISO regulations. Extra clear to be legible when recovered.	Markings as required by ISO regulations. Extra clear to be legible when recovered.
Number of encapsulations	Single encapsulation to reduce self-shielding. Double encapsulation for added protection from the environment and to reduce contamination levels in manufacturing.	Double encapsulation to facilitate handling and re-use by over-encapsulation.	Double encapsulation to facilitate re-use by re-encapsulation. Irrelevant to re-use without re-encapsulation.	Single encapsulation to facilitate access to active material.	Generally as many layers of encapsulation and shielding as practicable. Not compatible with most conditions of use.	Generally as many layers of encapsulation and shielding as practicable. Not compatible with most conditions of use.

4.6 DISPOSAL

Disposal is the emplacement of SRSs in an appropriate facility without the intention of retrieval [23].

Many countries have existing or proposed near surface radioactive waste disposal facilities. However, the specific activity of many radioactive sources exceeds the waste acceptance criteria for such facilities, since the source constitutes a high, localized concentration in the facility. Deep geological disposal offers the highest level of isolation available within disposal concepts currently being actively considered. Such facilities are under consideration for the disposal of spent nuclear fuel, high level waste and intermediate level waste in a number of countries. However, they are expensive to develop and only viable for countries with extensive nuclear power programmes. Therefore, increasing attention has been given to the disposal of DSRS in borehole disposal facilities with a view to providing a safe and cost effective disposal option [24].

When designing a new sealed source the type of application and COU are usually the primary considerations and not the disposal of the source. Generally, SRSs are designed and manufactured to perform as required under the COU and to be cost effective in the materials and manufacturing techniques used.

However, all factors discussed in Section 3 are still important to the conditioning and storage of the SRS for disposal, as shown in Table 3.

5 REVIEW OF RECOMMENDED WORKING LIFE (RWL)

Some manufacturers recommend in the source certificate or other source documentation specify a period of time after which the user should consult the manufacturer as to whether the source can be further used. There is no generally accepted definition of the ‘Recommended Working Life’ (RWL) for sealed sources. According to different interpretations the RWL may be:

- The finite life of the source, after which the source is no longer considered to provide adequate containment of the radioactive source material; or
- The useful life of the source, after which it is no longer delivering a dose adequate for the application; or
- A set period of time after which the source must be inspected and assessed to determine if it can further remain in service.

As of yet, there has been no clear direction from national competent authorities or international organizations such as ISO on the definition and requirements associated with the specification of a RWL.

Examples of some sources for which a RWL is specified by the manufacturer are the following:

- Alpha sources with a specified RWL of about 2 years;
- Gamma sources with a specified RWL of 10-20 years;

- ^{14}C beta sources with a specified RWL of 25-30 years;
- Check sources (^{60}Co, ^{137}Cs, ^{133}Ba) with a specified RWL of 5-8 years.

The concept of the 'Recommended Working Life' of a SRS was first published in a paper in the Radiological Protection Bulletin No. 34, May 1980, by E. A. Lorch [25]. This paper is still the only publication that attempts to define the RWL, although regulatory bodies now quote the concept widely. The Lorch paper defines the RWL as follows: "The recommended working life is our recommendation of the period within which the source should be replaced. The period given has been assessed on the basis of factors such as toxicity of the nuclide, total initial activity, source construction (design, source insert type, etc.), half-life of the nuclide, typical application environments, operational experience, test performance data, etc. Adverse environments could affect the appearance and integrity of a source. It is the user's responsibility to regularly inspect and test the source in order to assess at what point during the recommended working life the source should be replaced."

Currently, the Lorch definition of RWL has been used by some regulatory bodies, without clearly defining the intent and requirements of the RWL. Some country's competent authorities have prohibited the use and shipment of sources after the end of their RWL, or required sources to be recalled at the end of their RWL. This interpretation of the RWL discourages manufacturers to specify a RWL, since it does not define the environment in which the sealed source shall operate. If monitoring of a source is performed throughout its initially specified RWL, as is done for almost all sealed sources by routine contamination checks, the manufacturer/user should have the option to extend the RWL if no evidence of leakage is found. Prohibiting the use and shipment of sources after their RWL expires is counterproductive in that it promotes leaving potentially dangerous sources in the field with no avenue for safe disposal and may also lead to unnecessarily premature replacement of sources.

The IAEA Safety Guide RS-G-1.10 on 'Safety of Radiation Generators and Sealed Radioactive Sources' [26] addresses the RWL as follows: "Some manufacturers also specify a recommended working life for sources, which is the period of time over which the source is expected to maintain its integrity. In specifying the recommended working life, account is taken of the nature of the radioactive material, its half-life and the encapsulation of the source. A source that has exceeded its recommended working life should be inspected by the manufacturer or other appropriate body to ensure that the integrity of the source has been maintained. The regulatory body may permit sources that have exceeded their recommended working lives to continue in service subject to confirmation of continuing integrity".

For the majority of sources, the normal working environment is well known in advance and the source can be specifically designed to withstand the effects of mechanical deterioration, such as corrosion, fatigue and stress cracking induced by the conditions in which it operates. For example, if a known environmental hazard is corrosion, corrosion resistant materials can be selected and the source designed to ensure it is fit for use. If the hazard is cycling and fatigue, or any other mechanical loading, the source can be designed to resist the applicable loads. Therefore, provided the source is designed to be fit for use per ISO 2919 [10], the only case a RWL would be useful is when there is significant uncertainty in the environment requiring an enhanced inspection regime, or where design considerations show the source will deteriorate after a certain period of time.

In summary the RWL would be useful when:

- The source is used in a severe environment, or the environment or design constraints were not fully understood at the time of the design. A surveillance program to monitor the performance of the source in use;

- The source integrity is degrading with time. The case of alpha emitters is a good example of this, where pressure builds up, potentially compromising the containment system. Either the design must be proven to account for any long-term pressure build-up or a RWL specified at which time the source integrity should be reevaluated and, if necessary, the source be retrieved, conditioned and disposed of in a way to mitigate the damaging effects of the pressure build-up.

The following points for clarification may be subject to further consideration by source manufacturers and regulators.

- Exceeding the RWL does not necessarily mean the source is unfit for further use or transport. It means that an assessment is required;

- The assessment should include leakage and/or contamination testing and a review of the operating experience for that source model and the effects of the COU;

- The RWL of an individual source can be extended, preferably by the manufacturer, based on an adequate assessment. The results of assessments can be extended to source models used in comparable applications;

- Independently from the manufacturer’s assessment made for the purpose of extending the RWL, it is the user's responsibility to carry out routine inspections and contamination testing and to maintain the COU in accordance with the manufacturer’s instructions.

Whenever a RWL is given by a manufacturer, it should be supported by points of clarification similar to those above and by a clear description of the COU. This information should be included in the source certificate issued by the source manufacturer.

6 CONCLUSIONS AND RECOMMENDATIONS

The IAEA recognizes the important role that radioactive source manufacturers and suppliers play in achieving the objective of safety and security during the source life cycle, including the management of disused radioactive sources. Most sealed source manufacturers currently use similar geometries, materials, sealing techniques and encapsulation configurations. These designs and manufacturing techniques follow the relevant ISO standards and have been proven over time to reduce contamination levels during fabrication and handling, and to ensure source integrity and longevity. The current source designs and materials ensure as best as possible that the sealed sources will maintain their integrity in use and when they become disused unless extreme conditions occur such as mechanical damage or unexpected corrosion which are beyond the design basis. No significant improvement opportunities to current designs have been identified.

The following design considerations are important from the point of view of the management of sources after the end of their useful life:

- To facilitate source retrieval, unless there is an overriding operational reason, device designers should always consider that the source should be removable from the device;

- The design of a source should consider how the source could be re-used or recycled with minimal contamination and waste;

- The design of a SRS must strive to balance the needs of the application, which are paramount, and the conditioning and disposal of the source, which is also important. Features should be selected that meet the requirements for the application, but where possible will also ease the safe management of the SRS when it becomes disused;

- The correct identifying markings, as well as the legibility and condition of the markings on a source are critical for disused source management. Special design consideration should be given to ensure long-term legibility of the source identification, especially the serial number. Any markings on sealed sources of categories 1-3 and possibly of the upper range of category 4 must only be read if the source is adequately shielded.

Several points of clarification related to the source recommended working life have been proposed for consideration by source manufacturers and regulators.

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ACRONYMS

COU	conditions of use
DSRS	disused sealed radioactive source
EBW	electron beam welding
GTAW	gas tungsten arc welding
HAZ	heat affected zone
HVL	half value layer
ICSRS	International Catalogue of Sealed Radioactive Sources and Devices (IAEA)
ISO	International Organization For Standardization
LBW	laser beam welding
NDT	non-destructive testing
RTG	radioisotope thermoelectric generators
RWL	recommended working life
SHARS	spent high activity radioactive sources
SRS	sealed radiation source
TIG	tungsten inert gas welding

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ISSN 1011–4289