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Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry

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TRAINING COURSE SERIES 40

RADIATION PROTECTION AND THE MANAGEMENT OF RADIOACTIVE WASTE IN THE OIL AND GAS INDUSTRY

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

RADIATION PROTECTION AND THE MANAGEMENT OF RADIOACTIVE WASTE IN THE OIL AND GAS INDUSTRY

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2010

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FOREWORD

The oil and gas industry, a global industry operating in many Member States, makes extensive use of radiation generators and sealed and unsealed radioactive sources, some of which are potentially dangerous to human health and the environment if not properly controlled. In addition, significant quantities of naturally occurring radioactive material (NORM) originating from the reservoir rock are encountered during production, maintenance and decommissioning. The oil and gas industry operates in all climates and environments, including the most arduous conditions, and is continuously challenged to achieve high efficiency of operation while maintaining a high standard of safety and control — this includes the need to maintain control over occupational exposures to radiation, as well as to protect the public and the environment through proper management of wastes that may be radiologically and chemically hazardous. The oil and gas industry is organizationally and technically complex, and relies heavily on specialized service and supply companies to provide the necessary equipment and expertise, including expertise in radiation safety.

This training manual is used by the IAEA as the basis for delivering its training course on radiation protection and the management of radioactive waste in the oil and gas industry. Enclosed with this manual is a CD-ROM that contains the presentational material used in the training course, the course syllabus and additional notes for course presenters. The course material is based principally on IAEA Safety Reports Series No. 34 *Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry*, published by the IAEA in 2003. The training course is aimed at regulatory bodies; oil and gas field operators and support companies; workers and their representatives; health, safety and environmental professionals; and health and safety training officers.

A pilot training course was held in the Syrian Arab Republic in 2000 as part of the development of Safety Reports Series No. 34. Following the publication of that report in 2003, a consultants meeting was held to start the drafting of the material for this training manual. Further training courses were held in Nigeria in 2003, Indonesia in 2004, and the Libyan Arab Jamahiriya and Qatar in 2006. Experience gained in presenting these training courses enabled the course content to be refined and the drafting of this training manual to be finalized in a further two consultants meetings in 2008–2009. Particular acknowledgement is made of the contributions made by J. van der Steen and R. Wheelton. The IAEA officer responsible for this training manual was D.G. Wymer of the Division of Radiation, Transport and Waste Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The oil and gas industry is a global industry that operates in many Member States of the IAEA. There are several facets to the industry including:

- The construction sector responsible for manufacturing and fabricating facilities and equipment;
- The production sector responsible for developing and exploiting commercially viable oil and gas fields;
- ‘Downstream’ sectors dealing with transport of the raw materials and their processing into saleable products;
- Marketing sectors responsible for the transport and distribution of the finished products.

Radioactive materials, sealed sources and radiation generators are used extensively by the oil and gas industry, and various solid and liquid wastes containing naturally occurring radioactive material (NORM) are produced. The presence of these radioactive materials and radiation generators results in the need to control occupational and public exposures to ionizing radiation.

Various radioactive wastes are produced in the oil and gas industry, including the following:

- Discrete sealed sources, e.g. spent and disused sealed sources;
- Unsealed sources, e.g. tracers;
- Contaminated items;
- Wastes arising from decontamination activities, e.g. scales and sludges.

These wastes are generated predominantly in solid and liquid forms and may contain radionuclides of artificial or natural origin with a wide range of half-lives.

The oil and gas companies themselves are not experts in every aspect of the technology applied in their industry. Frequently the necessary expertise is provided to the industry by specialized support organizations. Obviously it is in the interests of the oil and gas industry to demonstrate an appropriate standard of basic radiation safety, environmental protection and waste management and to have a common understanding of requirements and controls to establish efficient and safe operations.

1.2. OBJECTIVE

As one means of promoting safety in the oil and gas industry, as well as encouraging a harmonized approach to regulatory control, the IAEA organizes training courses in cooperation with governments and institutions in Member States. These are aimed at individuals in developing countries with responsibilities in the area of regulating the radiological aspects of the oil and gas industry and the implementation of the necessary control measures. The objective of this training manual is to provide a reference document to support the delivery of IAEA training courses on radiation protection and the management of radioactive waste in the oil and gas industry.

1.3. SCOPE

This training manual describes the technologies involving radioactive materials and radiation generators that are used within the various oil and gas industry sectors. It provides specific guidance on:

- Ensuring the radiological health, safety and welfare of workers and the public, and protection of the environment;
- The safe management of radioactive waste;
- Organizational responsibilities.

It forms a framework within which the regulatory bodies of Member States, oil and gas field operators, service companies and workers can develop a common understanding.

The training manual reviews the applications of ionizing radiation at onshore and offshore oil and gas industry facilities, transport and distribution systems, and service company bases. Good working practices are described for the following work activities involving potential exposures to ionizing radiation and radioactive materials:

- Industrial radiography, including underwater radiography;
- Installed gauges, including those used to make level and density measurements;
- Portable gauging equipment;
- Well logging, including ‘measurement while drilling’ and wireline techniques;
- Work with radiotracers;
- The accumulation and disposal of NORM and the decontamination of equipment contaminated by NORM;
- Radioactive waste management;
- Accidents involving radioactive sources and materials.

Training course lecturers may not necessarily teach directly from this text, but may use it to enhance their presentations and as general reference material. Students will find this training manual a useful reference during and after the training course sessions. The group discussions provided in this training manual are used during the course to enhance communication and understanding and to evaluate progress in learning. Other exercises may also be introduced if it is determined that they are more suitable for the specific participants.

1.4. STRUCTURE

This training manual consists of 16 sections. After this introductory section, Sections 2 and 3 provide reviews of radioactivity and radiation and of radiation protection principles, while Section 4 provides a general overview of the basic concepts of occupational radiation protection. Good comprehension of these three topics is essential for deriving full value from the training sessions. Section 5 describes the basic technology and terminology associated with the oil and gas industry, the typical construction of oil and gas wells, and the processes in which ionizing radiation is applied.

Sections 6–16 address the main technical content of the training course. Section 6 describes the responsibilities for radiation protection in the oil and gas industry. Section 7 covers the applications of sealed sources and radiation generators, the types of source used, and their radiation protection and radioactive waste safety aspects. Sections 8 and 9 deal with two ‘special focus topics’ — gamma radiography and nuclear gauges. Section 10 deals with the use of unsealed radioactive material, including the radiation protection aspects and the management of radioactive waste arising from its regular use. A third ‘special focus topic’ — on personal protective equipment — is covered in Section 11. The origin and deposition of NORM in oil and gas production, NORM treatment and NORM transport facilities are described in Section 12, which also discusses radiation protection measures in dealing with NORM and the options for managing and disposing of different types of waste arising at oil and gas facilities and at decontamination plants. Section 13 deals with radiation monitoring in the workplace. Section 14 deals with emergencies and contingency planning, as a result of accidents with sealed and unsealed sources. Section 15 describes a case study from the United States of America, concerning an incident involving a ruptured well logging source. Finally, Section 16 covers the planning and activities associated with the decommissioning of oil and gas facilities.

The course consists of six modules, comprising 29 separate lectures and eight group discussions. Several modules are supported by group discussions, including exercises, designed to encourage students to make practical use of the lecture material. Notes for use in these group discussions are provided at the end of the document, together with details of the training course programme. A CD-ROM is also included, containing the presentational material used in the training course, the course syllabus and additional notes for presenters.

1.5. THE IAEA AND RELEVANT SAFETY-RELATED PUBLICATIONS

The IAEA is an independent, intergovernmental, science- and technology-based organization that serves as the global focal point for nuclear cooperation. It was set up as the world’s “Atoms for Peace” organization in 1957 within the United Nations family. The IAEA works with its Member States and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies. The IAEA Statute, the original version of which was approved by 81 nations in 1956, outlines the three pillars of the IAEA’s work:

(i) Safeguards and Verification: The IAEA is the world’s nuclear inspectorate, with more than four decades of verification experience. Inspectors work to verify that safeguarded nuclear material and activities are not used for military purposes.

(ii) Safety and Security: The IAEA helps countries to upgrade nuclear safety and security, and to prepare for and respond to emergencies. Work is keyed to international conventions, standards and expert guidance. The main aim is to protect people and the environment from harmful radiation exposure. In the safety area, the IAEA’s activities cover nuclear installations, radioactive sources, radioactive materials in transport, and radioactive waste. A core element is setting and promoting the application of international safety standards for the management and regulation of activities involving nuclear and radioactive materials.

(iii) Science and Technology: The IAEA helps countries mobilize peaceful applications of nuclear science and technology. The work contributes to goals of sustainable development in the fields of energy, environment, health and agriculture, among others, and to cooperation in key areas of nuclear science and technology. The main areas of activity are technical cooperation, research and development and energy and electricity generation. Through its technical cooperation activities, the IAEA supports cooperative projects achieving tangible social and economic benefits for people in developing countries. Many channels and partnerships provide expert services, specialized equipment, training and other types of support.

More information can be found on the IAEA's website http://www.iaea.org.

The safety standards established by the IAEA provide support for Member States in meeting their obligations under general principles of international law. These standards also promote and assure confidence in safety and facilitate international commerce and trade. The standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories:

(i) Safety Fundamentals: These present the fundamental safety objective and principles of protection and safety, and provide the basis for the safety requirements;

(ii) Safety Requirements: An integrated and consistent set of Safety Requirements establishes the requirements that must be met to ensure protection of people and the environment, both now and in the future;

(iii) Safety Guides: These provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that is necessary to take the measures recommended (or equivalent alternative measures). The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety.

Supporting publications on protection and safety are issued in other series, in particular the IAEA Safety Reports Series. Safety Reports may describe good practices and give practical examples and detailed methods that can be used to meet safety requirements. This training manual is based closely on the structure and the content of IAEA Safety Reports Series No. 34 *Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry* [1]. The following 13 other IAEA publications are also relevant to the material provided in the training course:

(i) Fundamental Safety Principles: Safety Fundamentals SF-1 [2];

(ii) International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (the BSS): Safety Series 115 [3];

(iii) Occupational Radiation Protection: Safety Guide RS-G-1.1 [4];

(iv) Application of the Concepts of Exclusion, Exemption and Clearance: Safety Guide RS-G-1.7 [5];

(v) Predisposal Management of Radioactive Waste, Including Decommissioning: Safety Requirements WS-R-2 [6];

(vi) Management of Radioactive Waste from the Mining and Milling of Ores: Safety Guide WS-G-1.2 [7];

(vii) Decommissioning of Medical, Industrial and Research Facilities: Safety Guide WS-G-2.2 [8]

(viii) Regulatory Control of Radioactive Discharges to the Environment, Safety Guide WS-G-2.3 [9];

(ix) Assessing the Need for Radiation Protection Measures in Work Involving Minerals and Raw Materials: Safety Report 49 [10];

(x) Manual on Gamma Radiography: Practical Radiation Safety Manual IAEA-PRSM-1 [11];

(xi) Manual on Nuclear Gauges: Practical Radiation Safety Manual IAEA-PRSM-3 [12];

(xii) Workplace Monitoring for Radiation and Contamination: Practical Radiation Technical Manual IAEA-PRTM-1 (Rev.1), 2004 [13];

(xiii) Personal Protective Equipment: Practical Radiation Technical Manual IAEA-PRTM-5 [14].

2. RADIOACTIVITY AND RADIATION

This section is included for completeness and for those persons entering radiation protection from other fields, such as the safety of other hazardous material. For students with a recognized basic training in radioactivity and radiation this section should not be considered as essential reading.

2.1. BASIC ATOMIC AND NUCLEAR STRUCTURE

2.1.1. Atoms and nuclei

The simplest unit into which matter can be broken down is the atom. Atoms may stand in isolation (e.g. noble gases), may form molecules (e.g. water or air) or combine in a special solid state (e.g. semiconductors). Atoms can be regarded as having two main parts. The first part is the central core, called the nucleus, where almost all of the mass of the atom resides. Orbiting the nucleus, a great distance away (on a nuclear scale), are very small lightweight negatively charged particles called electrons. The size of an atom is about 10^{10} m (1/10 000 µm).

The nucleus of the atom consists of a tightly bound group of particles of two types, protons and neutrons. Both these particles have about the same mass, but are different in that protons have a positive charge, whereas neutrons have no charge. The simplest possible atom consists of only one proton in the nucleus, surrounded by one electron. The proton and electron charges cancel each other and the atom, as a whole, is electrically neutral (see Fig. 1).

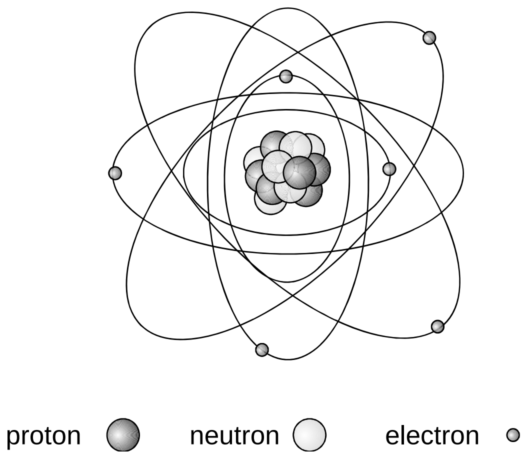

FIG. 1. Structure of an atom

2.1.2. Elements

The number of protons in the nucleus of the atom determines the identity of that element. An atom with only one proton is an atom of the element hydrogen. There are approximately one hundred known elements, and these can all be seen in the Periodic Table of the Elements (Fig. 2). A listing of some elements of interest is given in Table 1.

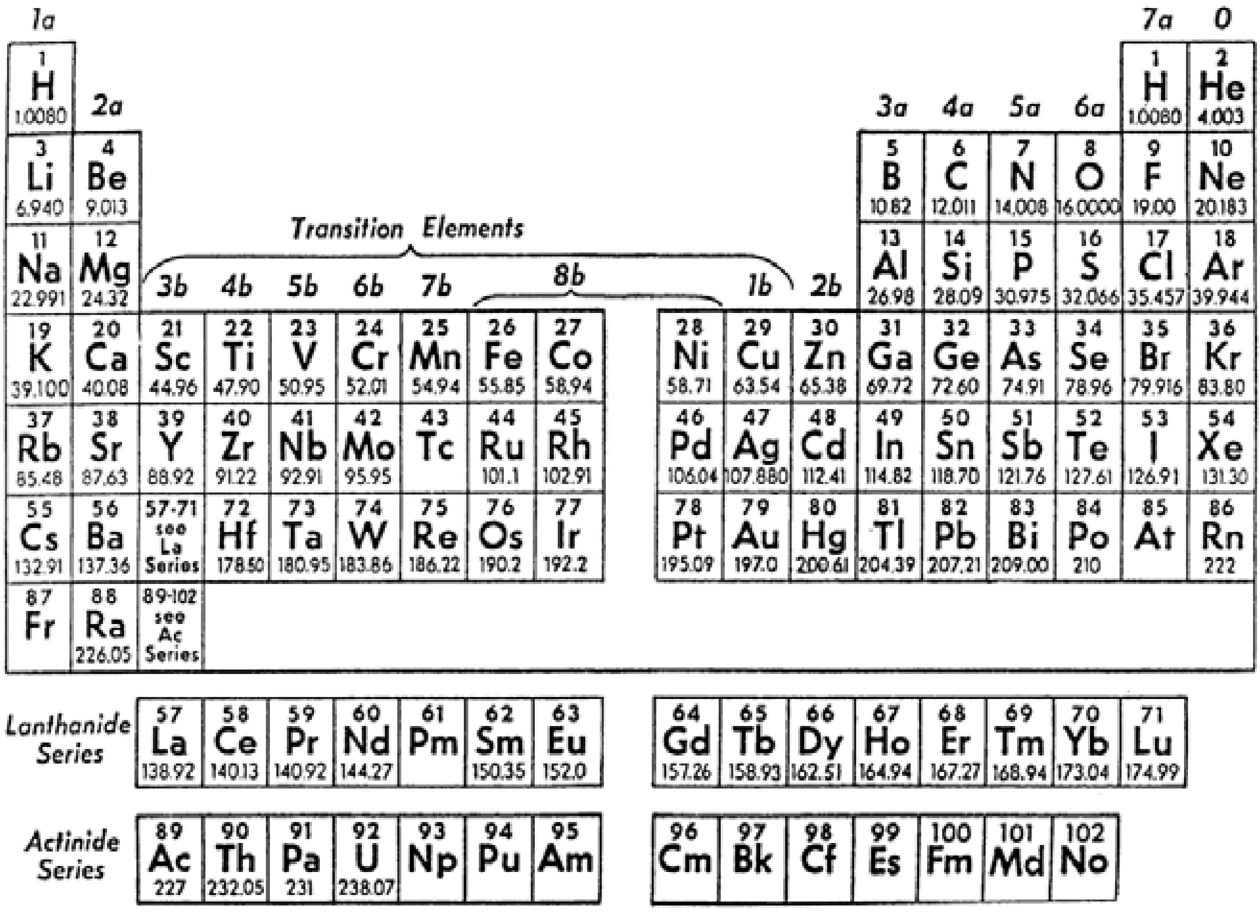

FIG. 2. Periodic table of the elements

TABLE 1. SOME ELEMENTS OF INTEREST

Atomic number	Element	Symbol
1	Hydrogen	H
2	Helium	He
6	Carbon	C
7	Nitrogen	N
8	Oxygen	O
11	Sodium	Na
14	Silicon	Si
15	Phosphorus	P
26	Iron	Fe
27	Cobalt	Co
38	Strontium	Sr
47	Silver	Ag
53	Iodine	I
55	Caesium	Cs
79	Gold	Au
82	Lead	Pb
88	Radium	Ra
92	Uranium	U
94	Plutonium	Pu

This list shows each element along with its symbol and atomic number. The atomic number is the number of protons in the nucleus. This is also the same as the number of electrons in the electrically neutral atom.

It is difficult to get a perspective on how small the nucleus is, and how most of an atom is actually the empty space between that nucleus and the electrons. A simple analogy could be to consider that if all the electrons were removed from all of the atoms in a human being, so that the nuclei could be brought together to touch each other, then it would be possible to get the nuclei of 8.3 million people into the volume of a single pinhead! However, because most of the mass is in the nuclei, this pinhead would weigh about 6×10^8 kg.

2.1.3. Isotopes

The number of neutrons may vary for a given element. Changing the number of neutrons does not essentially influence the chemical properties of the atom. But the mass of the atom changes as protons and neutrons are of roughly equal mass.

If a neutron is added to the nucleus of the simplest hydrogen atom (originally consisting of one proton and one orbiting electron), a different atom is formed. It has about twice the mass of the original atom, but is still hydrogen, as it still has only one proton. This is said to be an isotope of hydrogen, and happens to be given a special name, deuterium. If another neutron is added to the nucleus, another isotope of hydrogen, called tritium, is formed.

Some examples of isotopes are shown in Table 2.

TABLE 2. SOME EXAMPLES OF ISOTOPES

Element	Number of protons	Number of neutrons	Mass number
H (Hydrogen)	1	0	1
H-2 (Deuterium)	1	1	2
H-3 (Tritium)	1	2	3
Fe-54 (Iron)	26	28	54
Fe-56 (Iron)	26	30	56
Fe-57 (Iron)	26	31	57
Fe-58 (Iron)	26	32	58
U-235 (Uranium)	92	143	235
U-238 (Uranium)	92	146	238

2.1.4. Notation

A convention designed to enable easy reference to each isotope uses the following nomenclature:

$${}^{A}_{Z}X$$

where:

X is the element symbol;

Z is the number of protons (= atomic number);

A is the sum of the number of protons and neutrons (called the mass number).

Some examples are: ${}^{3}_{1}H$, ${}^{12}_{6}C$, ${}^{60}_{27}Co$, ${}^{238}_{92}U$.

Due to the fact that the atomic number and symbol provide the same information, the former is often omitted, for example, ${}^{3}H$, ${}^{12}C$, ${}^{60}Co$ and ${}^{238}U$. In a commonly used alternative notation they are often represented as follows, H-3, C-12, Co-60, and U-238.

2.1.5. Prefixes

In nuclear physics, it is often necessary to express very large and very small numbers. It is therefore important to become familiar with the prefixes that are listed in Table 3.

TABLE 3. PREFIXES

Multiplying factor	Prefix	Symbol	Multiplying factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-3}	milli	m
10^{21}	zetta	Z	10^{-6}	micro	μ
10^{18}	exa	E	10^{-9}	nano	n
10^{15}	peta	P	10^{-12}	pico	p
10^{12}	tera	T	10^{-15}	femto	f
10^{9}	giga	G	10^{-18}	atto	a
10^{6}	mega	M	10^{-21}	zepto	z
10^{3}	kilo	k	10^{-24}	yocto	y

2.2. RADIOACTIVITY

For any element there is a limited range in which the number of neutrons can be part of the nucleus and still be stable. If there are too few neutrons or too many neutrons in the nucleus, the atom is unstable. An unstable atom will try to become more stable by emitting energy in the form of radiation, and it is said to be radioactive.

Radioactivity can be simply defined as that process in which unstable atoms attempt to stabilize themselves by emitting radiation.

Using the previous example of hydrogen, when the nucleus consists of two neutrons and one proton (i.e. the isotope tritium), the atom is unstable and therefore radioactive. The combination of one proton and three neutrons is so unstable, that for all practical purposes it does not exist.

2.2.1. Chart of radionuclides

All of the existing known isotopes (stable and unstable) can be shown on a chart such as that in Fig. 3. Each square represents one isotope (i.e. one combination of protons and neutrons). On the left is shown the number of protons in the isotope and, along the bottom, the number of neutrons is shown. A curved line of stable isotopes can be seen by the shaded squares on the chart. This is called the line of stability. The chart itself is called the Chart of the Nuclides and is published with useful information about each isotope in its own square.

2.2.2. Radioactive decay and half-life

The further an isotope is distanced from the line of stability the more radioactive it is. When an unstable (radioactive) atom emits radiation to become more stable, it is said to disintegrate or decay. Radioactive decay is an interesting process in that it has regular and predictable aspects as well as totally random aspects. The moment at which any one particular atom decays is random and cannot be predicted. However, the time in which, on average, half of a certain (large) number of atoms of a particular isotope will decay is regular, known and entirely predictable. This is somewhat analogous to the situation in which a large number of coins are placed in a tray all with the same side down. If they are thoroughly shaken up, half of the coins will have one side up and half will have the other side up on average. However, prior to shaking, it cannot be predicted which way up any particular coin will land.

Each kind of radioactive isotope has a specific known time period in which half of the atoms will decay. This is called the half-life. If the number of atoms of a particular radioactive isotope is plotted against time, a curve such as that shown in Fig. 4 is obtained.

2.2.3. Quantities and Units

There are special quantities to characterize radioactive material:

- The *half-life* is the time after which half of a given number of radioactive nuclei has decayed. The corresponding unit is usually given in years (a), days (d), hours (h), minutes (min) or seconds (s).
- The *activity* of a radioactive material gives the number of decays per unit of time. The corresponding unit is the becquerel (Bq). The conversion of activity into dose is treated in Section 3.1. One becquerel is equivalent to one atom decaying (or disintegrating) each second.

Due to the fact that some radioisotopes decay more rapidly than others, i.e. they have a shorter half-life, equal masses of different radioisotopes can have widely differing activities. The activity per unit mass of a certain radionuclide is called the *specific activity* of that radionuclide, and is a constant. The corresponding unit that is most commonly used is becquerels per gram (Bq/g). In most cases, a certain radioactive material consists of a mixture of a radionuclide and inactive material. In these cases the term 'specific activity' is not relevant. The activity per unit mass of such a mixture depends on the mixing ratios of radionuclide and inactive material and is called the *activity concentration* (also in becquerels per gram).

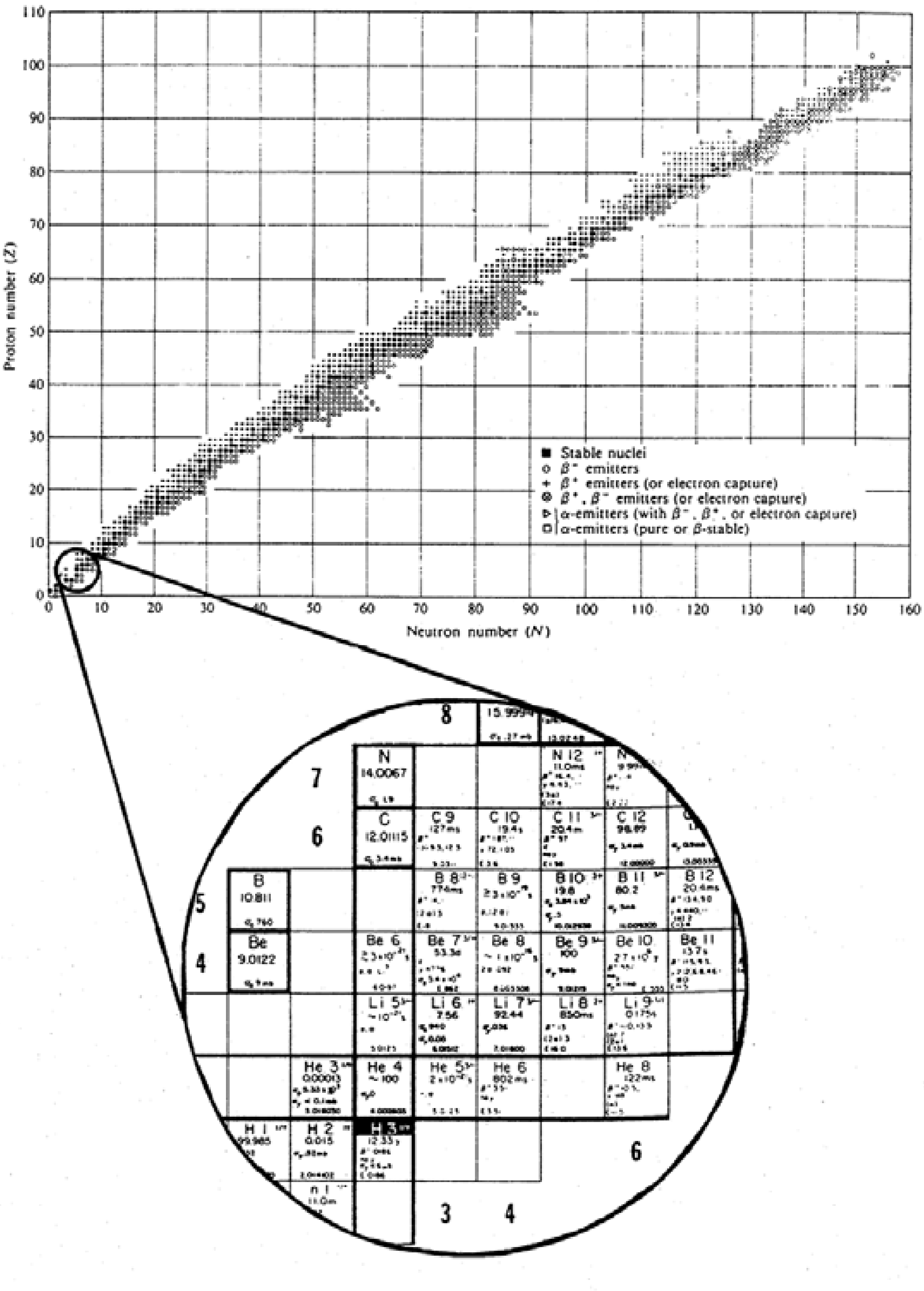

FIG. 3. Chart of radionuclides

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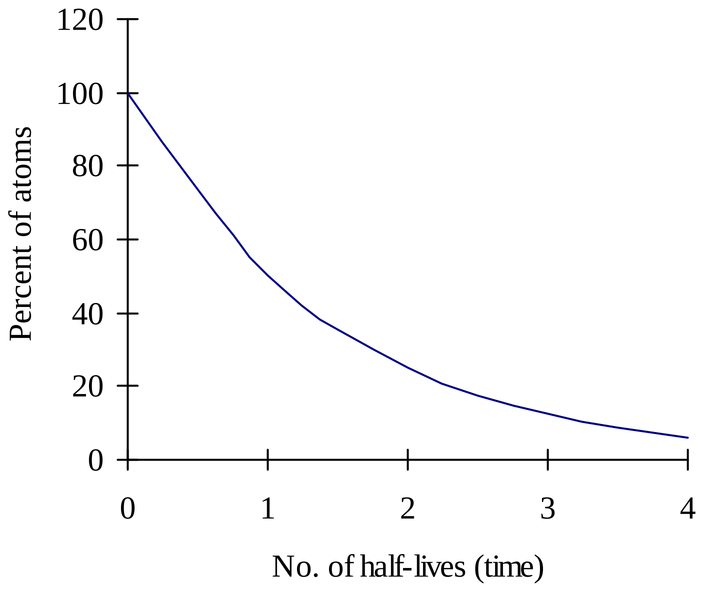

FIG. 4. Radioactive decay curve

In some cases, the half-life of a radionuclide is extremely long. Examples are ^{40}K, ^{238}U and ^{232}Th, with half-lives of 1.3×10^9, 4.5×10^9, and 1.4×10^{10} years, respectively. These half-lives are comparable to the age of the world, and a large portion of such radionuclides have decayed only partially since its formation. They are therefore called *primordial radionuclides* or *radionuclides of natural origin*. They are ubiquitous in nature and are the cause of the terrestrial background radiation.

2.2.4. Decay chains

Many radionuclides loose their surplus of energy in a single step. The resulting nuclide is stable and therefore part of the line of stability. It is also possible that the radionuclide decays via distinct separate steps. In such cases the surplus of energy of the original radionuclide is lost in a chain of several decays, before the resulting nuclide becomes ‘at rest’ on the line of stability. An example is the decay of ^{90}Sr:

$$^{90}_{38}Sr \rightarrow ^{90}_{39}Y \rightarrow ^{90}_{40}Zr$$

where:

$^{90}_{38}Sr$ is called the parent radionuclide, with a half-life of 29.1 a;

$^{90}_{39}Y$ is called the progeny radionuclide, with a half-life of 64 h;

$^{90}_{40}Zr$ is stable.

2.2.4.1. Metastable radionuclides

A specific type of decay is the formation of metastable radionuclides. In this case, the progeny radionuclide has already a stable proton/neutron combination, but still has a surplus of energy. The metastable state releases its surplus of energy only by emitting gamma radiation, and therefore there is no change in the number of protons and neutrons. The decay process itself is again of a stochastic nature, and is characterized by a specific half-life. An example is the decay of ^{81}Rb:

$$^{81}_{37}\text{Rb}\rightarrow{}^{81\text{m}}_{36}\text{Kr}\rightarrow{}^{81}_{36}\text{Kr}$$

where:

$^{81}_{37}$Rb is the parent radionuclide, with a half-life of 4.6 h;

$^{81\text{m}}_{36}$Kr is the metastable progeny radionuclide, with a half-life of 13 s;

$^{81}_{36}$Kr is stable

2.2.4.2. The natural uranium and thorium decay series

There are also much longer decay chains. The radionuclides of natural origin ^{238}U and ^{232}Th decay via a series of progeny radionuclides before they reach their stable endpoints on the line of stability. The full radioactive decay chains of these radionuclides are shown in Tables 4 and 5. In situations where the progeny radionuclide is contained in the matrix of certain minerals throughout their existence, such as for instance in geological deposits, all progeny radionuclides have the same activity as the parent, because the latter has the longest half-life. This is called radioactive equilibrium. However, when the deposit is disturbed, by leaching or processing, the decay chain may also become disturbed, as the elements to which the radioactive progeny belong may behave differently during the disturbing process.

TABLE 4. URANIUM-238 DECAY SERIES

Radionuclide	Half-life	Major mode of decay
^{238}U	4.468 × 10^9 a	Alpha
^{234}Th	24.10 d	Beta
$^{234\text{m}}$Pa	1.17 min	Beta
^{234}U	245 700 a	Alpha
^{230}Th	75 380 a	Alpha
^{226}Ra	1600 a	Alpha
^{222}Rn	3.8235 d	Alpha
^{218}Po	3.10 min	Alpha
^{214}Pb	26.8 min	Beta
^{214}Bi	19.9 min	Beta
^{214}Po	164.3 µs	Alpha
^{210}Pb	22.20 a	Beta
^{210}Bi	5.012 d	Beta
^{210}Po	138.376 d	Alpha
^{206}Pb	Stable	—

TABLE 5. THORIUM-232 DECAY SERIES

Radionuclide	Half-life	Major mode of decay
^{232}Th	1.405×10^{10} a	Alpha
^{228}Ra	5.75 a	Beta
^{228}Ac	6.15 h	Beta
^{228}Th	1.912 a	Alpha
^{224}Ra	3.66 d	Alpha
^{220}Rn	55.6 s	Alpha
^{216}Po	0.145 s	Alpha
^{212}Pb	10.64 h	Beta
^{212}Bi	60.55 min	Beta 64.06% Alpha 35.94%
^{212}Po	0.299 µs	Alpha
^{208}Tl	3.053 min	Beta
^{208}Pb	Stable	—

2.3. RADIATION

As already mentioned, an unstable nucleus will eventually become more stable by emitting particulate and/or electromagnetic radiation. The type of radiation emitted will depend on the type of instability. If a nucleus has too many neutrons for the number of protons (i.e. it is below the line of stability) it will tend to become more stable by essentially converting a neutron to a proton and emitting an electron. Electrons emitted from the nucleus are called *beta particles (β-radiation).* Typically, additional electromagnetic energy will also be emitted. Electromagnetic energy from the nucleus is called *gamma radiation (γ-radiation).*

If a nucleus has a large number of neutrons and protons, it is very heavy and will be located at the upper right end of the nuclide chart. If it has too many neutrons and protons it will be unstable, radioactive, and tend to become more stable by emitting a particle consisting of two neutrons and two protons. This particle is called an alpha particle (*α-radiation*).

It is also possible that some radioactive materials emit neutrons. If α-emitting radionuclides are mixed with material of light elements (e.g. beryllium) the nuclear reactions of the α-particles with light nuclei lead to the emission of neutrons (neutron radiation). Fission of ^{235}U will also lead to the emission of neutrons.

There are other processes in which nuclei can become unstable, and other processes by which they reach stability, but for our practical purpose the emission of alpha, beta, gamma and neutron radiation are the most important processes.

2.3.1. Ionization

There are many other types of radiation energy to which humans are exposed. These include light, heat, radio and TV waves, ultra-violet, infrared, and microwave radiation. The major distinction between these and the radiation from the nuclei of atoms is that only the latter can cause ionization.

Ionization of an atom occurs when an electron is removed from a neutral atom thereby leaving a positively charged ion (Fig. 5). This process of ionization carries advantages and disadvantages. It is advantageous in that it enables the radiation to be detected, and it also enables the radiation to be shielded. However, the disadvantage is that the ionization of atoms in the human body causes harmful biological effects.

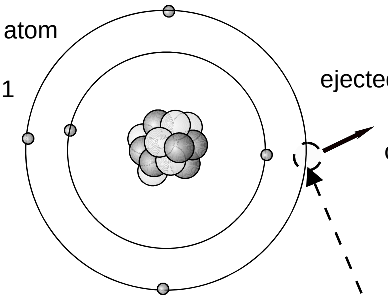

FIG. 5. The ionization process

2.3.2. Alpha radiation

An alpha particle is actually the nucleus of a helium atom because it has two protons. Due to the fact that it is a heavy particle and that it has a charge of +2, an alpha particle will give up its energy within a very short distance mostly by causing ionization. The implication of this is that alpha radiation is not very penetrating. This in turn means that it can be easily shielded. In fact most alpha particles cannot penetrate the dead layer of cells on the skin surface and therefore do not present any hazard while the alpha emitting radionuclide is external to the body. However, if the material becomes ingested or inhaled into the body then the alpha particles can ionize atoms in living cells. The rate of ionization in this case is very high and significant cell damage can occur. Another implication of the lack of penetrating power is that it makes alpha radiation difficult to detect. Special instruments with very thin windows or even without windows are required. In summary then (see Fig. 6), alpha radiation:

- Is not very penetrating, and can be shielded even by a sheet of paper;
- Is a significant internal hazard;
- Is detected only by special instruments.

2.3.3. Beta radiation

Beta particles, because they are electrons, are very much smaller and lighter than alpha particles. They are subsequently more penetrating but will travel in zigzag paths through materials. Their rate of ionization is much less than that of alpha particles. The penetration range of beta particles depends on their energy and the density of the material they are passing through. A beta particle of typical energy will not penetrate a thin sheet of metal, and will only travel about 10 mm in tissue. Hence, beta-emitting radionuclides are a hazard to skin and eyes as well as a hazard if they are incorporated into the body. Ease of detection of beta radiation depends on the energy. However, all but the lowest energies can be detected fairly easily. In summary then (see Fig. 6), beta radiation:

- Is more penetrating than alpha radiation, but can be shielded by a sheet of metal, and is an external hazard to the skin and eyes;
- Is an internal hazard;
- Its detection is dependent on the energy of the radiation.

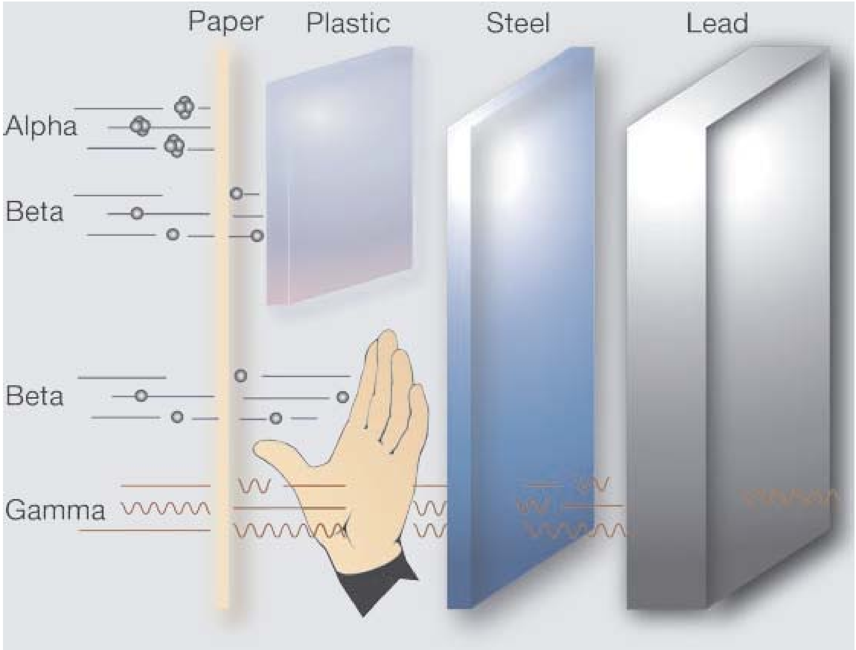

FIG. 6. The penetrating power of external radiation: alpha, beta and gamma

2.3.4. Gamma radiation

Gamma radiation is electromagnetic radiation similar to radar, radio and TV, microwave, light, ultra-violet, and infrared radiation. However, gamma radiation has higher energy, higher frequency and shorter wavelength than these similar forms of radiation. It also causes ionization whereas the others do not ionize at all. X-rays can be generally regarded as lower energy gamma rays that are machine produced instead of coming from a radioactive atom.

Gamma radiation is very penetrating depending on the energy of the radiation. High density material, or a large bulk of material, is required to shield gamma radiation. Consequently, it is relatively easy for gamma radiation to completely penetrate the body. In summary then (see Fig. 6), gamma radiation:

- Is very penetrating, but can be shielded by dense materials such as lead and steel;
- Is an external and an internal hazard;
- Is easily detected at very low levels.

2.3.5. Neutron radiation

In addition to the existence of neutrons in the nucleus, it is possible to have free neutrons as a form of radiation. Neutrons are unique among the types of radiation, in that they only have interactions with other nuclei (nuclear reactions). These interactions can be:

- Elastic scattering: For example, if the neutron hits a hydrogen atom (even in water), the moving neutron and the proton at rest behave like billiard balls. As the neutron and the proton have about the same mass, the neutron will be stopped completely in a central collision and the proton will carry away the full kinetic energy of the neutron. In non-central collisions the neutron and the proton share the kinetic energy. The neutron is slowed down.
- Inelastic scattering: A part of the kinetic energy of the neutron is absorbed by the target nucleus that in turn emits γ radiation.
- Neutron capture: The neutron is captured by a nucleus forming a new isotope of the nucleus with which it interacted. This is called neutron activation, because the resulting nuclei are radioactive and emit a characteristic γ radiation.
- Other types of nuclear reactions are possible, including fission.
- Neutrons are very penetrating and the ease with which they can be shielded and detected depends heavily on their energy. They can cause significant cell damage by indirect ionization and other processes as they pass through the body.

In summary then, neutron radiation:

- Is very penetrating, but can be shielded by hydrogenous material for fast neutrons, and by cadmium or boron for slow thermal neutrons;
- Is an external and internal hazard;
- Is detected only with special instruments.

3. RADIATION PROTECTION PRINCIPLES

The International Basic Safety Standards for Protection against Ionizing Radiation and the Safety of Radiation Sources (the BSS) [3] was published by the IAEA in 1996 and is the key international standard in relation to radiation protection. The BSS is based on the recommendations of the International Commission on Radiological Protection (ICRP), principally those set out in ICRP Publication 60 [15], and was prepared jointly by the Food and Agriculture Organization of the United Nations, the IAEA, the International Labour Organization, the Nuclear Energy Agency of the Organization for Economic Co-operation and Development, the Pan American Health Organization and the World Health Organization.

In 2007, the ICRP published, in Publication 103 [16], revised recommendations that take account of the latest available scientific information of the biology and physics of radiation exposure. These revised recommendations are based on a situation-based approach using planned, emergency and existing exposure situations rather than the process-based approach using practices and interventions in ICRP 60. As a consequence, there are some changes in terminology but the fundamental radiation protection principles remain the same. The new ICRP recommendations will be taken into account in the next version of the BSS, which is currently under development. The material presented in this training manual, and specifically in this section, is consistent with the current BSS, but uses the terminology of ICRP Publication 103.

For students with recognized training in radiation protection based on the BSS, this section should not be considered as essential reading.

3.1. SOME QUANTITIES AND UNITS

3.1.1. Absorbed dose

When radiation strikes a material, it will deposit energy in that material through a variety of interactions (e.g. ionization). A measure of the amount of radiation that a material has received is the quantity called absorbed dose. Absorbed dose, D, is the amount of energy deposited per unit of mass as a result of the interplay of ionizing radiation (this includes neutron radiation), and matter. The unit of absorbed dose is the gray (Gy), which is equal to an energy deposition of 1 J/kg. However, because energy deposition varies for different materials, the material also needs to be specified, for example as “ in air”, “in water”, “in an organ” or “in tissue”.

One difficulty with the use of absorbed dose for radiation protection purposes is that the biological effect of an absorbed dose in tissue is dependent on the type and energy of the incident radiation. To overcome this difficult, a quantity called equivalent dose is used.

3.1.2. Radiation weighting factors and equivalent dose

To take account of the radiation quality of interest, a weighting factor called the radiation weighting factor, w_R is used. The equivalent dose in tissue, H_T, is given by the expression:

$$H_T = \sum_R w_R . D_{T,R}$$

where:

$D_{T,R}$ is the absorbed dose averaged over the tissue or organ, T, due to radiation R.

Since w_R is dimensionless, the unit of equivalent dose is the same as that for the absorbed dose, namely J/kg, but to avoid confusion it has been given the special name sievert (Sv).

The value of the radiation weighting factor for a specified type and energy of radiation has been selected by the ICRP to be representative of values of the relative biological effectiveness of that radiation in inducing stochastic health effects at low doses. Cancer induction is an example of a stochastic effect, in that the probability of the effect is a function of the dose received. Some of the values of w_R are shown in Table 6.

TABLE 6. RECOMMENDED RADIATION WEIGHTING FACTORS [16]

Radiation type	w_R
Photons	1
Electrons	1
Protons	2
Alpha particles	20
Neutrons	A continuous function of neutron energy, E_n (see also Fig. 7):
	$2.5 + 18.2e^{-[\ln(E_n)]^2/6}$ for $E_n < 1$ MeV*
	$5.0 + 17.0e^{-[\ln(2E_n)]^2/6}$ for 1 MeV $\leq E_n \leq$ 50 MeV
	$2.5 + 3.25e^{-[\ln(0.04E_n)]^2/6}$ for $E_n > 50$ MeV

* MeV is the kinetic energy of the neutron. 1 MeV = 1.602×10^{-13} J.

3.1.3. Tissue weighting factors and effective dose

There are circumstances where doses to individual organs can be assessed (e.g. for the purpose of determining limits on the ingestion or inhalation of radioactive material). Thus a method is needed to combine the organ doses to give either an overall measure of the dose or an assessment of the biological risk. To do this, tissue weighting factors, w_T, have been determined that take account of the relative radiosensitivity of different tissues (T). The effective dose, E, is given by

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

Tissue weighting factors are shown in Table 7. The values in Table 7 have been developed from a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose, they apply to workers, to the whole population and to either sex. The ICRP has, however, not yet published new dose coefficients based on these new weighting factors. Therefore, the dose coefficients currently published in the BSS for verification of compliance with dose limits (see Section 3.3.6) are still valid, even though they are based on the previous weighting factors of ICRP Publication 60 [15].

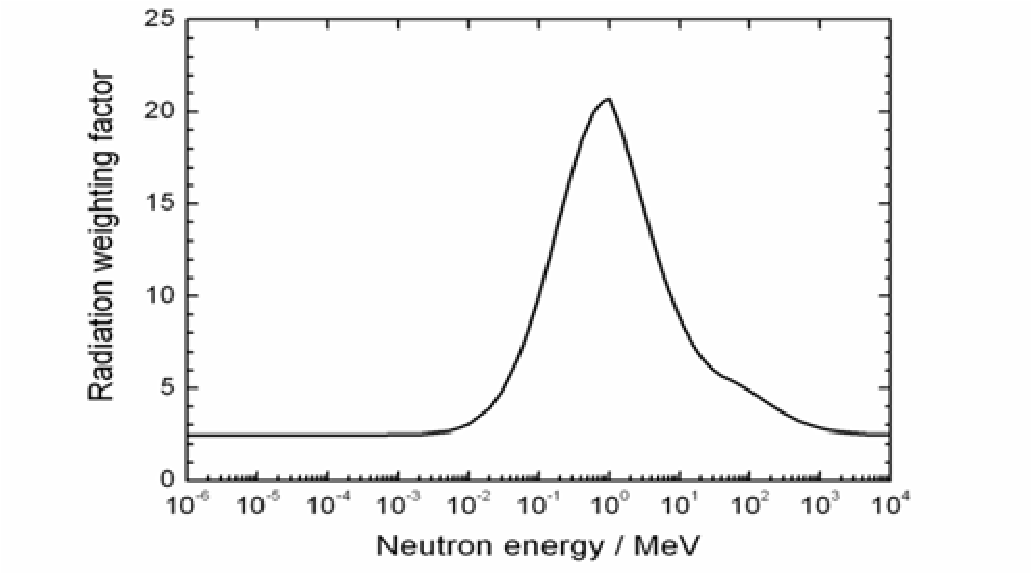

FIG. 7. Radiation weighting factor, w_R, for neutrons versus neutron energy

TABLE 7. RECOMMENDED TISSUE WEIGHTING FACTORS [16]

Tissue	w_T
Bone marrow (red), colon, lung, stomach, breast, remainder tissues*	0.12
Gonads	0.08
Bladder, oesophagus, liver, thyroid	0.04
Bone surface, brain, salivary glands, skin	0.01
Total	1.00

* Remainder tissues: adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀).

3.1.4. Committed equivalent dose and committed effective dose

The committed equivalent dose is a quantity that takes into account the time that a radionuclide will be resident in a person’s body. When radioactive material is deposited inside the body, the various tissues of the body are committed to a certain dose. The magnitude of this dose is a function of many factors including the radionuclide, its half-life, and the metabolism of the element in the body. For the purpose of determining annual intake limits for *occupationally exposed adults*, the convention is adopted of assessing the total equivalent dose to an organ that will accrue in the 50 years following an intake of a radionuclide. The dose commitment assessed in this way is known as the committed equivalent dose, $H_T(50)$. For *members of the public*, the time period is 50 years for adults and to age 70 years for infants and children.

The summation of the committed equivalent dose in each significant organ or tissue multiplied by its weighting factor gives the committed effective dose. Thus, for adults:

$$E(50) = \sum_T w_T . H_T (50)$$

3.1.5. Collective equivalent dose and collective effective dose

In discussion of the effects of radiation on human populations, a number of collective quantities are useful. The collective equivalent dose, S_T, is the summation of the individual equivalent doses received by a group of people.

The collective effective dose, S, is similarly defined except that the effective dose is used in the summation. The unit of both of these quantities is man-sievert (man-Sv). A given source or practice may give rise to a collective effective dose rate which varies as a function of time. The collective effective dose commitment is the integral of this over time.

3.1.6. Operational quantities

One of the quantities in radiation protection for limiting the exposure of persons is *effective dose.* There is no technical instrument that has such a complicated response to radiation as living organs have in a human body. Therefore, it is necessary to find instruments that give an estimate of the *effective dose.* That means that the *effective dose* as such is no longer measured, but other quantities are measured instead. Suitable technical instruments can measure these so-called *operational quantities.*

The *operational quantities* taken for radiation protection are *ambient dose equivalent,* relating to strongly penetrating radiation (gamma or neutron radiation), or *directional dose equivalent,* relating to weakly penetrating radiation (alpha and beta radiation).

3.2. BIOLOGICAL EFFECTS

The upper end of the range of interest for dose and dose rate can best be illustrated by reference to those levels required to cause short term biological effects.

3.2.1. Short term biological effects

Biological effects of radiation vary greatly depending on such factors as the amount of exposure, rate of exposure, area of body irradiated, type of radiation and individual biological variability.

Relatively large doses of radiation are required to produce short term biological effects. At high dose rates, the appropriate dose quantity is absorbed dose (Gy). The radiation weighting factors, w_R, given in Table 6 and the tissue weighting factors, w_T given in Table 7 are appropriate only for low doses.

If enough individual cells are damaged by ionizing radiation, then specific clinical symptoms will be evident. Most of these symptoms and effects can be classified as deterministic. A deterministic effect is one in which the *severity* of the effect is a function of the dose, and there is a threshold below which there is no clinically observable effect. Fig. 8 illustrates the form of this relationship. This curve shows that up to a certain dose the effect is negligible. As the dose increases, the effect increases up to a point where there is some maximum effect.

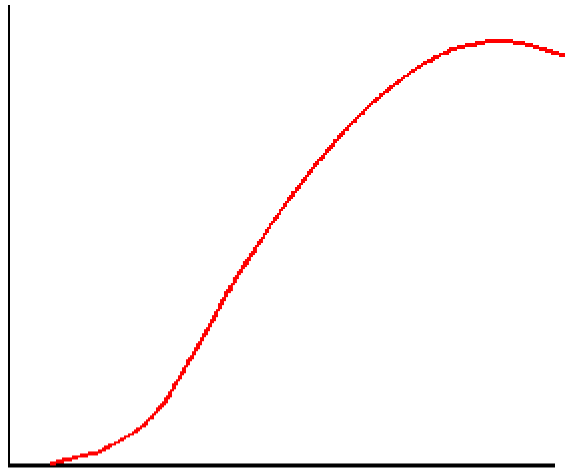

FIG. 8. Deterministic effects

Radiation sickness is characterized by a group of symptoms that includes diarrhoea and vomiting, nausea, lassitude, haemorrhaging, emaciation, infection and, ultimately, death. The onset and severity of these symptoms is mainly a function of dose.

Table 8 gives a broad indication of the dose levels for certain short term effects following *whole body* irradiation over a short period of time. If only part of the body is irradiated it would require much larger doses to produce the same effect.

TABLE 8. DOSES FOR ACUTE BIOLOGICAL EFFECTS

Effect	Dose (Gy)
No discernible effect	0.25
Blood changes, no illness	1.0
Radiation sickness, no deaths	2.0
Death to 50% of irradiated people	4.5
Death to 100% of irradiated people	10.0

3.2.2. Long term biological effects

The major long term biological effects from smaller doses received over a longer period of time are the increased risks of cancer and severe hereditary effects in progeny.

3.2.2.1. Cancer

Cancer induction is a stochastic effect, in that the *probability* of the effect is a function of dose, perhaps with no threshold. The shape of the dose response function is uncertain. It is probably sigmoidal in shape, but is often conservatively assumed to be linear through the origin, giving rise to the so-called ‘linear no-threshold’ (LNT) approach to radiation protection. The forms of the two relationships are illustrated in Fig. 9.

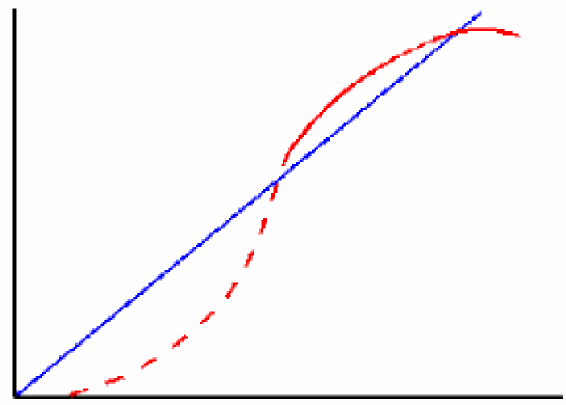

FIG. 9. Stochastic effects

Some organs are more sensitive to cancer induction than others. The sensitivities for different organs are given by the tissue weighting factors. All radiation-induced cancers have some long latent period before they appear.

For doses over about 100 mSv or for high dose rates, the cancer fatality risk is reasonably well known from observations of the survivors of the atomic bomb attacks on Hiroshima and Nagasaki. International bodies such as ICRP and UNSCEAR quantify this risk at about 10 fatalities per 100 man-Sv.

At doses lower than this, or at low dose rates, the situation is much less clear. However, it seems that the risk is lower by about a factor of two. UNSCEAR recommends the use of a dose and dose-rate effectiveness factor (DDREF) of 2 to project the cancer risk determined at high doses and high dose-rates to risks that would apply at low doses and low dose-rates. This reduces the risk to a value of about five latent cancer fatalities per 100 man-Sv at doses less than 100 mSv (see Table 9 for the nominal risk coefficients). This means that if 10 000 people were exposed to a total dose of 10 mSv in a short period of time, five of them may die in years to come due to a cancer induced by that dose. However, in that population of 10 000, about 2000 persons could eventually be expected to die from cancer induced by other mechanisms.

3.2.2.2. Genetic effects

In epidemiology, hereditable effects of radiation in humans have not been detected with a statistically significant degree of confidence. However, there is compelling evidence that radiation causes heritable effects in experimental animals. It is therefore prudent to assume also the existence of hereditary effects in humans. Risk estimation therefore rests on genetic experimentation with a wide range of organisms and on cellular studies, with limited support from the negative human findings. With this in mind, ICRP estimates the risk of hereditable effects at 0.2×10^{-2} per Sv [16].

3.2.3. The linear non-threshold dose-response relationship

The basic philosophy of radiation protection, as developed by the ICRP, is to avoid short term biological effects and to restrict long term biological effects to an acceptable level. It is based on the assumption that, at doses below about 100 mSv, a given increment in dose will produce a directly proportional increment in the probability of incurring cancer or heritable effects attributable to radiation. The ICRP considers that the application of the LNT approach combined with a judged value of the DDREF provides a prudent base for purposes of practical radiation protection, i.e. the management of risks from low-dose radiation exposure in prospective situations.

The nominal risk coefficients that have been derived in ICRP Publication 103 are given in Table 9.

TABLE 9. NOMINAL RISK COEFFICIENTS (10^{-2} Sv^{-1}) FOR STOCHASTIC EFFECTS AFTER EXPOSURE TO RADIATION AT LOW DOSE RATE [16]

Exposed population	Cancer	Heritable effects	Total
Whole	5.5	0.2	5.7
Adult	4.1	0.1	4.2

3.3. THE SYSTEM OF RADIATION PROTECTION

The system of radiation protection is embodied in a set of radiation protection requirements contained in the BSS [3]. In the next sections, the system of radiation protection as described in the BSS is given. However, where appropriate, the terminology of ICRP Publication 103 is used [16].

3.3.1. Exposure situations

Three types of exposure situation are defined in ICRP Publication 103 for the purposes of establishing radiation protection principles, namely, *planned exposure situations, emergency exposure situations* and *existing exposure situations*.

3.3.1.1. Planned exposure situations

Planned exposure situations are situations involving the deliberate introduction and operation of radiation sources. Planned exposure situations may give rise both to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur (potential exposures), i.e. adding radiation exposure to that which people normally receive from existing radiation sources, or that increase the likelihood of their incurring exposure. In these situations, radiation protection can be planned in advance, before exposures occur, and the magnitude and extent of the exposure can be reasonably predicted. In the BSS, planned exposure situations are generally addressed by referring to the term ‘practices’. In introducing a planned exposure situation all aspects relevant to radiation protection should be considered, i.e. design, construction, operation, decommissioning, waste management, and remediation of contaminated land and facilities.

3.3.1.2. Emergency exposure situations

Emergency exposure situations are situations that may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected situation, and require urgent action in order to avoid or reduce undesirable consequences. Exposure of members of the public or of workers, as well as environmental contamination can occur in these situations. Response actions should be planned because potential emergency exposure situations can be assessed in advance, to a greater or lesser accuracy depending upon the type of installation or situation being considered. In the BSS, emergency exposure situations are addressed under the heading "Intervention".

Emergency exposure situations require protective action to reduce or avert temporary exposures. These situations include:

(i) Accidents and emergencies in which an emergency plan or emergency procedures have been activated;

(ii) Any other temporary exposure situation identified by the regulatory body or the intervening organization as warranting intervention.

In planning for emergency situations, reference levels should be applied as part of the process of optimization.

3.3.1.3. Existing exposure situations

Existing exposure situations are exposure situations that already exist when a decision on control has to be taken, including prolonged exposure situations after emergencies. There are many types of existing exposure situations that may cause exposures high enough to warrant radiation protection actions, or at least their consideration. Exposures to natural sources of radiation, including radon in dwellings and workplaces, are well-known examples. But there are also man-made existing exposure situations, such as residues in the environment resulting from emissions of radionuclides from operations in the past that were not under regulatory control, and contaminated land resulting from an accident.

Radiation protection actions in existing exposure situations are addressed in the BSS as 'chronic exposure situations' under the heading "Intervention".

Existing exposure situations requiring remedial action to reduce or avert chronic exposure, include:

(i) Exposure to natural sources, such as radon in buildings and workplaces;

(ii) Exposure to radioactive residues from past events, such as to the radioactive contamination caused by accidents, after the situation requiring protective action has been terminated, as well as from the conduct of practices and the use of sources not under the system of notification and authorization;

(iii) Any other chronic exposure situation specified by the regulatory body or the Intervening Organization as warranting intervention.

As in the case of emergency exposure situations, reference levels should be applied in the process of optimization.

There are also existing exposure situations for which it is obvious that actions to reduce doses are not warranted. The decision as to what components of existing exposure are not amenable to control requires the judgement of the regulatory body or other national authority, taking into account the controllability of the source and economic, societal and cultural circumstances.

3.3.2. Exposure categories

The BSS distinguishes between three categories of exposures: occupational exposure, public exposure, and medical exposure of patients.

3.3.2.1. Occupational exposure

The BSS defines occupational exposure as *"All exposures of workers incurred in the course of their work, with the exception of exposures excluded from the Standards and exposures from practices or sources exempted by the Standards"*. Exposures of pregnant workers are controlled such that the embryo or foetus is afforded the same broad level of protection as required for members of the public.

3.3.2.2. Public exposure

Public exposure encompasses all exposures of the public other than occupational exposure and medical exposure of patients. A broad range of different natural and man-made radiation sources contribute to the exposure of members of the public. The component of public exposure due to natural sources is by far the largest. This, however, provides no justification for reducing the attention paid to smaller, but more readily controllable, exposures to man-made sources.

3.3.2.3. Medical exposure of patients

Radiation exposure of patients occurs in diagnostic, interventional and therapeutic procedures. The exposure is intentional and for the direct benefit of the patient. The features of radiological practices in medicine, particularly in radiotherapy where high-dose biological effects such as cell killing are used to treat cancer and other diseases, require a radiation protection approach which differs from that in other planned exposure situations. Radiation protection of patients is outside the scope of this training manual.

3.3.3. Principles

For proposed and continuing planned exposure situations, the system of protection is based on the general principles given below:

(i) Practices should produce sufficient benefit to offset the radiation harm that they may cause *(justification)*;

(ii) In relation to any particular source within a practice, the magnitude of the individual doses, the number of people exposed, and the likelihood of exposures where they are not certain to be received, should be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses to individuals (*dose constraints*), or the risks to individuals in the case of potential exposures (*risk constraints*), so as to limit the disparity likely to result from the inherent economic and social judgements (the *optimization* of protection);

(iii) For sources within practices, individual doses are subject to dose limits.

3.3.4. Justification

ICRP Publication 103 [16] refers to the principle of justification by stating: *"Any decision that alters the radiation exposure situation should do more good than harm"*. It means that by introducing a new radiation source, by reducing existing exposure, or by reducing the risk of potential exposure, one should achieve sufficient individual or societal benefit to offset the detriment it causes. The expected change in radiation detriment should be explicitly included in the decision-making process. The consequences to be considered are not confined to those associated with radiation. They include also other risks, costs and benefits of the human activity, and in practice the radiation detriment may only be a small part of the justification process.

There are two different approaches to applying the principle of justification. The first approach is used in the introduction of new practices, where radiation protection is planned in advance and the necessary actions can be taken at the source. In these situations the introduction should produce sufficient net benefit to the exposed individuals or to society to offset the radiation detriment.

The second approach is used where exposures can be controlled mainly by modifying the exposure pathways, and not by acting directly on the source. The main examples are existing and emergency exposure situations, where the application of the justification principle implies decision-making to take action to avert further exposure. Any decision to reduce doses has some disadvantages, and should be justified in the sense that it should do more good than harm.

In accordance with the ICRP recommendations, the BSS states that, *"No practice or source within a practice should be authorized unless the practice produces sufficient benefit to the exposed individuals or to society to offset the radiation harm that it might cause; that is, unless the practice is justified, taking into account social, economic and other relevant factors"*. Thus, all the merits and harm associated with the practice and the possible alternatives under consideration should be taken into account in reaching the decision.

3.3.5. Optimization

The principal of optimization of protection, with constraints on the magnitude of individual dose and risk, is central to the system of protection, and is intended for application to those situations that have been deemed to be justified. It applies to all three exposure situations, i.e. to planned, existing and emergency situations. ICRP Publication 103 defines optimization as the source-related process to keep the likelihood of incurring exposures, the number of people exposed, and the magnitude of individual doses *as low as reasonably achievable (ALARA)*, taking economic and societal factors into account.

A wide range of techniques is available to optimize radiation protection. Some of these techniques are drawn from operational research, some from economics, and some from engineering. The techniques available include procedures based on cost-benefit analysis. It is important to recognize that other techniques, some quantitative, others qualitative, may also be used in the optimization of radiation protection. In the past, the ICRP has provided recommendations on how to apply the optimization principle in several documents, and these recommendations are stated in ICRP Publication 103 as remaining valid.

The BSS addresses the requirement for optimization by stating: *"In relation to exposures from any particular source within a practice, except for therapeutic medical* *exposures, protection and safety shall be optimized in order that the magnitude of individual doses, the number of people exposed and the likelihood of incurring exposures all be kept as low as reasonably achievable, economic and social factors being taken into account, with the restriction that the doses to individuals delivered by the source be subject to dose constraints"*.

The IAEA provides guidance on how to apply optimization in occupational radiation protection. In Safety Guide RS-G-1.1 [4], it is stated that *"From the practical viewpoint, the optimization principle calls for an approach that:*

(a) Considers all possible actions involving the source(s) and the way workers operate with or near the source(s);

(b) Implies a 'management by objective' process with the following sequence: setting objectives, measuring performance, evaluating and analysing performance to define corrective actions, and setting new objectives;

(c) Can be adapted to take into account any significant change in the state of techniques, the protection resources available, or the prevailing social context;

(d) Encourages accountability, such that all parties adopt a responsible attitude to the process of eliminating unnecessary exposures.

To implement optimization, it is recommended in Safety Guide RS-G-1.1 that the following points be taken into account:

(i) The resources available for protection;

(ii) The distribution of individual and collective exposure among different groups of workers, and between workers and members of the public;

(iii) The probability and magnitude of potential exposure;

(iv) The potential impact of protection actions on the level of other (non-radiological) risks to workers or members of the public.

In practice, and particularly in day to day operations, there will be limited opportunity to undertake complex quantitative calculations to determine what is optimal, and professional judgements may need to be made on a qualitative and, sometimes, intuitive basis. There are nevertheless a number of situations where the formal techniques such as cost-benefit analysis can provide a valuable aid to decision-making in radiation protection. Their application is most likely in circumstances where the decisions are complex and the expenditure potentially large.

3.3.6. Dose limits

The BSS states that, for practices: *"The normal exposure of individuals shall be restricted so that neither the total effective dose nor the total equivalent dose to relevant organs or tissues, caused by the possible combination of exposures from authorized practices, exceeds any relevant dose limit specified in Schedule II, except in special circumstances provided for in Appendix I. Dose limits shall not apply to medical exposures from authorized practices."*

3.3.6.1. Individual dose limits

It is important to recognize that dose limits are set so that any continued exposure just above the dose limits would result in additional risks that could be reasonably described as "unacceptable" in normal circumstances. There are basically two objectives in limiting dose. The first is to keep doses below the threshold level for deterministic effects and the second is to keep the risk of stochastic effects at a tolerable level. The stochastic effects occur at considerably lower doses and are therefore the basis for dose limitation. The dose limits prescribed in the BSS are summarized in Table 10.

TABLE 10. DOSE LIMITS IN PLANNED EXPOSURE SITUATIONS

Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over five consecutive years; 50 mSv in any single year	1 mSv in a year[a]
Equivalent dose		
Eye lens	150 mSv in a year	15 mSv in a year
Skin	500 mSv in a year	50 mSv in a year
Hands and feet	500 mSv in a year	–

[a] In special circumstances, an effective dose of 5 mSv, provided that the average dose over five consecutive years does not exceed 1 mSv per year.

3.3.6.2. Potential exposures and risk limits

Not all exposures occur as predicted. There may be accidental departures from planned operating procedures, or equipment may fail. Such events can be foreseen and their probability of occurrence estimated, but they cannot be predicted in detail. The individual and collective harm resulting from an exposure that is not certain to occur should be included in the system of radiation protection. Ideally, dose limits should be supplemented by risk limits that take account of both the probability of incurring a dose and the harmful effects of that dose if it were to be received.

3.3.7. Dose constraints

A dose constraint is a prospective and source-related value of individual dose from a source in planned exposure situations that serves to define the range of options to be considered in the optimization of protection for that source. It is a level of dose above which it is unlikely that protection is optimized for a given source of exposure and for which, therefore, action should usually be taken. The necessary action includes determining whether protection has been optimized, whether the most appropriate dose constraint has been selected and whether further steps to reduce doses to acceptable levels would be appropriate. For public exposure, the dose constraint is an upper bound on the annual doses that members of the public should receive from the planned operation of any controlled source. The dose constraint for each source is intended to ensure that the sum of the doses to the critical group from all controlled sources remains within the dose limit.

For planned exposure situations, the BSS states that *"except for medical exposures, the optimization of the protection and safety measures associated with any particular source within a practice shall be subject to dose constraints that:*

(a) *do not exceed either the appropriate values established or agreed to by the Regulatory Authority for such a source or values which can cause the dose limits to be exceeded; and*

(b) *ensure, for any source (including radioactive waste management facilities) that can release radioactive substances to the environment that the cumulative effects of each annual release from the source be restricted so that the effective dose in any year to any member of the public, including people distant from the source and people of future generations, is unlikely to exceed any relevant dose limit, taking into account cumulative releases and the exposures expected to be delivered by all other relevant sources and practices under control."*

3.3.8. Reference levels

For emergency and existing exposure situations, reference levels represent the level of dose, or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and for which protective actions should be planned and optimized. The chosen value for a reference level will depend upon the prevailing circumstances of the exposure situation under consideration.

A reference level is also defined more broadly as an action level, intervention level, investigation level or recording level. Such levels are helpful in the management of operations as 'trigger levels' above which some specified action or decision should be taken. They may be expressed in terms of measurable quantities or in terms of any other quantities to which measured quantities can be related.

3.3.8.1. Action level

An action level is *'The level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations'*. Action levels often serve to protect members of the public, but they also have relevance in the context of occupational exposure in chronic exposure situations, particularly those involving exposure to radon in workplaces. In terms of ICRP 103 the concept of action levels has now been superseded by a different concept, which is called simply a 'reference level'.

3.3.8.2. Intervention level

An intervention level is *'The level of avertable dose at which a specific protective action or remedial action is taken in an emergency exposure situation or chronic exposure situation'*. The use of this term is normally confined to interventions related to the protection of members of the public.

3.3.8.3. Investigation level

An investigation level is *'The value of a quantity such as effective dose, intake, or contamination per unit area or volume at or above which an investigation should be conducted'*. If investigation levels are exceeded, a review of the appropriate protection arrangements should be initiated to address the cause.

3.3.8.4. Recording level

A recording level is *'A level of dose, exposure or intake specified by the regulatory body at or above which values of dose, exposure or intake received by workers are to be entered in their individual exposure records'*.

3.4. NORMAL LEVELS OF EXPOSURE

In order to have some perspective on the significance of certain radiation doses and dose rates, a scale of reference is needed. Giving the lower and upper ends of the dose rate range of interest, together with significant values from a regulatory viewpoint provides this scale. The lower end of the range is best provided by reference to normal, everyday levels of exposure to both natural and man-made background radiation.

3.4.1. Natural background radiation

All living organisms are continually exposed to ionizing radiation, which has always existed naturally. The sources of that exposure are cosmic rays that come from outer space and from the surface of the sun, terrestrial radionuclides that occur in the earth's crust, in building materials and in air, water and foods and in the human body itself. Some of the exposures are fairly constant and uniform for all individuals everywhere, for example, the dose from ingestion of potassium-40 in foods. Other exposures vary widely depending on location. Cosmic rays, for example, are more intense at higher altitudes, and concentrations of uranium and thorium in soils are elevated in localized areas. Exposures can also vary as a result of human activities and practices. In particular, the building materials and design of houses and their ventilation systems strongly influence indoor levels of the radioactive gas radon and its decay products, which contribute significantly to doses through inhalation.

The 2000 report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [17] provides data on natural background radiation. The results are presented in Table 11. The exposure components have been added to provide an estimate of the global average exposure. The global average exposure does not pertain to any individual, since there are wide distributions of exposures from each source. The consequent effective doses combine in various ways in each location, depending on the specific concentration of radionuclides in the environment and in the body, the latitude and altitude of the location and many other factors. The annual global per caput effective dose due to natural radiation sources is 2.4 mSv. However, the range of individual doses is wide. In any large population about 65% would be expected to have annual effective doses between 1 mSv and 3 mSv, about 25% of the population would have annual effective doses less than 1 mSv and 10% would have annual effective doses greater than 3 mSv.

3.4.2. Artificial sources of radiation

In addition to natural background, people are exposed to various artificial radiation sources. By far the largest contribution to artificial sources is the medical use of radiation in diagnosis. UNSCEAR quotes the estimated annual dose from this source in its 2000 report to be about 0.4 mSv per caput worldwide, but there is an upward trend in such exposures, reflecting the more widespread use and availability of medical radiation services throughout the world.

The exposure of the world's population from nuclear test explosions in the atmosphere was considered to be quite dramatic at the time of the most intensive testing (1958–1962), when it was realized how widespread it had been. The practice resulted in the unrestrained release of large amounts of radioactive materials directly into the atmosphere. Of all man-made practices or events, atmospheric nuclear testing involved the largest releases of radionuclides into the environment. The annual doses reached, on average, 7% of the natural background at their maximum in 1963. Residual levels of longer-lived radionuclides still present in the environment contribute little to the current annual exposure of the world population.

TABLE 11. ANNUAL EFFECTIVE DOSE FROM NATURAL BACKGROUND RADIATION [17]

	Effective Dose (mSv/y)	
	Worldwide Average	Typical Range
External:		
Cosmic rays	0.39	0.3–1.0[a]
Terrestrial gamma rays	0.48	0.3–0.6[b]
Internal:		
Inhalation (mostly radon)	1.26	0.2–10[c]
Ingestion	0.29	0.2–0.8[d]
Total	2.4	1–10

[a] Range from sea level to high ground elevation.
[b] Depending on radionuclide composition of soil and building materials.
[c] Depending on indoor accumulation of radon gas.
[d] Depending on radionuclide composition of foods and drinking water.

Radiation doses from the various sources of exposure received by the world population are compared in Table 12 [17]. The values given in Table 12 are the annual doses averaged over the world population, which are not necessarily the doses that any one individual would experience. Because of considerable variations in exposures, depending on location, personal habits, diet, and so on, doses to individuals differ.

TABLE 12. DOSE PER CAPUT IN 2000 FROM NATURAL AND MAN-MADE SOURCES [17]

	Worldwide annual effective dose per caput (mSv)	Range or trend in exposure
Natural background	2.4	Typically 1-10 mSv, depending on circumstances at particular locations, with sizeable populations also at 10-20 mSv
Diagnostic medical examinations	0.4	Ranges from 0.04-1.0 mSv at lowest and highest levels of health care
Atmospheric nuclear testing	0.005	Has decreased from a maximum of 0.15 mSv in 1963. Higher in northern hemisphere and lower in southern hemisphere
Chernobyl accident	0.002	Has decreased from a maximum of 0.04 mSv in 1986 (average in northern hemisphere). Higher at locations nearer accident site
Nuclear power production	0.0002	Has increased with expansion of programme but decreased with improved practice

4. BASIC CONCEPTS OF OCCUPATIONAL RADIATION PROTECTION

4.1. OCCUPATIONAL EXPOSURE

As described in section 3.3.2.1, the BSS [3] defines occupational exposure as *"All exposures of workers incurred in the course of their work, with the exception of exposures excluded from the Standards and exposures from practices or sources exempted by the Standards"*. It is these occupational exposures that should be the responsibility of the operating management.

Excluded exposures are those that are essentially unamenable to control. Examples of such exposures given in the BSS are those from potassium-40 in the body, from cosmic rays at the earth's surface, and from unmodified concentrations of radionuclides in most raw materials.

The main criterion for exemption is that the radiation risks to individuals caused by the exempted practice or source be sufficiently low as to be of no regulatory concern.

4.2. CONTROL OF EXPOSURE TO EXTERNAL RADIATION

One of the key principles of radiation protection is the optimization of protection, in terms of which "…..the magnitude of individual doses, the number of people exposed and the likelihood of incurring exposures all be kept as low as reasonably achievable, economic and social factors being taken into account….." [4]. The dose received is the product of the dose rate and the time exposed:

Dose = Dose rate × Time

Therefore, dose from external radiation can be reduced by either reducing the dose rate, or by shielding, or by moving a greater distance from the source, or by reducing the time spent near the source:

- Reducing the time spent near the source of radiation will reduce the total dose that a person receives. This principle is applied in many situations as a safety measure.

- Increasing distance from a source is a very good way of reducing the radiation dose rate and hence the total dose. For small sources emitting gamma rays, the inverse square law applies. Doubling the distance will reduce the dose rate to one quarter.

- Placing shielding material between a source and the person will also reduce the dose rate. For gamma radiation, dense materials such as lead and steel are the most effective.

4.3. CONTROL OF THE CONTAMINATION HAZARD

It is important to have a clear concept of the distinction between radiation and contamination. Radiation is the particle or energy emitted from radioactive material (or generating devices such as X ray machines). Contamination is radioactive material where it is not wanted. Contamination can occur in many forms including dust particles, liquid, or gas.

4.3.1. Containment

Normally, radioactive material is placed or kept in some sort of containment. This may be anything from a glass vial, to the cladding on a fuel pin, to a special stainless-steel capsule. Contamination generally occurs when for some reason the containment is damaged or broken. Once contamination is outside of a controlled or contained environment it can spread very quickly and easily. Therefore, the basic method of control is by taking great care to keep the radioactive material in a known place.

4.3.2. External and internal personal contamination

Once contamination is in an uncontrolled environment, it may inadvertently come in contact with people. All the time it is external to the body, it is generally more of a nuisance than a hazard, but it still requires to be located and cleaned up. However, when contamination gets inside the body the hazard is much greater.

Once inside the body, the methods of time, distance and shielding cannot be applied to reduce the dose. Generally, the body is committed to a certain dose until the material is excreted or until it diminishes through radioactive decay. Therefore, it becomes very important to prevent radioactive material becoming incorporated into the body. Ways by which it could get inside include inhalation of dusts, gases or smoke, ingestion via the mouth from smoking, eating or drinking with contaminated hands, or incorporation through wounds, grazes or cuts.

4.3.3. Protective clothing

The general purpose of protective clothing is to prevent a person from becoming contaminated either externally or internally. The level of protection required will vary according to the level of the contamination hazard. Protective clothing can vary from a laboratory coat and gloves, to several layers of coveralls, with a complete positive pressure body suit and self-contained breathing apparatus. Detailed information about protective clothing and other personal protective equipment (PPE) can be found in Section 11.

4.3.4. Fixed and removable contamination

A distinction is often made between fixed and removable contamination without taking care to define the terms. Once contamination gets on a surface, all or part of it can become impossible to remove. It is then called fixed contamination. Fixed contamination no longer presents a contamination hazard, but a radiation hazard.

For this reason, limits for fixed contamination are given in terms of a dose rate (in μSv/h, for instance), whereas limits for non-fixed contamination are expressed in activity per unit area (in Bq/cm^2, for instance).

4.4. CONTROLLED AREAS

Restricting access to a particular area provides a basic method of implementing control over both radiation and contamination. This method is particularly useful in accident situations. For radiation, a controlled area keeps people remote from the source and hence controls the hazard by distance and time. For contamination, it keeps people remote from the loose radioactive material. If there is only one point where personnel are surveyed on entry and exit, then the radioactive material can be prevented from spreading outside of the area and hence is contained. Personnel can also be controlled to ensure that they have the necessary protective clothing on entry to the restricted area.

4.5. RADIATION PROTECTION PROGRAMMES

A radiation protection programme is a system of measures that primarily ensures the health and safety of workers and the public from radiation and radioactive material. Measures are also taken with the objective of minimizing environmental impact. The nature and extent of these measures are related to the magnitude and likelihood of radiation exposures. The radiation protection programme should include a training programme for the personnel concerned.

The BSS [3] and the Safety Guide on Occupational Radiation Protection RS-G-1.1 [4] provide specific objectives of radiation protection programmes and guidance on how to achieve these objectives. The basic components of a typical radiation protection programme involve individual dosimetry for workers handling the material as well as dose rate and contamination surveys of working areas. In addition to routine issues, consideration has to be given to non-routine and emergency radiological protection.

Record keeping is an important element of any radiation protection programme. Documented evidence shows that the programme is achieving its objectives and also provides indications of trends and areas where further improvements are needed. Record keeping is essential to demonstrate compliance with regulatory requirements.

4.6. APPLICATION OF ANNUAL LIMITS

When a dose limit is exceeded, employers are required by the BSS to promptly communicate this to the regulatory body and the worker(s) involved in the event. Suitable arrangements should therefore be in place for such communication.

Situations in which workers exceed the single year limit of 50 mSv should be considered exceptional. These may occur as the consequence of an emergency, accident or intervention. In the event that a worker receives a single year exposure that exceeds 50 mSv, it would be appropriate for the worker to continue working with radiation provided that:

(a) The regulatory body, having due regard to the health of the worker, considers there is no reason to prevent continuing work with radiation;

(b) The management and the regulatory body, in consultation with the worker (through his or her representatives where appropriate), agree on a temporary dose restriction and the period to which it applies.

A restriction based pro rata on the remaining period of time to which the dose limit relates might be appropriate, and further restrictions may need to be applied in order to keep within the dose limit of 100 mSv in five years.

Regulatory bodies should ensure that systems are in place that prevent workers who have received an exposure close to a relevant dose limit being deprived of their right to work. Situations may arise in which a worker has unintentionally received a total dose that is close to the relevant dose limit, such that further planned exposures may result in that limit being exceeded. This situation should be treated in a similar manner to that of a worker who exceeds a dose limit.

In general, the dose limits apply equally to male and female workers. However, because of the possibility of a greater sensitivity of the foetus to radiation and the requirement for the foetus to receive the same broad level of protection as for members of the public, additional controls may have to be considered for pregnant workers.

4.7. APPLICATION OF THE BSS TO NATURAL SOURCES OF RADIATION

4.7.1. Scope of regulation

Paragraph 2.5 of the BSS [3] states that "Exposure to natural sources shall normally be considered as a chronic exposure situation and, if necessary, shall be subject to the requirements for intervention …", meaning that in such circumstances the exposure does not fall within the scope of regulation in terms of the requirements for practices. However, there are some industrial activities giving rise to exposure to natural sources that have the characteristics of practices and for which some form of control in accordance with the requirements for practices may be more appropriate. Paragraph 2.1 of the BSS states that "The practices to which the Standards apply include … practices involving exposure to natural sources specified by the [regulatory body] as requiring control …".

The Safety Guide on Application of the Concepts of Exclusion, Exemption and Clearance [5] states that it is usually unnecessary to regulate (as a practice) material containing radionuclides of natural origin at activity concentrations below 1 Bq/g for radionuclides in the uranium and thorium decay series and below 10 Bq/g for ^{40}K.[1] The Safety Guide states that the aforementioned values may be used in the definition of the scope of national regulations or to define radioactive material for the purpose of such regulations, as well as to determine whether material within a practice can be released from regulatory control.

4.7.2. Graded approach to regulation

Where the activity concentration values specified in Ref. [5] are exceeded, a graded approach to regulation as a practice is adopted in accordance with the requirements of the BSS (paras 2.8, 2.10–2.12 and 2.17) and the guidance given in Ref. [5]. The application of the graded approach to the regulation of operations involving exposure to NORM is described in Refs [10] and [18] and is summarized below.

4.7.2.1. Initial assessment

An initial assessment is made of the process, the materials involved and the associated exposures. For industries engaged in the processing of NORM, the exposure pathways to workers and members of the public that are most likely to require consideration are those involving external exposure to gamma radiation emitted from bulk quantities of process material and internal exposure via the inhalation of radionuclides in dust. Internal exposure

[1] These criteria do not apply to radon, residues in the environment and commodities such as foodstuffs, drinking water and construction materials, which are normally treated as chronic exposure situations and subject to the requirements for intervention, nor do they apply to material in transport.

via the inhalation of the progeny of ^{222}Rn (radon) and ^{220}Rn (thoron) emitted from process material may also need to be considered. Internal exposure via ingestion is unlikely to require consideration under normal operational circumstances.

The assessment of the effective dose received by an individual involves summing the personal dose equivalent from external exposure to gamma radiation in a specified period and the committed equivalent dose or committed effective dose, as appropriate, from intakes of radionuclides in the same period. The assessment method is described in more detail in Ref. [18].

4.7.2.2. Regulatory options

The four basic options open to the regulatory body, in ascending order of degree of control, are as follows:

(i) The regulatory body may decide that the optimum regulatory option is not to apply regulatory requirements to the legal person responsible for the material. The mechanism for giving effect to such a decision could take the form of an exemption. For exposure to NORM, exemption is likely to be the optimum option if the material does not give rise to an annual effective dose received by a worker exceeding about 1–2 mSv, i.e. a small fraction of the occupational dose limit [4], bearing in mind that the dose received by a member of the public in such circumstances is likely to be lower by at least an order of magnitude [10].

(ii) Where the regulatory body has determined that exemption is not the optimum option, the minimum requirement is for the legal person to formally submit a notification to the regulatory body of the intention to carry out the practice. As in the case of a decision to grant an exemption, this is an appropriate option when the maximum annual effective dose is a small fraction of the applicable dose limit, but it provides the added reassurance that the regulatory body remains informed of all such practices.

(iii) Where the level of exposure to NORM is such that neither exemption nor the minimum regulatory requirement of notification is the optimum regulatory option, the regulatory body may decide that the legal person has to meet additional (but limited) obligations to ensure that exposed individuals are adequately protected. These obligations would typically involve measures to keep exposures under review and to ensure that the working conditions are such that exposures remain moderate, with little likelihood of doses approaching or exceeding the dose limit.[2] The mechanism for imposing such obligations on the legal person is the granting of an authorization in the form of a registration [18].

(iv) Where an acceptable level of protection can only be ensured through the enforcement of more stringent exposure control measures, an authorization in the form of a licence may be required [18]. This is the highest level of the graded approach to regulation and its use for practices involving exposure to NORM is likely to be limited to operations involving significant quantities of material with very high radionuclide activity concentrations, for instance, operations involving the exploitation of ores for their radioactive properties.

[2] For situations in which workers are exposed to gamma radiation and radionuclides in inhaled dust, Ref. [4] states that "Control, if considered necessary, would include the use of methods to suppress or contain any airborne dusts and general radiological supervision".

4.7.2.3. Control measures for authorized practices

A detailed account of the control measures that may be appropriate for authorized practices involving work with minerals and raw materials is given in Refs [7, 18]. In terms of the graded approach to regulation, the nature and extent of such measures will be commensurate with type of practice and the levels of exposure, but will generally entail the establishment of some form of radiation protection programme with suitable provisions for monitoring and dose assessment at a more detailed level than in the initial assessment referred to in Section 4.7.2.1.

Specific radiological measures in the workplace such as control of the occupancy period or even shielding may sometimes be appropriate to minimize external exposure to NORM. Materials with relatively low activity concentrations give rise to modest gamma dose rates (typically no more than a few microsieverts per hour), even on contact. In such cases, discouraging access, for example by storing materials in mostly unoccupied areas, may be sufficient. In areas containing materials with relatively high activity concentrations, physical barriers and warning signs may be necessary.

Exposure to airborne dust is likely to be controlled already in many workplaces through general occupational, health and safety (OHS) regulations. Control of the air quality for the purpose of minimizing dust levels may also help to reduce radon and thoron concentrations. Therefore, the extent to which existing OHS control measures are effective in minimizing workers' radiation exposure is something that the regulatory body would first need to establish before deciding to impose additional control measures for purely radiological reasons. In some workplaces, existing OHS control measures alone may provide sufficient protection against internal exposure. In other workplaces, additional control measures specifically for radiation protection purposes may become necessary for achieving compliance with the BSS. Engineered controls are the favoured option, with working procedures and, finally, protective respiratory equipment being considered only where further engineering controls are not effective or practicable.

Complete containment of material is often impractical, especially where large quantities of low activity concentration materials are involved, but spills and the spread of materials outside the area are often of no radiological significance unless substantial and persistent airborne dust levels result. Prevention of resuspension of dust is therefore likely to be the most effective approach. Specific measures to control surface contamination only become meaningful where materials with higher activity concentrations are present.

In the case of exposure to radon in workplaces, the regulatory body should establish a level, expressed in terms of the radon concentration, for determining whether the exposure is to be subject to the requirements for practices. The BSS state that that level is generally expected to be 1000 Bq/m^3.

Worker awareness and training are particularly important for supporting the introduction of local rules and for creating an understanding of the precautions embodied in such rules.

5. THE OIL AND GAS INDUSTRY

This section describes the structure of the oil and gas industry, the fundamental terminology and the general methods used in oil and gas recovery processes. An understanding of these aspects is essential to appreciate the many applications of man-made radiation sources and generators, as well as the existence of NORM associated with this industry and to which reference is made in Section 12.

The industry operates in all climates and environments, including the most arduous conditions. Technology and organizations are challenged continuously to achieve high efficiency while maintaining a high standard of safety and control. Regulatory bodies are required to keep pace with the operational and technological developments in order to retain control with respect to national interests relevant to safety, health and the environment.

5.1. INDUSTRY STRUCTURE

The oil and gas industry involves a wide range of organizations, companies and individuals in the mapping and evaluation of geological formations, the development and maintenance of facilities to extract and process natural hydrocarbon resources, and the distribution of their products. Although some reserves are extracted at low to moderate production rates by 'independent' oil and gas companies of relatively small size, the industry is dominated by a limited number of 'majors'—multinational organizations large enough to mobilize resources, equipment and manpower on a global scale. Some countries have State-owned oil and gas companies.

The industry is organizationally and technically complex and consequently has developed an extensive specific vocabulary. It often occurs that a number of oil and gas companies invest in the development of a particular field and an 'operator' is appointed with the responsibility for managing the development and production of the field. The operator usually establishes contracts with numerous 'service companies' and 'supply companies' that provide the necessary equipment and expertise. The work of such companies may include the use of radioactive sources and machines that generate ionizing radiation which, to the uninitiated, may not be immediately apparent. The radioactive sources may be incorporated as an essential component of larger equipment that is shipped to a field or it may be a significant item that utilizes ionizing radiation and is mentioned only in technical terms in shipping, technical, or similar documentation. In these circumstances, the regulatory bodies who have to exercise control over the import, transport and use of radioactive materials and machines must be informed accordingly.

5.2. RIGS AND DRILLING METHODS

5.2.1. Rigs

The search for oil and gas and the development of discovered resources are conducted on land and at sea. Oil and gas rigs for exploration on land are designed for portability, and supporting services are supplied by companies with self-contained, fully equipped road vehicles (Fig. 10). Inland barge rigs may be used in marshy conditions. All the necessary tools and equipment for the work, including radiation sources as appropriate, will be mobilized. At sea, the necessary mobility to explore for reserves is provided by the use of 'floater rigs' such as 'jackups', submersibles, semisubmersibles ('semisubs') and drill ships. The first two floaters mentioned operate in shallow waters and sit on the sea bed to obtain stability before well drilling begins. The last two operate in deeper water and attain stability by either partially submerging (in the case of 'semisubs') or by other means such as using 'thrusters' linked with satellite navigational aids to remain on station over the drill site. When oil or gas is discovered, a production platform or installation is placed over the well or, in deeper waters, production floaters may be used. Offshore platforms and installations are constructed using large diameter steel pipe or cement to provide columnar support in the form of a 'jacket'. This is usually cemented to the seabed and 'modules' are built on top of the jacket to provide accommodation for crew and production facilities (Fig. 11). The development of a field may involve numerous wells being drilled from a platform and 'topside plant and equipment' to separate and process the oil, gas, water and solids that flow from the well(s). The wells are not necessarily drilled vertically downwards; 'directional drilling' allows them to deviate in preferred directions below ground, even horizontally, over considerable distances and depths. The same topside plant and equipment may be used to serve separate fields or remote satellite fields.

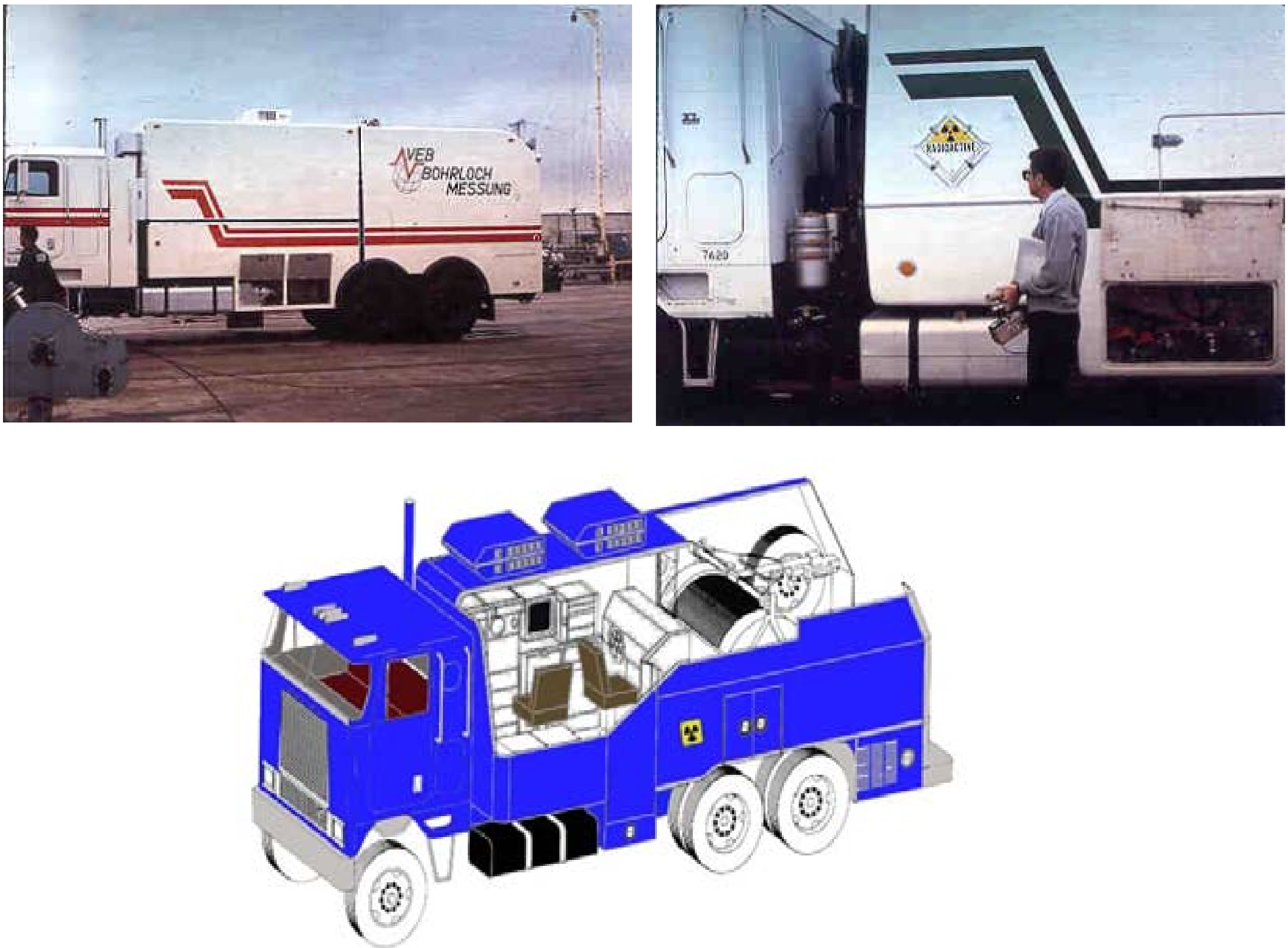

FIG. 10. Heavy duty well logging trucks

FIG. 11. Offshore production platform

5.2.2. Drilling and well construction methods

Most wells are formed by ‘rotary drilling’ techniques (see Fig. 12). The familiar mast or derrick supports a ‘drill string’ which comprises a large hook-like device called the swivel, a square or hexagonal hollow pipe called the kelly, a drill pipe (D), a thicker-walled drill pipe called the drill collar (C), and the drill bit (B). On the ‘drill floor’, a clamp-like device in the rotary table grips the kelly and rotates the drill string causing the bit to ‘make hole’. The heavy drill collar (up to approximately 30 m in 10 m lengths) causes the bit to grind into the rock. As the hole being drilled gets deeper, the ‘joint’ between the kelly and the drill pipe is broken (unscrewed) and additional lengths of drill pipe in about 10 m lengths are added. As drilling continues, a pump (P) forces drilling fluid or ‘mud’ down the inside of the drill string to the bit from where it returns up the ‘annulus’ between the drill string and the wall of the hole bringing the ‘cuttings’ to the surface. On the surface, the cuttings are removed by the ‘shale shaker’ (S) and the mud may be desanded, desilted or degassed before being returned to the mud pits or tanks (T) for recirculation. In addition to lifting the cuttings, drilling mud exerts pressures that help to keep underground (oil, gas and water) pressures under control. The mud also deposits a clay veneer on the wall of the ‘open’ hole to prevent it caving in or ‘sloughing’. The density and consistency of drilling mud is carefully controlled—this process may involve the use of radiation sources. In case of an uncontrollable gas or oil flow during the drilling, a so-called ‘blow-out preventer’ (BOP) can be closed by remote control. This BOP is situated below the drill floor. While closing, the BOP will cut the drill string and other equipment that is within this safety valve.

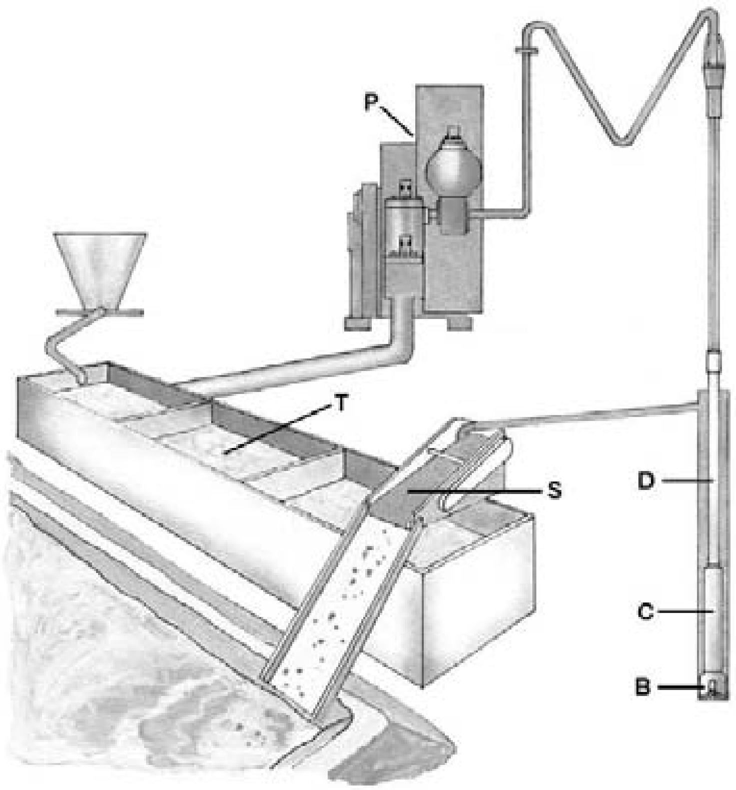

FIG. 12. Oil well drilling and components of the circulation system

The open hole is next ‘cased’ by lowering (‘running’) a large diameter ‘casing string’. This is steel pipe normally fitted with external apparatus such as centralizers, scratchers and collars. Their purpose includes maintaining the casing coaxial with the hole and other functions that may demand the installation of radiation sources. Cement slurry is pumped down to the bottom of the casing from where it then rises to fill the annulus between the casing and the wall of the hole. Drilling may continue in a cased hole resulting in a well with a surface casing, intermediate casing and the final production hole through the ‘formation of interest’ where oil or gas may be located. Tests carried out by a well logging company, some of which will utilize radiation sources [19] (Fig. 13), will determine whether a well is viable and worth ‘completing’ or is ‘abandoned’ as a dry test well.

5.2.3. Well completions, development and workovers

Radioactive materials may also be used while ‘completing a well’ which involves cementing in the final section of production casing and then ‘perforating’ the production casing in the ‘pay zone’ to allow the oil or gas to flow from the formation. Oil, gas, water and solids are brought to the surface through small diameter ‘production tubing’, which is first fixed coaxial with the casing. A ‘packer’, expanded just above the pay zone on the outside of the production tubing string, prevents the fluids rising up the annulus. The production tubing is suspended from a collection of valves called the ‘Christmas tree’ installed at the ‘wellhead’ at the top of the casing enabling the flow of fluids to be controlled. Other emergency valves called subsurface safety valves are usually mounted below the Christmas tree in the tubing of the well or possibly on the seabed in the case of offshore oil and gas fields.

FIG. 13. A wireline for well logging

Periodically, ‘workovers’ are carried out to replace production tubing or carry out necessary maintenance on the well. A number of techniques involving radioactive materials may be used to assess the success of techniques to ‘stimulate’ the flow of oil and gas from a formation that is found to have low permeability in the pay zone. ‘Acidizing’ involves injecting acid to dissolve, for example, limestone or dolomite. ‘Fracturing’ involves injecting a special fluid at very high pressure to break open the rocks. ‘Proppants’ such as sand, walnut husks and aluminium pellets are mixed with the fracturing fluid to keep open the fractures when the pressure is allowed to dissipate. Similarly, radioactive materials are used to monitor other techniques to ‘enhance recovery’ and increase the amount of recoverable reserves. These techniques include ‘gas lift’ and ‘waterflood’ in which some of the wells (‘injection wells’) are used to inject water back into a selected region of the formation to drive reserves towards the producing wells.

In order to enhance recovery from existing facilities, ‘sidetracks’ or lateral wells may be drilled from existing wellbores into new parts of the field (for example oil pockets) or a nearby reservoir. Conventionally this involves removing the existing completion, inserting a ‘whipstock’ (a drill deflector wedge) where the drilling assembly is to leave the old wellbore and then running a new completion after the sidetrack has been drilled. Such well developments and workovers increasingly involve technological advances in ‘coiled tubing’ techniques. Coiled tubing is small bore steel pipe, up to almost 8 km in length, mounted on a reel. An ‘injector head’ connected to the wellhead pushes the coiled tubing through special seals into the wellbore. After a special milling tool has cut a window through the old completion, coiled tubing fitted with a bottom hole assembly, comprising a drilling bit, directional control equipment and a drilling motor powered by the fluids pumped through the tubing, can be used to form the sidetrack. Measurement signals are continually sent from the downhole drilling assembly to the surface enabling the drilling assembly to be guided along the desired path to the target formation. Such measurements while drilling is in process may utilize radioactive sources. The new wellbore can be lined with tubing or left ‘barefoot’ to allow oil to flow into the old production system.

5.2.4. Topside plant and downstream equipment

Production tubing carries fluids and solids to the surface where, in the case of offshore oil and gas fields, they will enter the ‘risers’ to carry them to sea level. The risers are usually not rigid steel pipes but flexible pipes—referred to as ‘umbilicals’—connected to floating production rigs and ships. Entering the production plant above water (‘topside’), the flow of fluids and solids is controlled by the Christmas trees and directed into a manifold and then through several large, usually cylindrical vessels called ‘separators’ to allow the solids to settle and the water, oil and gas to separate into ‘streams’. The streams are subjected to further treatments to remove oil from the water and noxious compounds, such as hydrogen sulphide, from the gas. The water may then be either reinjected or discharged and the natural gas will be exported, flared or used to generate power for production purposes. The crude oil may be ‘transported’ immediately by pipeline for refining or held in vessels awaiting appropriate transport arrangements by tankers. Under certain circumstances, NORM may be deposited with other solids in the well tubulars, topside plant, and downstream equipment such as storage, transport and treatment systems.

Solid deposits in the crude oil and gas pipelines are removed periodically by driving solid plastic or rubber plugs down the pipeline under the fluid pressure. These plugs, called ‘pigs’, are released from pig launchers upstream and retrieved from ‘pig traps’ downstream possibly in the refinery or petrochemical site (Fig. 14).

FIG. 14. Pipeline pig trap (courtesy: Atomic Energy Commission of Syria)

Oil refining and the processing of petrochemicals is a complex subject, a description of which is beyond the scope of this manual. The processes involve mixing and heating chemicals and materials under carefully controlled conditions. Industrial chemical sites feature a range of very large vessels interlinked by pipework. Automation provides chemical plants with a higher degree of safety and efficiency than would be feasible by manually operating valves and controls to transfer materials between the vessels. The vessels are usually identified by names indicating their function such as distillation columns, exchangers, reactors and absorption towers. Radioactive materials are used to significant advantage in these process controls. They also feature in investigations to assess the efficiency of a plant, determine the reasons for poorly performing processes or material transfers and, in general, pinpoint where problems are occurring, often without the need to interrupt production or to open systems that may be pressurized.

6. ORGANIZATIONAL RESPONSIBILITIES AND TRAINING

Radiation protection and the safe management of radioactive waste in the oil and gas industry rely on the organizations and people involved meeting certain responsibilities. These organizations and people are:

- The various regulatory bodies;
- The registrants, licensees and employers, i.e. the operating organizations (operators) responsible for the oil and gas fields and the distribution of the products and the service companies (or organizations) that work under contract for the operator;
- The workers.

6.1. RESPONSIBILITIES OF REGULATORY BODIES

National arrangements may specify a number of organizations that have regulatory authority over different aspects of the oil and gas industry. They may for example include organizations that regulate:

- The development and production of oil and gas;
- The transportation of radioactive and other hazardous material;
- The possession, use, and disposal of radioactive material.

These various regulatory bodies must coordinate any overlapping responsibilities. In these circumstances it is important to identify a lead regulatory body with the responsibility for radioactive material, which will promulgate appropriate rules and regulations and ensure their enforcement. Additionally, it has to develop a method for authorizing persons and organizations that need to own, use, store, transport or dispose of radioactive material. It is desirable that the regulatory body or its nominated agents be able to perform periodic on-site inspections to ensure compliance with the applicable rules and regulations. The inspection will include a review of required documentation and a physical inspection of the facilities to determine whether approved safe practices are in use. Checks are made to confirm that adequate training is provided that is in accordance with programmes approved by the regulatory body as required. It is important that any findings as a result of an inspection are communicated to the persons or organizations involved and follow-up inspections are performed to verify that corrective actions are implemented [20, 21].

The regulatory body needs to establish criteria to ensure that it receives notifications from the licensee of any accidents or incidents involving radioactive material. The types of incidents reported include spills, leaks or any other loss of control of radioactive material, excessive exposures to radiation workers or members of the public, and lost radioactive material. Reports of loss include all relevant information such as the make and identification numbers of equipment and details of the radioactive material involved by nuclide, activity and serial number, where applicable. The regulatory body sees to it that the licensee’s reports include a description of the incident, investigations of exposures to individuals, and actions taken to prevent a recurrence of that type of incident.

The regulatory body needs to develop a system to document and track incidents and accidents that occur during the use of radioactive material and means of disseminating the ‘lessons learned’ to other similar bodies and to the industry. This is essential for a regulatory programme to be able to identify trends and take corrective actions to prevent similar future accidents and/or incidents.

6.2. RESPONSIBILITIES OF REGISTRANTS, LICENSEES AND EMPLOYERS

Registrants and licensees, and employers of workers who are engaged in activities involving normal exposures or potential exposure are responsible for:

(a) The protection of workers against occupational exposure;

(b) Compliance with any other relevant requirements of the BSS.

To fulfil their responsibilities with respect to all workers engaged in activities that involve or could involve occupational exposure, employers, registrants and licensees must ensure that:

(a) Occupational exposures are limited;

(b) Occupational protection and safety are optimized;

(c) Decisions regarding measures for occupational protection and safety are recorded and made available to the relevant parties, through their representatives where appropriate;

(d) Policies, procedures and organizational arrangements for protection and safety are established, with priority given to design and technical measures for controlling occupational exposures;

(e) Suitable and adequate facilities, equipment and services for protection and safety are provided, the nature and extent of which are commensurate with the expected magnitude and likelihood of the occupational exposure;

(f) Necessary health surveillance and health services are provided;

(g) Appropriate protective devices and monitoring equipment are provided and arrangements made for its proper use;

(h) Suitable and adequate human resources and appropriate training in protection and safety are provided, as well as periodic retraining and updating as required;

(i) Adequate records are maintained;

(j) Arrangements are made to facilitate consultation and cooperation with workers with respect to protection and safety, through their representatives where appropriate;

(k) Necessary conditions to promote a safety culture are provided.

6.2.1. The operating organization (operator)

For the purposes of this section, the operating organization is the organization responsible for the production and distribution of the oil and gas extracted by the facility (or facilities) under its authority. This organization may or may not be registered or licensed to own, possess, or use radioactive material including NORM. The operator establishes sufficient methods, for example employing a qualified expert using risk assessment techniques, to determine whether the operations involve work with ionizing radiation and require a licence and/or safe systems of work for the operations. The operator establishes procedures to ensure the safe and controlled handling of radioactive material brought onto the premises by other licensees. If the activities involving ionizing radiation fall under the direct responsibility of the operator, then the operator has to apply for an authorization, as required by the regulatory body. The operator further needs to appoint a radiation protection officer (RPO) who is technically competent and knowledgeable in radiation protection matters. The RPO will take the lead in developing and implementing a radiation protection plan. The duties of the RPO may include:

(a) Radiation and contamination monitoring;

(b) Identification and inventory of accumulations of NORM;

(c) Maintaining an inventory of any other sources of radiation possessed by the operator;

(d) Approving and overseeing the work of any contractor or service company using ionizing radiation on the operator's property;

(e) Hazard assessments and identification of controlled and supervised areas;

(f) A quality management programme for maintaining protection measures;

(g) Controlling access to controlled areas;

(h) Arranging radiological assessments of samples and individual dose assessments;

(i) Drawing up and reviewing written administrative procedures for work in areas where radioactive material is handled;

(j) Checks to ensure compliance with authorized conditions and other regulatory requirements;

(k) Supervision of work in areas that are controlled due to radiation levels or storage of radioactive material;

(l) Advising and requiring the use of appropriate personal protective equipment in controlled areas;

(m) The provision of general advice to, and ensuring the training of, personnel;

(n) Investigating and documenting incidents or unusual occurrences;

(o) Submitting any reports to the regulatory body, as dictated by national regulations;

(p) Maintaining records and documents in accordance with national regulations.

The operator establishes procedures that ensure the safe handling of radioactive material including NORM. Moreover, the operator develops safety procedures that inform the employees of the type and nature of the radiation and how to protect against unnecessary exposure to radiation. The operator also establishes a method for the inventory and tracking of the accumulation of NORM and acceptable radioactive waste management methods. It is desirable that the safety procedures lay down the responsibilities at all levels of the operating organization.

The RPO has the authority to halt any operation if an uncontrolled or unacceptable radiation hazard exists or is perceived to exist. The RPO is responsible for individual monitoring, workplace monitoring and maintenance of any necessary protective equipment for the personnel. The RPO is responsible for ensuring that occupationally exposed employees are adequately trained or instructed as to the radiation hazards, and that information on radiation hazards is communicated to other employees (see also Section 6.4).

6.2.2. Service companies

Service companies perform radiography, drilling, tracer work, workovers, well logging, 'fishing' operations (retrieval of disconnected sources downhole), perforations, NORM decontamination, maintenance and repair, etc. Some of these companies are licensed to possess and use radioactive material and have appointed RPOs (see previous section). Others are not licensed and do not own or use radioactive material but can be involved in activities in which radioactive material is used. One example of this situation is the erection of a drill rig or workover rig at the well site during logging or tracer operations. Another example is when a well logging source becomes stuck downhole and an unlicensed fishing company is hired to attempt recovery of the stuck source. In these situations it is the responsibility of the licensed company to inform the non-licensed company of the radiation hazards and oversee the radiation protection aspects of the work performed by the unlicensed company. Likewise, it is the responsibility of the licensed company to report any incidents or accidents involving the radioactive material to the regulatory body. The licensed company cooperates with the service company to ensure that the necessary assessments of the doses received by workers are made and recorded according to national regulations.

6.2.3. Cooperation between registrants or licensees and employers

If workers are engaged in work that involves or could involve a source that is not under the control of their employer, the registrant or licensee responsible for the source and the employer must cooperate by the exchange of information and otherwise as necessary to facilitate proper protective measures and safety provisions. This cooperation will inevitably include the workers, through their representatives where appropriate. The cooperation between the registrant or licensee and the employer must include, where appropriate:

(a) The development and use of specific exposure restrictions and other means in order to ensure that the protective measures and safety provisions for such workers be at least as good as those provided for employees of the registrant or licensee;

(b) Specific assessments of the doses received by such workers;

(c) A clear allocation and documentation of the respective responsibilities of the employer and the registrant or licensee for occupational protection and safety.

In such cases, which will often involve transient, temporary or itinerant workers, the specific responsibilities assigned to the registrant and licensee include the provision of:

(a) Appropriate information to the employer for the purpose of demonstrating that the workers are provided with protection in accordance with the BSS;

(b) Such additional available information requested by the employer on compliance with the BSS prior to, during and after the engagement of such workers by the registrant or licensee.

6.3. RESPONSIBILITIES OF WORKERS

It is important for all workers directly involved in work with ionizing radiation, especially those with primary qualifications in other disciplines such as diving, to be adequately trained and competent for any necessary involvement. Educational needs will vary considerably depending on the radiation application. For many applications a basic level of education will be sufficient to understand the need to follow radiation protection instructions. Information must be provided to those who are not involved but may indirectly be affected by the work and need information or specific instructions to minimize their potential exposure. The level of instruction needs to be appropriate for the different levels of competence such as qualified experts, radiation protection officers, qualified workers occupationally exposed to radiation, general workers and other persons.

It is important that workers be familiarized with all radiation signs and warnings. Workers need to be encouraged to report to the RPO any violation of a rule or policy relating to radiation protection procedures and to report immediately any incident, accident or other occurrence likely to adversely affect radiation protection, health and safety.

Workers can, by their own actions, contribute to the protection and safety of themselves and others at work by:

(a) Following any applicable rules and procedures for protection and safety specified by the employer, registrant or licensee;

(b) Using properly the monitoring devices and the protective equipment and clothing provided;

(c) Cooperating with the employer, registrant or licensee with respect to protection and safety and the operation of radiological health surveillance and dose assessment programmes;

(d) Providing the employer, registrant or licensee such information on their past and current work as is relevant to ensure effective and comprehensive protection and safety for themselves and others;

(e) Abstaining from any wilful action that could put themselves or others in situations that contravene the requirements of the Standards;

(f) Accepting such information, instruction and training concerning protection and safety as will enable them to conduct their work in accordance with the requirements of the Standards;

(g) Providing feedback to the management, particularly when adverse circumstances arise related to the radiation protection programme.

6.3.1. Protection of the embryo or foetus

Female workers and employers both have responsibilities regarding the protection of the embryo or foetus. The worker herself should, on becoming aware that she is pregnant, notify the employer in order that her working conditions may be modified if necessary. When the pregnancy is notified, it is not to be considered as a reason to exclude a female worker from work, but it is the responsibility of the employer to adapt the working conditions in respect of occupational exposure so as to ensure that the embryo or foetus is afforded the same broad level of protection as required for members of the public.

6.4. TRAINING

The main purpose of training is to provide essential knowledge and skills and to foster the correct attitudes with regard to the safe handling and security of sealed and unsealed radiation sources. Individuals who are occupationally exposed to ionizing radiation, or who may be exposed in the course of their work, need to receive adequate training in radiation protection. In addition, there are people who, though they may not be occupationally exposed to ionizing radiation, need to be trained in radiation protection and safety in order to perform their duties safely. General guidance on training and the responsibilities for building competence in protection and safety can be found in IAEA Safety Guide RS-G-1.4 [22].

It is important that suitably qualified professionals—whose credentials have been approved by the regulatory body as required—provide the training of all persons concerned. Trainers must be familiar with the particular technologies, specific procedures and working environments in the oil and gas industry.

The aims and objectives of each training course need to be specified clearly in advance. Radiation protection training should be tailored to the particular practice and designed so that the worker develops the necessary skills to work safely. Basic training includes an explanation of local rules, safety and warning systems, and emergency procedures. The depth to which each training subject is to be covered depends on the specific radiation application, and also considers the potential hazards associated with the application. On-the-job training always needs to be included. Caution needs to be exercised whenever persons who may not be engaged in the task involving the exposure might be working in the vicinity of radiation sources and therefore need to be informed beforehand of the relevant hazards through the provision of appropriate information or training. The level of work experience needed for workers handling radioactive material will depend on the specific radiation application. However, supervision by the person responsible for the area, by the qualified operator or by the RPO, is always needed.

6.4.1. Radiation protection officer

The RPO will need to have had suitable training to supervise effectively the work with radiation, ensure compliance with national rules and regulations and put into effect an appropriate response in the event of an emergency. A broad level of knowledge in radiation protection is needed, including training in emergency preparedness and response, as well as training in specific areas of work, e.g. industrial radiography, use of gauges, well logging, radiotracer studies, decontamination of equipment contaminated with NORM. More detailed information on training of the RPO can be found in IAEA Safety Report No. 20 [23].

6.4.2. Qualified workers

A qualified worker has responsibility for the day-to-day use of sealed radiation sources, or works with unsealed sources or NORM. The worker must have a significant level of expertise in this specific area of work, e.g. industrial radiography, use of gauges, well logging, radiotracer studies and decontamination of NORM-contaminated equipment. In addition, in order to exercise responsibility as a qualified worker, the worker will need to have had a minimum standard of training in radiation safety. The topics to be covered by lectures and practical exercises will be the same as those defined for the RPO training course, but will be covered in less detail. The radiation safety training course for the qualified worker should be provided over a period of not less than two days.

Radiation protection and safety training needs to be tailored to the particular application and should be designed so that the worker develops the necessary skills to work safely. On-the-job training is essential in addition to the training course.

6.4.3. General workers

The amount of radiation safety information, instruction or training needed for the worker will depend on the extent to which the worker is occupationally exposed to ionizing radiation. At the most basic level, general workers will all need induction training to ensure that they are capable of recognizing and understanding warning signs, signals and barriers. All workers need to comply with radiation safety instructions given by qualified workers and RPOs.

Workers who are partially involved with radiation, for example individuals working with gauges (in which the source remains within the protective housing), industrial radiography assistants and maintenance personnel, will need further radiation safety training commensurate with the degree of their involvement. The level of training needed will depend on the specific application. However, supervision by the qualified worker or by the RPO is always necessary.

The radiation safety training provided for workers will be effected by means of briefings, demonstrations and practical exercises. This will typically take not less than one hour and not more than eight hours.

6.4.4. Managers and safety officers

Managers and safety officers who are not directly involved in work with ionizing radiation frequently have a responsibility to coordinate or facilitate the radiation safety objectives of RPOs and qualified workers. The managers and safety officers are involved in the issue of work permits on the work site. Therefore, it is essential that these managers and safety officers are knowledgeable as regards radiation safety issues. It is appropriate for managers and safety officers to receive training equivalent to that of an RPO.

6.4.5. Refresher training courses

Refresher courses are essential for all levels of radiological safety training. Such refresher training should be provided at appropriate intervals or as directed by the relevant regulatory body.

6.5. NON-COMPLIANCE

Any instance of non-compliance with the regulatory requirements identified during handling of radioactive materials should be brought to the notice of the responsible person for the radiation protection. That person should take immediate steps to mitigate the consequences of non-compliance, investigate its causes, circumstances and consequences, take appropriate actions to remedy the causes of the non-compliance and to prevent recurrence, and communicate as soon as practicable with the competent authorities on the causes of non-compliance and on corrective and preventive actions taken.

7. SEALED RADIATION SOURCES AND RADIATION GENERATORS IN THE OIL AND GAS INDUSTRY

7.1. PRACTICES INVOLVING SEALED SOURCES AND RADIATION GENERATORS

7.1.1. Industrial radiography

Oil and gas operators commonly employ service companies that carry out industrial radiography. Radiography is a form of non-destructive testing (NDT) performed to provide quality assurance during engineering projects. The oil and gas industry uses gamma radiography, and to a lesser extent X radiography, to ensure that all constructions and fabrications are completed to the required standard. It is essential for all components and connections, particularly welds in the plant and equipment, to withstand the very high physical forces (for example, forces generated by hydrostatic pressures) associated with oil and gas production. Radiography is carried out during the construction and maintenance of rigs and platforms, particularly during the development of the plant and equipment above the waterline. It is also common when pipelines are being laid and prior to the 'hook up' when the production and export systems are to be connected. More information on radiation sources, equipment and safe operating procedures associated with site radiography, which is commonly carried out, are described in IAEA Safety Reports Series No. 13 [24] and in Section 8, which is based on the IAEA Practical Radiation Safety Manual on Gamma Radiography PRSM 1 [11].

The radiography service companies usually set up independent bases close to construction yards and other land based facilities where oil and gas are processed. These facilities enable them to store and maintain their radiation sources and ancillary equipment and to be readily available to carry out specific jobs on demand. Where the oil or gas field being developed or worked is at a more remote location, such as offshore, a radiography service company typically has a permanent presence often in facilities made available by the operator. Radiographers will follow the construction phase overland during pipe laying projects. They are typically crew members on pipe-laying barges when subsea pipelines are installed between oil and gas production installations and their processing facilities and markets. X ray and gamma pipeline crawlers are normally used on pipe laying barges and in the field during the construction of overland pipelines.

The oil and gas production industry contracts out underwater radiography almost exclusively. The work is usually carried out to examine seabed pipelines, subsea assemblies and platforms or rigs below the waterline. Different service companies may employ the divers and radiographers. The radiography company may subcontract the services (or rent equipment) to a specialist diving company. Alternatively, the operator may manage the workers directly. These approaches demand close supervision and cooperation from the separate service companies that specialize in diving and radiography.

7.1.2. Installed gauges

'Nuclear (or nucleonic) gauges' are installed extensively on plant and equipment associated with the oil and gas industry. Each gauge usually comprises one or more radioactive sources associated with at least one radiation detector. Typically, ^{137}Cs sources are used with activities of up to 5 GBq and occasionally up to 100 GBq, depending on the physical dimensions of the plant and the purpose of the gauge. The gauges are normally installed in a 'transmission mode' (rather than a backscatter mode) meaning that the radiation penetrates the medium but is attenuated to a measurable extent before it reaches a detector. The source usually remains installed in a steel or lead ‘housing’ of about 30 cm in diameter, fixed to the side of the vessel or pipeline, and the radiation detectors are mounted diametrically opposite the source housing on the wall of the vessel or pipeline (see Fig. 15). The radiation intensity at the detector depends on the density of the contents of the vessel or pipeline. More penetrating gamma radiation from a ^{60}Co source is needed for the vessels of largest diameter or greatest wall thickness or for denser media contained in the vessel or pipeline. An alternative arrangement involves attaching the source to the end of a cable which is used to move the source from the housing into a closed ‘dip tube’ inside the vessel. The tube helps to protect the source and defines a fixed geometry allowing an adjustable distance between the source and the detector.

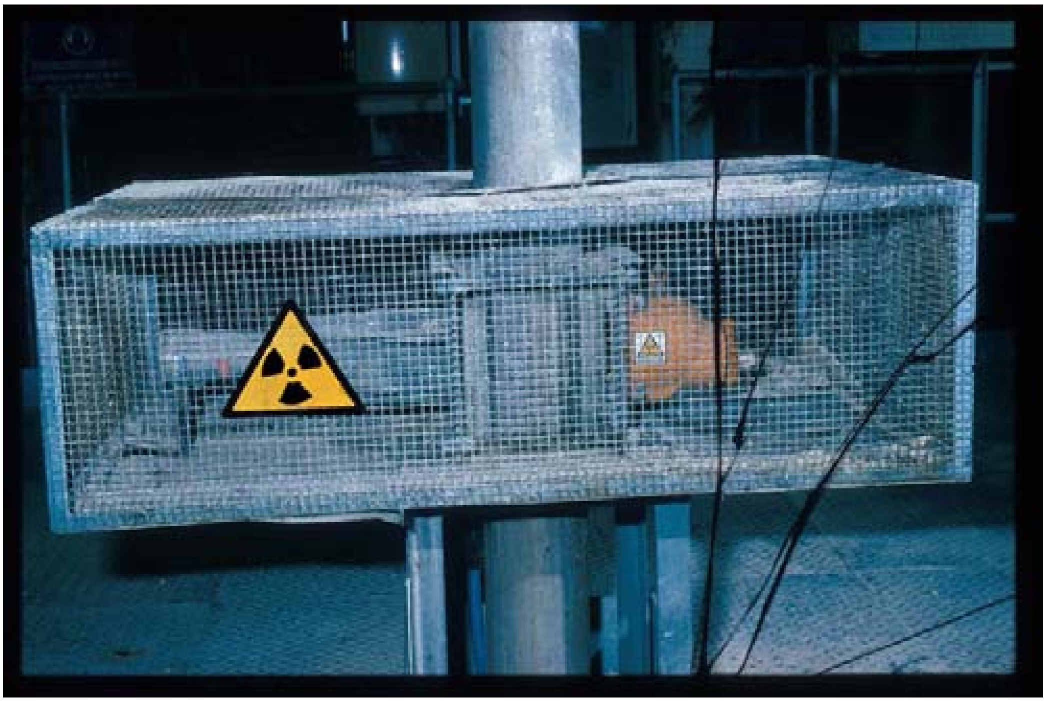

FIG. 15. Installed density gauge (Courtesy: HPA-RPD, UK)

Gauges are installed to monitor or control the density of fluid flowing through pipelines, e.g. on lines carrying cement slurry to ‘grout in’ (to cement with liquid mortar) a casing string, and on crude oil export lines.

Gauges (called photon switches) are also installed to monitor and control fluid levels in vessels and to detect the interface between fluids of different densities, such as the water, oil and gas interfaces in separators. They may be installed also on vessels such as mud tanks, the flare knockout drum, export gas scrubbers, and vent headers of storage tanks. Level gauges have been installed in irretrievable locations such as in the jacket legs of offshore platforms to indicate, as the legs are grouted into the seabed, that the cement slurry has risen to the required level in the outside portion of the leg. They are equally common downstream in oil refineries and petrochemical facilities.

The source housings of installed gauges are often brightly coloured and labelled with radiation warning signs so that they are clearly visible, even when they are mounted at a height or are otherwise inaccessible. It is important that they are fixed to the pipeline or vessel in such a manner that there is no space between the housing and the vessel or pipeline, and that access to the radiation beam cannot be gained. A control lever or other mechanism is usually provided on the source housing to allow a shutter inside the housing to be closed and the radiation beam to be shielded. This permits the shutter to be closed and locked in that position before allowing either: (a) vessel entry (assuming that the housing is attached to the outside of a vessel) or (b) removal of the housing from its installed position. The shutter is not locked in the open position. If it is necessary to hold the shutter open to counter equipment vibrations, a device that is easily removable in the event of an emergency, such as a shear pin, may be fitted to the shutter mechanism. Specific radiological safety recommendations for installed gauges are provided elsewhere [25]. More information on nuclear gauges is also provided in Section 9, which is based on the IAEA Practical Radiation Safety Manual on Nuclear Gauges (PRSM 3) [12].

7.1.3. Mobile gauging equipment and articles

Numerous mobile gauging devices utilizing radiation, as well as other articles containing radioactive material, are used in the oil and gas industry, especially by service companies. These include small articles such as smoke detectors and self luminous signs (‘beta lights’ containing gaseous tritium), hand held testing instruments, and larger equipment intended primarily for use only at service companies’ own bases.

Fire protection equipment service companies commonly use hand held level gauges to determine the fluid level in fire extinguisher bottles or cylinders. Attached to the same long handle are two short probes, one containing a ^{137}Cs source of several megabecquerels and the other a radiation detector (Fig. 16). As the probes are moved up either side of an extinguisher bottle a signal from the detector provides a reading on a meter. The level of fluid is indicated when the detector indicates a change in the intensity of attenuated radiation. A similar hand held probe containing a source that consists of ^{241}Am–Be is used primarily by NDT service companies to detect water trapped between lagging (insulation) and the insulated surface of a pipe or vessel. Fast (high energy) neutrons emitted by the source are ‘thermalized’ (reduced in energy) and scattered back to a detector in the probe if water is trapped behind the lagging. Water that is discovered using this procedure can then be released before it causes corrosion that would weaken the pipe.

FIG. 16. Mobile gauge for detecting the level of liquids in closed fire extinguisher cylinders (Courtesy: HPA-RPD, UK)

The ‘pipe wall profiler’ is an example of the larger equipment. It contains a ^{137}Cs source of several gigabecquerels and a detector mounted on an annulus and is used to check the wall thickness and uniformity of steel pipes intended for use in tubing strings. The annulus revolves at high speed around the axis of each pipe while the pipe is moved through the centre of the annulus. The service company issues certificates to indicate that the tubes are of an appropriate standard to be used in the high temperature and pressure environment of an oil or gas well.

Mobile level gauge systems incorporating appropriate sealed radiation sources are used commonly to determine the height of a fluid level or an interface between different fluids. One such investigation is carried out on offshore platforms to determine the level of potentially corrosive water ingress into subsea sections of ‘flooded members’. Divers manipulate the gauging system or it is attached to the remotely operated vehicle of a miniature submarine. Other examples include: the detection of liquid levels in storage containers, still bases, reactors and transport tankers; checking for blockages by solid deposits and accumulations on internal pipe walls; and determining the location of vessels’ internal structures such as packing levels in absorption towers and catalyst beds in reactors. For example, a reactor vessel at a petrochemical site could be investigated using a gamma transmission gauge showing that the catalyst had been spent and the packed beds had expanded, thereby narrowing the vertical separations between adjacent beds. The results may help the plant management to decide when to regenerate the catalyst. This ‘density profiling’ is most often used to investigate distillation columns. The vapour spaces are clearly differentiated from the relatively high radiation attenuation detected as the source or detector descends past the levels of the tray structures. ‘Reference scans’ (when the columns are operating normally) and ‘blank scans’ (when the columns are empty) permit the detection not only of flooding, foaming, missing or collapsed trays, but also of more subtle faults such as a high liquid level on the trays and high vapour density. It is also possible to quantify more accurately the foam densities forming in different parts of the column. Using a fast neutron (e.g. ^{241}Am–Be) source to scan down the side of a vessel, it is possible to detect phase changes of hydrogenous substances, for example, to determine water, oil and vapour interfaces. Neutron sources have been used to monitor flare stack lines for ice deposits that start to form when condensates freeze in very cold weather and create a potential flare stack hazard.

Radioactive sealed sources may be incorporated in a pipeline pig (Fig. 17) to track and possibly help locate it in the event that the pig is stopped by a stubborn blockage. Similarly, a pig labelled with a sealed source may be used to locate a leak in an umbilical pipeline; when the pig passes the leak in the hose, the driving force is lost and the location of the source (in the pig) indicates where the leak is occurring.

FIG. 17. Radioactive sealed sources incorporated in a pipeline pig (Courtesy: Scotoil Group plc)

7.1.4. Well logging

7.1.4.1. Logging tools and techniques

Well logging companies place rugged, highly technical ‘logging tools’ in the well to measure physical parameters in the well, the geological properties of the rocks around the well, and the presence of elements in the rocks (Fig. 18, see also Fig. 13). Among the many types of tools there are means to measure fluid temperature, pressure, density, and flow rates; detect casing corrosion and hardware; and measure rock density, porosity and isotopic content. Some of the tools contain one or more radiation detectors and radioactive sources or a machine that generates ionizing radiation. These are referred to as nuclear logging tools.

FIG.18. Well logging tool string suspended by a derrick above an oil well (Courtesy: Baker Hughes INTEQ)

In ‘wireline logging’ systems, the drill string is first removed from the well and the logging string (a series of logging tools connected together) is then lowered to the bottom of the well on a cable (the wireline). The cable also carries the measurement data signals back to the surface where they are recorded on a log. As the wireline tool is slowly raised, the log plots the parameter being measured against the well depth. ‘Logging-while-drilling’ and ‘measurement-while-drilling’ systems avoid the need to first remove the drill string by incorporating the logging tools in the drill collar or coiled tubing. Signals are sent back to the surface by means of a positive mud-pulse telemetry system. Equipment at the wellhead interprets the mud pulses and logs the data.

There are four common nuclear logging techniques:

(i) The first, sometimes called the ‘gamma measurement’ technique (different logging companies may use brand names), simply measures and identifies the gamma rays emitted by naturally occurring radionuclides in rocks to help to distinguish the shale content of sedimentary rocks for lithological identification. The log records the uranium, thorium and potassium content of the rocks.

(ii) The second technique, which provides a neutron–neutron or compensated neutron log, demands a radioactive source of up to several hundred gigabecquerels of ^{241}Am–Be or Pu–Be in the tool to emit 4–5 MeV neutrons. An elongated skid hydraulically presses the tool against the wall of the well and two radiation detectors, located at different distances from the source in the tool, measure the neutrons backscattered from the rock formation. The relationship between the two readings provides a ‘porosity index’ for the rock. This indicates how porous the rock is and whether it is likely to contain hydrocarbons or water.

(iii) The third type of tool, called the gamma–gamma or density tool, also contains two detectors and a ^{137}Cs source usually of up to 75 GBq. The amount of gamma backscatter from the formation provides the density log that, together with the porosity log, is a valuable indicator of the presence of gas. A brand name may refer to this technique.

(iv) The fourth technique, called neutron–gamma logging, involves a tool that houses a miniature linear accelerator. It contains up to several hundred gigabecquerels of tritium (^{3}H, a very low energy beta particle emitter). When a high voltage (typically 80 kV) is applied to the device, it accelerates deuterium atoms (^{2}H) that bombard the tritium target and generate a large number of very high energy (14–15 MeV) neutrons in pulses lasting a few microseconds. Certain nuclides become radioactive when hit by this neutron flux, and their subsequent radioactive decay within the next few milliseconds can be monitored when the process is repeated a great number of times per second. Either the gamma radiation emitted as the activated atoms decay or the thermal neutron decay characteristics are measured to identify the activated species of atoms [26]. The chlorine, or salt water, content of the rocks are of particular interest. A brand name may refer to this technique.

The gamma and neutron sources used in these tools are normally transported in separate heavy containers called shipping shields or carrying shields. They are Type A transport packages (or sometimes Type B for the neutron source) meeting the specifications for category III labelling as defined by the IAEA Regulations for the Safe Transport of Radioactive Material [27]. They may be transported by road in the vehicles of the logging companies to the land well (Fig. 19). When they are to be used offshore, the shields are usually contained in an overpack [27]. This may be a large thick-walled box (external dimensions about 1.75 m × 1.75 m × 1.75 m) that also serves as a storage container at the well site (Fig. 20). The shields do not provide adequate shielding for storing the sources without use of the large container. When the tools are hoisted into position above the well, the logging engineer transfers the sources from the shields to the tools using a handling rod of approximately 1.5 m long (Fig. 21). The dose rates of the ^{137}Cs source are significant [28, 29] but not normally isotropic due to the construction of the source assembly. Dose rates may exceed 7.5 µSv/h for up to 30 m in the forward direction and about 4 m behind the engineer. The radiation from the source is directed away from any occupied areas. The dose rates of the neutron sources can exceed 7.5 µSv/h for distances up to about 4 m. In addition to a ‘set’ of sources used in the logging tools, the logging engineer will need a number of ‘field calibration sources’ to carry out final checks on the tools before beginning the log. ‘Master calibrations’ are periodically performed on the tools at the logging company’s operations base. These tests will involve putting the sources into the tools or a section of the tool (Fig. 22), and either placing the tool inside a calibration block or placing a block over the source position on the tool. The master calibration for the neutron–gamma logging tool involves generating neutrons while the tool is inside a tank filled with a suitable fluid (for example, clean water). The tank and its contents remain radioactive for a short time (up to 30 min) after the tool has been switched off (Fig. 23).

FIG. 19. Radioactive source being transported by road (Courtesy: HPA-RPD, UK)

FIG. 20. Transport container used as a temporary store for well logging sources (Courtesy: HPA-RPD, UK)

FIG. 21. Wireline engineers transferring radioactive sources to logging tools on the drill deck (Courtesy: HPA-RPD, UK)

FIG. 22. Wireline engineer using a handling tool to transfer a radioactive source during a calibration procedure (Courtesy: HPA-RPD, UK)

FIG. 23. Controlled area in which low dose rate radiation test sources are used during tests in the workshop (Courtesy: HPA-RPD, UK)

The instrument technicians assigned to the service company’s base will use a range of sources of relatively low activity to aid in adjusting the settings of the radiation detectors.

The logging tools and the sources they contain are subjected to very high temperatures and pressures downhole. The sources normally fall within the definition of ‘special form radioactive material’ as sealed sources satisfying the test criteria specified by the IAEA [27] and ISO standards [30]. Nevertheless the source(s) are normally given the further protection of a special container (a ‘pressure vessel’) whenever they are in the shield or logging tool. The sources also need frequent checks for leakage of radioactive material in accordance with test criteria specified by ISO standards [31].

7.1.4.2. Additional uses of sources

While running the casing it is normal practice to insert small radioactive sources as ‘depth correlation markers’—these provide clear indications on the logs when the logging tool reaches the defined depths. These sources each contain about 50 kBq of ^{60}Co in the form of malleable metal strips (or tags) or point sources (pellets). They are inserted into threaded holes in the casing collars or the tags may be placed in the screw threads at the casing joints—the former configuration avoids the mutilation of the radioactive source.

During well completions, tags are usually attached to the perforating gun so that when the explosive charge is detonated and jets of plasma (very hot ionized gas) perforate the casing, the radioactive material contaminates the perforations. These sources are generally known as PIP tags after the original brand name (Precision Identification Perforation markers). A logging tool may be used to detect the spread and depth of the radioactive material to determine whether or not the charges have all fired at the intended depth and the perforating process has been successful. Some of the contamination may later be brought to the surface by the large volumes of fluids and solids flowing from the well but dilution factors are such that the activity concentrations will be very low in the topside plant and equipment.

The density of fluid may be measured at any depth in a well by using a small logging tool that resembles a large sewing needle (Fig. 24). A source of ^{241}Am of several gigabecquerels and a detector located opposite each other across the 'eye' of the needle to provide a measure the attenuation of gamma radiation that occurs when fluids enter between them. The sleeve shown in Fig. 24 is positioned over the gauge to prevent access to the source during storage and transport.

FIG 24. Gauge for measuring the density of well fluids (Courtesy: HPA-RPD, UK)

7.2. SAFETY OF SEALED SOURCES

Sealed radioactive sources used in the oil and gas industry are normally manufactured to specifications defined by ISO [30]. In normal circumstances, the radioactive material will remain encapsulated throughout its working lifetime and be returned intact to the supplier, manufacturer or other receiver authorized by the regulatory body. Sealed sources are subjected routinely to leakage tests at appropriate intervals to confirm that no leakage of the radioactive material has occurred. They are usually contained within shielding materials that are appropriate to the radiation and the application in order to optimize the protection afforded to those workers closely associated with the application and to others in the industry. Under normal circumstances, and with regard to reasonably foreseeable incidents, accidents and other occurrences, there is usually only a potential external radiation hazard. External exposure hazard controls rely on:

- The operator's established logistical organization;
- Communication, coordination and cooperation;
- Regulatory compliance (international and local);
- Provision and maintenance of all appropriate equipment;
- Adequate information, instruction and training.

Appropriate measures to control such hazards are described below and guidance on occupational radiation protection are given in a number of publications, including specific guidance on various practices [3, 4, 11, 12, 24, 27] (see also Sections 8 and 9).

7.2.1. Radiation safety during normal working conditions

Radiation sources are in common use throughout the oil and gas industry, and therefore represent sources of potential exposure of a wide range of workers in that industry. The transport and movement of packages and freight containing sources potentially exposes workers employed by various transport service companies supplying the industry's material needs by land, sea and air (Fig. 19). There is a need for good logistical organization by the operator to ensure that the sources and the workers trained to use or install them are mobilized to arrive in a coordinated manner. The industry is accustomed to good communications, ensuring that consignors and consignees are fully aware of the sources' movements and in-transit storage locations. Temporary and permanent storage arrangements for the sources on their arrival must meet standards satisfying the responsible regulatory body. These standards are likely to include requirements for security; intelligible warnings in local or multiple languages; adequate shielding; and separate storage away from other hazards, other (non-radioactive) materials, and working places (see Fig. 25).

FIG. 25. Store for radioactive sources (Courtesy: HPA-RPD, UK)

Work that includes the removal of radiation sources from shielded containers, particularly those manipulated during radiography and well logging, normally demands barriers to designate the extent of the controlled areas [4]. This presents a problem where space is limited, such as on offshore production platforms, and where the work must be carried out at a specific location, such as the radiographic examination of items in situ and well logging on the drill floor. Oil and gas production is almost continuous (except during shutdowns and workovers) and at isolated drill sites personnel will normally remain nearby even when they are off duty. Constraints need to be imposed on the radiography consistent with those of the working environment. One possibility would be to limit the source activity to an appropriate value, for example 1 TBq of ^{192}Ir, depending on the extent of the work site and any controlled areas designated while the work is in progress. This may result in a need to tolerate longer film exposure times and a reduced rate of radiograph production. Best use needs to be made of places that are most remote from normally occupied areas, e.g. by moving items to be radiographed on offshore platforms to the lowest level (the cellar deck) where feasible. The walls, floors and ceilings on offshore platforms/rigs may not provide enough shielding to reduce the dose rates to acceptable values in surrounding areas. The use of shielding placed near the source and carrying out the work in the vicinity of topside plant, such as storage tanks and vessels that provide shielding, will minimize the extent of controlled areas. It is important to provide good beam collimation, enabling beams produced during radiography and well logging to be directed away from occupied areas, and to adhere to appropriate procedures.

Warning systems such as public announcements, audible signals (for example, a portable air horn) and visible signals (for example, a flashing light in the vicinity of the work) help to restrict access to controlled areas.

7.3. WASTE MANAGEMENT OF SEALED SOURCES

The proper management of spent and disused sources by the owner/operator is of particular importance since such sources may still contain significant amounts of radioactive materials. If not properly managed this type of radioactive waste has the potential to present serious risks to human health and the environment. In many ways the waste management of sealed sources is more easily facilitated compared with the management of unsealed sources and NORM wastes due to their physical form and structure (i.e. contained) and incorporated safety features. A radioactive waste management programme applicable to sealed sources has to be documented and submitted to the regulatory body for review and approval. General guidance on the components and structure of such a programme is given in Refs [32, 33]. The most important aspects of the waste management programme are described in Sections 7.3.1 to 7.3.7.

7.3.1. Waste minimization strategies

The development of strategies to minimize waste generation is a high priority in the waste management programme. Some degree of waste minimization with regard to sealed sources can be achieved through:

- The use of relatively short lived radionuclides where possible;
- The use of the minimum quantity of radioactive material consistent with achieving the objective of the work application;
- Ensuring that sources are not physically damaged;
- Routine monitoring for source leakage (to minimize contamination of other items);
- The reuse of sealed sources and ancillary equipment e.g. shielding containers;
- Recycling by the manufacturer.

On-site decay storage is the preferred method of waste minimization in the case of short-lived radionuclides (half-life < 100–200 d), e.g. ^{192}Ir.

7.3.2. Waste inventories and characterization

A detailed waste inventory is maintained which includes:

- Source type, radionuclide and activity;
- All sources removed from regulatory control;
- All sources transferred to other facilities, e.g. manufacturer, storage, disposal.

Waste characterization information can be obtained from the manufacturer of the source.

7.3.3. Waste storage facilities

Suitable on-site storage areas are needed for spent and disused sources and for sources undergoing decay storage. Aspects to consider in the design of such facilities include:

- Physical security;
- Access controls;
- Handling systems and other operational aspects;
- Gamma dose rates on the exterior of the facility.

7.3.4. Pre-disposal management of radioactive waste

Pre-disposal management of radioactive waste may include a number of processing steps covering pre-treatment, treatment and conditioning as well as storage and handling operations and transport prior to disposal. In the case of sealed sources used in the oil and gas industry the options are generally limited to decay storage and transport to a centralized conditioning, interim storage or disposal facility.

7.3.5. Disposal methods

The preferred disposal option is that, when purchasing sealed sources, contractual arrangements be made that allow the return of sources to the manufacturer following use. This is particularly important in the case of high activity sources that cannot be removed from regulatory control until after many years of decay storage or for sources containing long lived radionuclides. Long lived sources are generally conditioned by means of encapsulation in welded steel capsules.

An alternative would be to transfer the sources to a waste management or disposal facility authorized by the regulatory body. If no disposal facility is available, the operator makes provision for the safe long term storage of spent and disused sources preferably at a centralized storage facility approved by the regulatory body. The storage facility:

- Ensures isolation;
- Ensures protection of workers, the public and the environment;
- Enables subsequent handling, movement, transport or disposal.

Sealed sources should never be subjected to compaction, shredding or incineration. Neither should they be removed from their containers nor the containers modified, as this can lead to the contamination of other items and areas.

7.3.6. Transport of radioactive waste

All waste must be packaged and transported in accordance with the IAEA Regulations for the Safe Transport of Radioactive Materials [27]. The necessary waste inventory and waste characterization information should accompany waste consignments.

7.3.7. Record keeping and reporting

A suitable and comprehensive record keeping system is usually required for radioactive waste management activities. The record system allows for the traceability of waste from the point of generation through to its long term storage and/or disposal. It is the responsibility of the regulatory body to determine the reporting requirements of the owner/operator with regard to radioactive wastes. However, the owner or operator also has responsibilities, namely, to always exercise a duty of care with respect to radioactive waste management activities and to have sufficient records to ensure that the waste management is performed appropriately.

8. SPECIAL FOCUS TOPIC: GAMMA RADIOGRAPHY

This section is an extract from the IAEA Practical Radiation Safety Manual (PRSM) entitled “Manual on Gamma Radiography, PRSM-1” [11]. PRSMs are practically-oriented documents aimed primarily at persons handling radiation sources on a daily routine basis, but which could also be used by the relevant authorities, supporting their efforts in the radiation protection training of workers or medical assistance personnel or helping on-site management to set up local radiation protection rules. Each PRSM is in three parts:

(i) An Applications Guide, which is specific to each application of radiation sources and describes the purpose of the practice, the type of equipment used to carry out the practice and the precautions to be taken;

(ii) A Procedures Guide, which includes step by step instructions on how to carry out the practice. In this part, each step is illustrated with drawings to stimulate interest and facilitate understanding;

(iii) A Basics Guide, common to all PRSMs, which explains the fundamentals of radiation, the system of units, the interaction of radiation with matter, radiation detection, etc.

This Special Focus Topic is based on the Procedures Guide, and is designed to stimulate discussion on good practice and to demonstrate how the Procedures Guide can be used for training purposes. The Procedures Guide contains the following instructions:

1. Follow authorized procedures when carrying out gamma radiography.

2. Only trained radiographers and authorized helpers who have had medical examinations and wear a dosimeter should carry out radiography. In normal circumstances, such workers should not have received greater than a dose limit (50 mSv to the whole body) in the current calendar year.

3. Before proceeding with the work, read and ask questions about these safety guides. Discuss the contributions all the workers involved will make to this important work.

4. Rehearse the procedures and only use equipment that has been specifically manufactured for gamma radiography. The radiographer should be familiar with all of the equipment, its mode of operation and potential problems. An understanding of the source, its appearance and how it is to be exposed are particularly important.

5. Only carry out radiography when all the necessary equipment is available:

   (i) A suitable source housed in an appropriate container;

   (ii) Guide tubes, control cables or other source handling tools;

   (iii) Collimators; barrier-making equipment;

   (iv) Warning notices and signals;

   (v) Dose rate meter;

   (vi) Emergency kit.

6. Record weekly maintenance carried out on the container, for example:

   (i) Clean the container, removing grit and moisture.

   (ii) Use only recommended lubricants to clean and maintain any moving parts.

   (iii) Check screws and nuts for tightness and screw threads and springs for damage.

   (iv) Confirm that the source locking mechanism works.

   (v) Remove the cover to examine the end of the pigtail for cleanliness, wear or damage. A wear gauge should be used.

   (vi) Connect the control cable to the pigtail and check by gently pulling or twisting that it does not accidentally disconnect.

   (vii) With the transit plug still in place, connect the cable housing to the locking ring and ensure a firm connection.

   (viii) Disconnect the cable housing and cable, relock the pigtail and then remove the transit plug from the guide tube port.

   (ix) Connect the guide tube, checking for crossed threads and a firm connection.

   (x) Remove the guide tube and replace the transit plug.

   (xi) Check that warning plates and source details are readable.

   (xii) Measure the dose rates close to the container's surface.

7. Report any faults to your supervisor.

8. Keep a record to show that weekly maintenance has been carried out on ancillary equipment, for example:

   (i) Check the control cable crank and container connection ring or other source handling tool for loose fittings.

   (ii) In a clean area, wind out a short length of cable to check for kinks and a smooth crank movement.

   (iii) Use only recommended lubricants to clean and maintain moving parts.

   (iv) Examine the cable end for damage or wear. A wear gauge should be used.

   (v) Examine the control cable housing for tears, dents or other damage which might affect cable movement.

   (vi) Examine guide tube and extension tubes for burred connector threads, dents or grit which might affect source movement.

9. Report any faults to your supervisor.

10. Prepare each radiographic shot in advance.

11. Consider moving the object to a place set aside for radiography where it will be either easier to prevent access or possible to do radiography without disrupting other construction work.

12. Calculate the current activity of the source and the exposure times needed.

13. If possible, choose shots which use a collimated beam and consider which beam directions are least likely to be occupied.

14. Examine whether it will be possible to use local shielding.

15. Calculate where the barriers will need to be to mark the Controlled Area and discuss with the site management when, and for how long, the area can be cleared of other workers.

16. Advise site management precisely when and where radiography will be carried out. Obtain any necessary permits and collect all documents.

17. Take all ancillary equipment to the location in advance. Deliver the barriers before the scheduled time, especially if only a short period (for example a meal break) has been set aside for the radiography to be carried out.

18. Collect the source store key and sign the source out.

19. Check that the container is locked and use a dose rate meter to confirm that the source is shielded. This also serves as a check on the dose rate meter by comparing the reading with those previously obtained.

20. Attach two transport labels to the container and display warning placards on the vehicle. Secure the container segregated from the occupants.

21. On site, at the arranged time, instruct helpers to first erect the barriers and warning notices and then to search the area to confirm that it is clear of other workers. Meanwhile, firmly fix the collimator in position and lay the guide tube out straight, checking that it was not damaged in transit.

22. Remove the container's transit plug (keep it clean and safe) and connect the guide tube.

23. Place the control crank near the container, uncoil the control cable and form it in a long loop, again checking for transit damage.

24. Unlock the container and remove the pigtail cover. Turn the control crank to reveal the cable and connect the cable to the pigtail. Confirm that this is a good connection before turning the crank to bring the control cable housing to the container to be secured.

25. Lay out the control cable as straight as possible and place the control crank preferably outside the marked area behind any available body shield.

26. Place a warning light or large notice near the collimator to mark the exposed source position.

27. The equipment is now ready to carry out a test exposure.

28. When the helpers have checked that the area is clear and have taken up their positions at the barrier in order to prevent unauthorized access, sound a prearranged signal (for example, a loud whistle) to warn everyone near the Controlled Area that the source is about to be exposed.

29. Turn the crank quickly whilst counting the revolutions to ensure that the source is driven the full extent of the guide tube and into the collimator.

30. Leave the Controlled Area by the safest and, if practicable, the shortest route.

31. Dose rates in excess of 7.5 μSv/h will briefly occur at the barriers as the source travels along the guide tube but when the source is in the collimator the barrier should properly mark the extent of the Controlled Area.

32. Use the dose rate meter to check that the barrier is positioned in the correct place, especially along the beam direction. Move the barrier positions if necessary.

33. Return to the control quickly and turn the crank whilst counting the revolutions to ensure that the source is fully retracted into the container.

34. Use the dose rate meter to check the guide tube from the collimator to the container and finally check the dose rates at the container to confirm that the source is safely shielded.

35. The photographic films and film identification markers can now be attached.

36. Expose the source as previously described and time the exposure to produce the radiograph. For short exposure times it might not be possible to completely leave the Controlled Area. A convenient point should be taken up where the measured dose rate is as low as practicable and in any case is less than 2 mSv/h.

37. After each exposure use the dose rate meter to check the guide tube from the collimator to the container and finally check the dose rates at the container to confirm that the source has safely retracted.

38. The guide tube and collimator can now be safely handled and repositioned, together with the next film and identification markers.

39. Throughout each exposure stay alert and use the dose rate meter to confirm that the exposure is proceeding normally. If anything unexpected happens, such as someone entering the Controlled Area or a site emergency, quickly return to the control and retract the source.

40. If for any reason the source fails to retract, stay calm and move away to the barrier.

41. Measure the dose rates and, if necessary, reposition or set up new barriers. Stay close to the area to prevent people entering and send helpers to inform the site management and to bring the emergency kit.

42. The contingency plan should follow previously agreed stringent guidelines using time, distance and shielding to limit individual doses.

43. If the crank will not turn it may be necessary to dismantle the control to pull the control cable back by hand.

44. If the pigtail has detached from the cable or the source has stuck in the guide tube it will first be necessary to locate the source. Winding out the cable might push the source back into the collimator.

45. If shielding is placed on top of the guide tube close to the container and the control cable housing is then pulled, that part of the guide tube containing the source will eventually be pulled under the shielding.

46. The dose rate being measured at some distance away will then fall.

47. Placing more shielding on top of the source will allow closer access either to disconnect the guide tube from the container or to carefully cut the plastic sheath and unwind the wall of the guide tube.

48. Handling tongs can be used to lift an end of the guide tube so that the source pigtail slides out onto a solid surface.

49. Using the handling tongs the pigtail can be picked up and placed back in the container.

50. UNDER NO CIRCUMSTANCES SHOULD THE SOURCE BE ALLOWED TO COME INTO CONTACT WITH THE HANDS OR ANY OTHER PART OF THE BODY.

51. After the final exposure or when it needs to be moved to another area the radiography equipment must be disassembled.

52. Use the dose rate meter to check the guide tube from the collimator to the container and finally measure the dose rates at the container to confirm that the source is safely shielded.

53. Form the control cable in a long loop with the crank near the container.

54. Keep the dose rate meter working by your side and disconnect the cable housing from the container, if necessary turning the crank slightly to achieve this.

55. Lock the pigtail in the container and turn the crank to reveal the connection between the cable and the pigtail. Disconnect the cable and fit the pigtail cover.

56. Coil the control cable and set it aside. Disconnect the guide tube from the container and insert the transit plug in place.

57. Lock the source in the container.

58. Ensure that the container still displays two legible transport labels. Safely return the container to the source store. If a vehicle is used it should display warning placards and the container should be secured away from the occupants.

59. Wipe the container clean before placing it in the store and note its safe return in the record book.

60. Return the key to a safe place and maintain the security of the store at all times.

9. SPECIAL FOCUS TOPIC: NUCLEAR GAUGES

This section is an extract from the IAEA Practical Radiation Safety Manual (PRSM) entitled "Manual on Nuclear Gauges, PRSM-3" [12]. PRSMs are practically-oriented documents aimed primarily at persons handling radiation sources on a daily routine basis, but which could also be used by the relevant authorities, supporting their efforts in the radiation protection training of workers or medical assistance personnel or helping on-site management to set up local radiation protection rules. Each PRSM is in three parts:

(i) An Applications Guide, which is specific to each application of radiation sources and describes the purpose of the practice, the type of equipment used to carry out the practice and the precautions to be taken;

(ii) A Procedures Guide, which includes step by step instructions on how to carry out the practice. In this part, each step is illustrated with drawings to stimulate interest and facilitate understanding;

(iii) A Basics Guide, common to all PRSMs, which explains the fundamentals of radiation, the system of units, the interaction of radiation with matter, radiation detection, etc.

This Special Focus Topic is based on the Procedures Guide, and is designed to stimulate discussion on good practice and to demonstrate how the Procedures Guide can be used for training purposes. The Procedures Guide contains the following instructions:

1. Follow authorized procedures when working with nuclear gauges.

2. Only trained and authorized workers should carry out the work. If appropriate, the workers should have had medical examinations and wear dosimeters.

3. Before proceeding with the work, read and ask questions about these safety guides. Discuss with your colleagues your contributions to this important work.

4. Use only established methods, suitable equipment and a sealed source of an activity which is appropriate to the gauge's purpose. A portable gauge should be used only when all the necessary ancillary equipment which is associated with the particular gauge is also available. This might include source handling tools, barriers, warning notices and signals and a dose rate meter.

5. Keep safe and properly stored:

   (i) Any source or housing which is waiting to be installed;

   (ii) Any source housing which has been removed from its installation; or

   (iii) Any portable gauge which is temporarily not in use.

6. Make regular, for example weekly, entries in a record to show that a check has been made on the stored items.

7. Keep a record to show where installed gauges are.

8. Keep the key for the source store in a safe place.

9. Before removing a gauge or interchangeable source from the store, remember to record who has them and where they are being moved to.

10. Check that the container is locked and use a dose rate meter to confirm that the source is shielded. This also serves as a check on the dose rate meter.

11. Attach two transport labels to the container and display warning placards on the vehicle. Keep the container segregated from the occupants.

12. Check installed gauges periodically, for example monthly, to confirm that they are safely installed. Measure accessible dose rates and ensure that a physical barrier marks the extent of any Controlled Areas.

13. Block any gaps in the shielding which might be inaccessible to the dose rate meter but not to fingers and hands. This is especially important if the gaps provide access to the primary beam.

14. Check that the shielding is firmly secured .

15. Check that warning signs are readable, especially on shielding and access doors or panels.

16. Maintenance workers should be reminded which person is to be contacted to ensure that the shutter is locked in the closed position before they enter these areas.

17. Before using a portable gauge, or working on an installed gauge, set up a barrier and warning signs either to mark the extent of the Controlled Area or as an indication to other persons in the vicinity to keep clear. Never leave a Controlled Area unattended.

18. Whilst working with a gauge, keep the dose rate meter with you and switched on. Use the dose rate meter to check that the shutter has closed after you have used a portable gauge. Likewise, check that the shutter is locked in the closed position before removing an installed gauge from its position.

19. Unless you are specifically trained and authorized to do so:

    (i) Never attempt to remove a source from its housing; and

    (ii) Never attempt to modify or repair the housing.

20. Appropriate handling tools and approved procedures must be used by persons who are responsible for manipulating sources. A source must not be allowed to be in contact with any part of a person's body.

21. Carry out the necessary routine maintenance. A portable gauge may require attention after each use but, before closely examining it, remember to use the dose rate meter to check that the shutter has closed or the source is otherwise safely shielded. Installed gauges will need less attention. Keep a record to show that the regular maintenance has included, for example:

    (i) Cleaning the outside of the housing to remove grit and moisture.

    (ii) Ensuring that external surfaces of the gauge are kept in good condition and that labels, warning signals and the tag displaying details of the source remain legible.

(iii) Using recommended lubricants to clean and maintain any moving parts.

(iv) Examining any screws and nuts for tightness.

(v) Checking to see that the source is securely held within the housing and that uniform dose rates are measurable on all external surfaces of the housing.

(vi) Examining source handling tools for damage to springs, screw threads or the like.

(vii) At the recommended intervals, and in the prescribed manner, carrying out leakage tests.

22. Report any faults to your supervisor.

23. If a gauge is involved in an accident or incident stay calm.

24. If the gauge is undamaged, do what is necessary to make it safe. For example, using a dose rate meter, confirm that the shutter is closed and place the gauge in its transport container.

25. If the housing appears to be damaged, move away from it and keep others away. Measure the dose rates and set up a barrier which marks the Controlled Area.

26. If it is suspected that the source has been very badly damaged, prevent access to those surfaces which might be contaminated by the radioactive substance. Detain anyone who may either have received a radiation dose or been in contact with a contaminated surface. Stay close but outside the marked area and send someone to inform your supervisor and obtain help. A leak test will indicate whether a source has been seriously damaged. A gauge which might be damaged should not be reused until it has been examined and, if necessary, repaired by a competent, authorized technician.

27. When work involving portable gauges or interchangeable sources is completed, a dose rate meter should be used to confirm that the sources are safely shielded.

28. Ensure that any container still displays two legible transport labels. If a vehicle is used, it should display warning placards to transport the container back to the source store.

29. A note of the return of sources should be made in the record book.

30. In the event of loss or theft of a source, inform your supervisor at once.

31. As soon as you have no further use for a gauge or a radioactive source, it should preferably be returned to the manufacturer or supplier. If any other method of disposal is used it must comply with your Government's laws. Radioactive substances being sent for disposal must be appropriately packaged and transported in accordance with the IAEA Regulations for the Safe Transport of Radioactive Material.

10. UNSEALED RADIOACTIVE MATERIAL

10.1. PRACTICES INVOLVING UNSEALED RADIOACTIVE MATERIAL

In the oil and gas industry, radioactive material may be used in solid, liquid, or gaseous forms to perform tracer studies. The objective of tracer studies is to provide the investigator with information concerning flow rates of liquids or gases, to determine if closed system leakage is occurring and to determine if a task has been successfully completed. To achieve the objectives of a tracer study, the radioactive material, including its physical form, must be compatible with the materials being studied, and the decay characteristic needs to be appropriate for the study being performed and to minimize residual contamination in the system or product being studied [34]. The radiotracer must have the ability to be easily detected and/or measured. Typical properties of a physical radiotracer include:

(a) Capability to follow the material under investigation but not display the same chemical behaviour as, or react with, other material in the system under investigation;

(b) Stability of form such that it will not degrade in the high temperatures, pressures or corrosive media into which it is introduced;

(c) Minimal radiotoxicity, i.e. dose per unit activity intake;

(d) Half-life compatible with the investigation schedule so as to minimize residual contamination in the system or product;

(e) Suitable radiation emissions making it readily detectable;

(f) Initial activity that is as low as reasonably achievable (ALARA), taking into account the radiotracer's half-life, the anticipated activity at the measurement locations and the detection limits of the techniques employed.

Alpha emitters are not easily detected and are generally not used as tracer material. Beta emitters, including ^{3}H and ^{14}C, may be used when it is feasible to use sampling techniques to detect the presence of the radiotracer, or when changes in activity concentration can be used as indicators of the properties of interest in the system. Gamma emitters, such as ^{46}Sc, ^{140}La, ^{56}Mn, ^{24}Na, ^{124}Sb, ^{192}Ir, ^{99m}Tc, ^{131}I, ^{110m}Ag, ^{41}Ar and ^{133}Xe, are used extensively since they can be easily detected and identified by their gamma spectrum. Using gamma emitters allows the investigator to run multiple tracer studies simultaneously and to detect and identify the tracer non-invasively with no or minimal disruption to production.

10.1.1. Radiotracer and marker studies

10.1.1.1. Upstream radiotracers

Radiotracers are used during completion, stimulation and recovery enhancements to determine that procedures have been carried out satisfactorily. Some examples are described below.

As cement is mixed for a well completion, a glass ampoule containing scandium oxide incorporating 750 MBq ^{46}Sc as powdered glass is released into the slurry tank just before the initial batch of cement is to be pumped downhole. By releasing the radioactive material directly into the cement, the contamination of equipment and the risk of spillage are minimized. The tank is monitored as the slurry is pumped to the bottom of the string and the grout rises to fill the annulus. As pumping continues, a logging tool is lowered down the well through the displacement fluid to detect and monitor the progress of the plug of radiotracer rising up the annulus until its appropriate position is reached.

To evaluate whether a fracturing process to stimulate the flow has penetrated rocks in the pay zone, plastic pellets coated with approximately 10 GBq of ^{110m}Ag are added to a proppant during the ‘frac job’. When the fracturing work is completed and surplus fluids are removed from the well, to prevent their solidification in the tubing string, the job is assessed by lowering a logging tool down the well to detect and map out the movement and final positions of the injection fluids and proppants.

Radiotracer ‘spikes’, comprising ^{99m}Tc and ^{131}I solutions, are released from logging tools into production wells to determine the time taken for the radioactivity to traverse the known distance between two radiation detectors, thus indicating the flow rate of the well fluids. When radiotracers are injected along with waterflood and gas drives, it is possible to identify the flow patterns, thief zones, channelling, flow rates of injected fluids in the reservoir and the relationship(s) between injector and producer wells. The activities injected are significant (see Fig. 26)—up to 1 TBq of ^{3}H and ^{14}C labelled compounds—but the activity concentrations of samples obtained at the producer wells are very low.

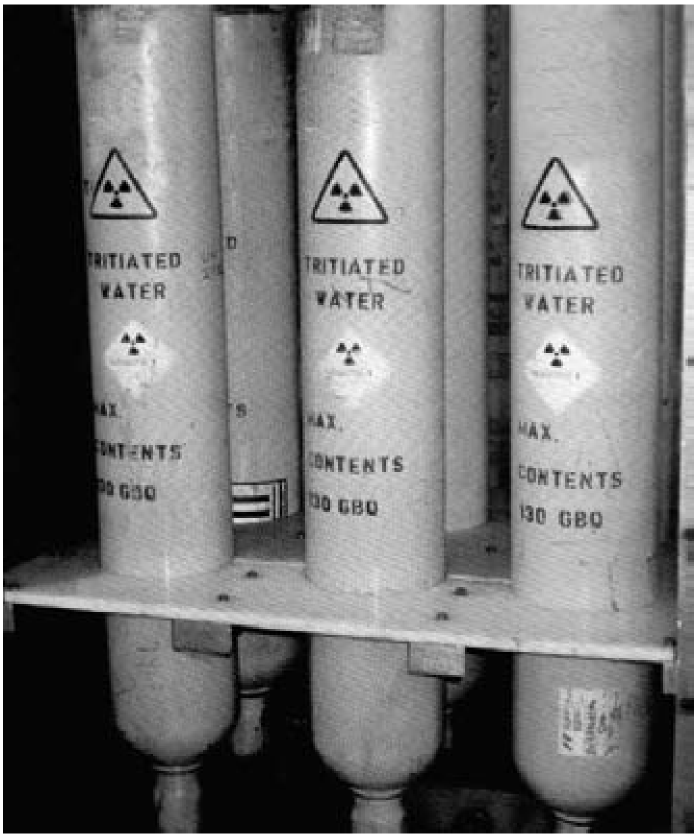

FIG. 26. Tritiated water for injection as a radioactive tracer (Courtesy: Scotoil Group plc)

In order to aid the detection of any spillage of solutions of these ‘soft’ beta emitters, they are sometimes spiked with a short half-life gamma emitter such as ^{82}Br, which will need measures to minimize external exposures at the injection well. ‘Hard’ beta emitters, such as the gaseous radiotracer ^{85}Kr, generate bremsstrahlung and also need measures to minimize external exposures.

10.1.1.2. Downstream radiotracers

Flow rate measurement is one of the most common applications of radiotracers. It is used to calibrate installed flow rate meters, measure the efficiency of pumps and turbines, investigate flow maldistribution and heat transfer problems and make plant or unit mass balances. The two methods in widest use rely on ‘pulse velocity’ and ‘dilution flow’ measurements.

The pulse velocity method [35] relies on the injection of a sharp pulse or spike of gamma emitter into the process stream. The flow needs to be turbulent and completely fill the pipe bore. Downstream, at a distance sufficient to ensure a good lateral mixing of the radiotracer with the process stream, two radiation detectors are positioned separated by an accurately measured distance L. As the radiotracer passes, the response of each detector is registered and the mean transit time T is measured. Knowing the mean internal cross sectional area A of the pipe bore, the mean linear flow velocity L/T can be calculated and converted to volume flow rate ($V=LA/T$).

The dilution flow method [36] does not need the flow to be full bore or in a closed circuit. The flow can be in open channels, ditches, sewers or rivers. A known activity concentration C of radiotracer is introduced at a known constant rate U. Downstream, at a distance that allows complete lateral mixing, samples are taken and the activity concentration S is measured. The volume flow rate V is very much greater than the injection rate U and may be calculated ($V=CU/S$).

Often a leak may be inferred from flow rate measurements. In other circumstances, leaks may be detected directly, for example when radiotracer seeps from a pipeline either above or below ground level.

Residence time measurements have also served to detect leaks across feed–effluent exchangers associated with catalytic reactors. A radiotracer is injected at the inlet of the vessel and a detector provides a signal to record the time of its entry. Another detector at the vessel outlet is used to measure the instantaneous concentration of tracer leaving the vessel. The response or ‘C curve’ of this detector represents the residence time distribution of material in the vessel. A long residence time indicates excellent mixing in the vessel and a short residence time indicates poor mixing (plug flow). The presence of a subsidiary peak prior to the main peak in the residence time distribution curve may indicate a leak across the exchanger. Mean residence time of materials in chemical process vessels and the distribution of residence times both influence the output and quality of the product. Analysis of C curves provides quantitative information relevant to the design of mixing characteristics of full size plant.

10.2. SAFETY OF UNSEALED RADIOACTIVE MATERIAL

10.2.1. Preparation of unsealed radiotracers

The radiotracers obtained from the isotope production facility may be suitable for use directly or may need to be prepared in a laboratory that the regulatory body has licensed to process the radioactive materials. Preparation might include ‘labelling’ or tagging the non-active substrates such as glass or plastic beads of known mesh size with radioactive material. The laboratory may bake the radioactive material on to the bead surfaces or otherwise incorporate the radioactive material into the beads. Alternatively, the radioactive material might be supplied in a suitable form, such as a coarse radioactive glass or sand and the laboratory will simply dispense a known aliquot of the radioactive material. The preparation is intended to aid in minimizing the handling and complexity of manipulations at the site where the radiotracer is introduced into the system to be investigated. The licensee must implement special procedures to minimize dispersal, surface contamination, and/or airborne contamination from liquids, powdered solids and gases.

The laboratory will need appropriate facilities including controlled areas for handling open radioactive material and to deal with potential contamination arising through routine handling or more serious spills. Engineered controls, such as a hood or an extraction ventilation system, will prevent the dispersal, ingestion or inhalation of radioactive material. A monitoring programme needs to include surface contamination measurements and dose rate surveys, airborne contamination measurements and individual monitoring for external and internal doses [37, 38].

The laboratory will package the radiotracer for transportation to the site. It is preferable that the design of the package and packaging be such that the radiotracer is ready for immediate application at the site. The design and any contamination on internal and external surfaces of the package must satisfy specifications and limits defined by the regulatory body. As consignor, the laboratory must be conversant with labelling and documentation required for the transport package(s).

10.2.2. Work with radiotracers

The operator will normally employ an injection company specializing in tracer techniques to be the end user of the radiotracer. The operator or the end user as required by the regulatory body will obtain a licence to carry out the work. The regulatory body will require a licence application to be accompanied by sufficient details of the radiotracer to be used, the intended radiation protection and operation procedures, sampling intentions if appropriate and proposals to deal with the radioactive waste expected to arise.

The injection company will prepare the well site or job site appropriately for handling and processing unsealed radioactive material for normal working and to mitigate the consequences of any incident that might occur. Usually the work will be carried out under circumstances that are much less ideal than in the laboratory. However, the same radiation protection principles can be applied. The injection company provides:

- Adequate containment for actual and potential contamination;
- Suitable equipment including personal protective equipment (including respiratory protection as appropriate) and monitoring instruments;
- Washing facilities and arrangements for good industrial hygiene measures.

Suitable preparation and adherence to predefined procedures will not only minimize the possibility of environmental contamination but also reduce the risk of external and internal exposure to radiation workers and other persons in the vicinity. These procedures include a survey to determine background conditions prior to the start of any operations by the injection company and the establishment of a controlled area around the work area to prevent unauthorized persons from being exposed to radiation or becoming contaminated with the radioactive material. Controlled areas, where there is a significant risk that the radiotracer material could be spilled, are arranged to contain any such spillage. All relevant exposure pathways must be considered including the inhalation of volatile material such as when ^{131}I is used in tracer studies. The risk of inhalation can be minimized or eliminated by using alternative non-volatile radionuclides such as ^{99m}Tc instead of ^{131}I.

When the radiotracer is to be injected into a high pressure system (see Fig. 27), it is particularly important that the service company uses suitable valve systems and operational procedures that minimize the possibility of contamination, for example checking that connections are tight before injecting the radiotracer. An experienced injection company will be aware of, and prepare for, the problems that may occur, such as a ‘sand-out’. This occurs when the pressure in the wellbore causes the backward flow of fluids to the surface. When a radiotracer has been injected into a well, a sand-out can result in surface contamination around the wellhead. The injection company is responsible for decontaminating any area or equipment that is contaminated as a result of the operations. This includes ancillary items not owned by the injection company, such as mixing vessels, flow lines, tubing and any other equipment contaminated by the radioactive material. The decontamination must reduce residual contamination to agreed clearance levels acceptable to the regulatory body. The injection company must carry out surveys to demonstrate that any equipment that has been contaminated by radiotracer, but will not remain under the control of the licensee, satisfies release requirements accepted by the regulatory body. Records of the contamination survey results must be copied to the facility operator. The injection company’s procedures should include contingency plans for all reasonably foreseeable incidents, accidents and other occurrences. All necessary equipment to implement those plans, including decontamination procedures, should be kept readily available.

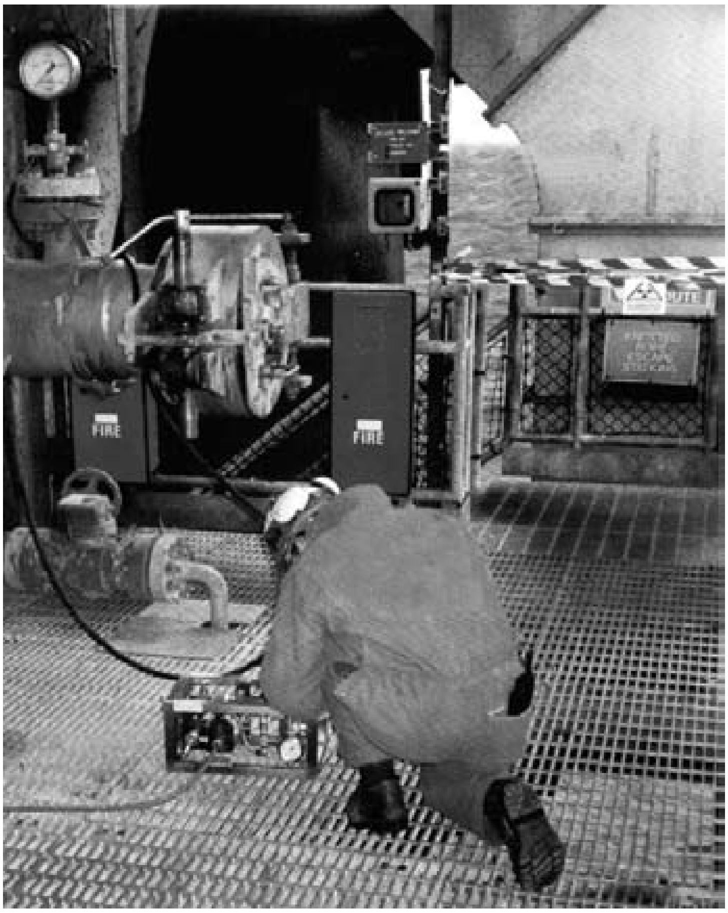

FIG. 27. Radioactive gas being injected at high pressure for use as a tracer (Courtesy: Scotoil Group plc)

10.3. WASTE MANAGEMENT

The proper management of unsealed radioactive sources and wastes by the owner/operator is of particular importance. If not properly managed and controlled, the waste has the potential to contaminate working and non-working areas and persons and may in some cases present serious risks to human health and to the environment.

Tracer work creates radioactive waste that must be stored and disposed of in accordance with the requirements of the regulatory body. The laboratory's waste is likely to include laboratory aprons, gloves and overshoes, absorbent materials, glassware and similar low level radioactive waste as well as possibly higher activity concentrations of excess radioactive material. The injection company's wastes will include absorbent materials, industrial personal protective equipment and surplus radiotracer. The service companies must maintain inventories of all radioactive materials received, sold, used, stored, decayed and disposed of.

All radioactive material declared as waste must be managed in accordance with the requirements of the regulatory body. This includes radioactive material that may have been ordered and received but not used. The regulatory body will issue a licence authorizing accumulations of radioactive waste of short half life to be kept until they have decayed to a sufficiently low level of activity concentration to be discarded.

A radioactive waste management programme applicable to unsealed sources needs to be documented and submitted to the regulatory body for review and approval. General guidance on the components and structure of such a programme is given in Ref. [32], and the important aspects are discussed in Sections 10.3.1 to 10.3.7.

10.3.1. Waste minimization strategies

The development of strategies to minimize waste generation should be a high priority in the waste management programme. A significant degree of waste minimization with regard to unsealed sources can be achieved by:

- Using relatively short lived radionuclides where possible;
- Using the minimum quantity of radioactive material consistent with achieving the objective of the work application;
- Applying strict controls during the use of unsealed sources in order to minimize the contamination of other materials and objects;
- Minimizing the presence of unnecessary materials and items in controlled areas where open sources are handled;
- Recycling of unused source material by the manufacturer;
- Decontaminating and cleaning items and areas.

On-site decay storage is the preferred method of waste minimization in the case of short lived radionuclides (half life less than 100–200 d), e.g. ^{192}Ir.

Waste volumes can be reduced by various methods, e.g. paper and plastic materials contaminated with radionuclides may be compacted or shredded. Other methods such as incineration would require that the waste be packaged and transported to a waste treatment facility authorized by the regulatory body.

Active practical measures (e.g. covering with plastic) should be taken during work with unsealed sources to prevent equipment from becoming contaminated. Contaminated equipment should be decontaminated wherever this is possible either at on-site or off-site facilities.

Equipment and materials that cannot be decontaminated to authorized clearance levels must be disposed of as radioactive waste in accordance with the requirements of the regulatory body.

10.3.2. Waste inventories and characterization

A detailed waste inventory has to be maintained which includes:

- Source type, radionuclide and activity;
- Lists of all sources removed from regulatory control;
- Lists of all radioactive waste transferred to other facilities e.g. manufacturer, storage, disposal.

Waste characterization information can be obtained from the manufacturer of the source.

10.3.3. Waste storage facilities

Suitable on-site and off-site storage areas are usually required for unsealed radioactive wastes. Storage may be required for purposes of decay, or as a management step prior to pretreatment, treatment and conditioning, or prior to disposal. Considerations in the design of such facilities include:

- Physical security;
- Access controls;
- Waste handling systems;
- Controls over contamination;
- Gamma dose rates on the exterior of the facility.

10.3.4. Pre-disposal management

This may include several processing steps that cover pre-treatment (e.g. collection and segregation), treatment, and conditioning (e.g. storage and handling operations and transport prior to disposal). In the case of unsealed sources the following aspects need to be carefully considered in the waste management programme:

(i) Aspects related to the collection of waste (e.g. minimization of waste volumes, design of waste collection receptacles);

(ii) Segregation of wastes at the point of generation, for instance:

  - Segregation of radioactive and non-radioactive wastes;
  - Segregation based on half-life (e.g. for the purpose of decay storage);
  - Segregation based on activity levels;
  - Segregation based on the physical and chemical form of the waste (e.g. solid, liquid);

(iii) Treatment aspects, such as:

- Compaction or decontamination of solids;
- Absorption of liquids into a solid matrix.

(iv) Conditioning, e.g. to meet packaging, handling and transport requirements.

10.3.5. Disposal methods

The preferred disposal option for unsealed radioactive waste is transfer to a waste management or disposal facility authorized by the regulatory body. Some degree of pre-disposal management such as compaction may be required to reduce waste volumes. In addition the waste would require to be properly packed for transport.

If no disposal facility is available, the operator will need to make provision for safe long term storage preferably at a centralized storage facility approved by the regulatory body. The storage facility:

- Ensures isolation;
- Ensures protection of workers, the public and the environment;
- Enables subsequent handling, movement, transport or disposal of the waste.

10.3.6. Transport

All waste must be packaged and transported in accordance with the IAEA Regulations for the Safe Transport of Radioactive Materials [27]. Waste consignments should be accompanied by the necessary waste inventory and waste characterization information.

10.3.7. Record keeping and reporting

A suitable and comprehensive record keeping system is usually required for radioactive waste management activities. The record system allows for the traceability of waste from the point of generation through to its long term storage and/or disposal. It is the responsibility of the regulatory body to determine the reporting requirements of the owner/operator with regard to radioactive wastes. However, the owner or operator also has responsibilities, namely, to always exercise a duty of care with respect to radioactive waste management activities and to have sufficient records to ensure that the waste management is performed appropriately.

11. SPECIAL FOCUS TOPIC: PERSONAL PROTECTIVE EQUIPMENT

The material presented in this Special Focus Topic is based on IAEA Practical Radiation Technical Manual PRTM-5 on Personal Protective Equipment [14].

11.1. GENERAL CONSIDERATIONS

Personal protective equipment (PPE) includes clothing or other special equipment that is issued to individual workers to provide protection against actual or potential exposure to ionizing radiation. It is used to protect each worker against the prevailing risk of external or internal exposure in circumstances in which it is not reasonably practicable to provide complete protection by means of engineering controls or administrative methods. Adequate personal protection depends on PPE being correctly selected, fitted and maintained. Appropriate training for the users and arrangements to monitor usage are also necessary to ensure that PPE provides the intended degree of protection effectively.

The principal types of PPE are explained, including protective clothing and respiratory protective equipment (RPE). Examples of working procedures are also described to indicate how PPE should be used within a safe system of work. The material presented in this Special Focus Topic will be of most benefit if it forms part of a more comprehensive training programme or is supplemented by the advice of a qualified expert in radiation protection. Some of the RPE described here should be used under the guidance of a qualified expert.

11.1.1. Control of exposure

Workers can be protected against ionizing radiation by using either one or a combination of the following means:

(a) Engineering controls,

(b) Administrative controls,

(c) Personal protective equipment (PPE).

Whenever it is reasonably practicable, protection should be provided ‘at the source’. This may involve selecting a radioactive substance of the most appropriate activity and form for a specific application, such as using a source of the minimum activity necessary and in a physical form that is least likely to spill. The term also implies that priority should be given to using engineering controls as a barrier around the source, automatically protecting workers in the vicinity against external and/or internal exposure. The practice should preferably be inherently safe by design.

Protection against external exposure may be achieved by using a combination of shielding and distance. Effective devices and warnings are needed to ensure that the source remains shielded and/or that the correct distance is maintained between the source and those who may potentially be exposed to the radiation hazards. Protection against internal exposure is achieved by containing radioactive substances and/or preventing their dispersal, to avoid causing contamination. Containment can be supplemented, if necessary, by further engineering controls such as extraction ventilation from a point (or points) close to where any dispersion is likely to occur. High efficiency particulate air (HEPA) filters incorporated into the ventilation system will remove radioactive particulates from the extracted air.

Administrative controls can be less effective than engineering controls because their effectiveness relies on the cooperation and awareness of individual workers to restrict exposures. For example, exposures might be restricted by limits on who may enter or on how long workers may remain inside controlled and supervised areas.

11.1.2. Types of personal protective equipment

As a last line of defence, where neither engineering controls nor administrative methods are reasonably practicable, workers should use PPE. The use of PPE may be the only means of controlling the exposure of workers involved in emergency operations. PPE includes clothing or other special equipment that is issued to protect each exposed worker. It is essential that all persons involved in the management and use of PPE are aware of its capabilities and limitations, in order to ensure that an adequate, reliable and planned degree of personal protection is provided.

Different PPE may be used to protect against external and internal exposures. Protective clothing may be designed to shield large areas of the wearer's body or individual organs, such as the eyes, against external irradiation. However, protective clothing and equipment is more frequently used to prevent radioactive substances either making direct contact with or entering the body and delivering internal exposures.

Respiratory protective equipment (RPE) is intended to prevent the inhalation of radioactive substances which would result in radiation doses to the lungs and other organs into which the substance(s) might ultimately pass or which might be irradiated by them.

11.1.3. Selection of personal protective equipment

Three essential items of information are necessary before selecting PPE:

(i) The nature of the exposure: Both qualitative and quantitative information is needed about conditions in the workplace. Surveys, as described in the Manual on Workplace Monitoring for Radiation and Contamination (IAEA-PRTM-1) [13], can be performed to determine the radionuclide(s) present, the type of potential exposure(s) and magnitude of possible doses, the physical form of the radiation source(s), and the nature and concentration(s) of any contamination. The radiological risks need to be considered together with other hazards to appreciate the difficulties of accomplishing the work wearing PPE.

(ii) Performance data for PPE: Data are needed to assess the ability of available and/or approved PPE to reduce the particular exposure(s). This information will usually be available from the manufacturers, who will have carried out tests under controlled conditions as specified in international or national regulations and standards.

(iii) The acceptable level of exposure: PPE should aim to minimize or even to eliminate exposure. In practice a decision will be made, preferably by a qualified expert, on whether the PPE could in theory provide adequate protection below internationally agreed dose limits or other applicable levels.

11.1.4. Fitting, using and maintaining personal protective equipment

Maximum protection will only be obtained in practice if the PPE is fitted, used and maintained to the standards specified for the manufacturer's tests.

PPE is manufactured in limited ranges of size for workers of average build, often of a single gender group only. It may be necessary to try different products of a similar specification to find PPE that is comfortable and a good fit and that provides the necessary protection. The workers' training must emphasize the need to fit and use the personal protection correctly each time.

PPE needs to be routinely cleaned, checked and maintained in accordance with the manufacturer's recommendations. The users can be relied upon to carry out or to arrange for cleaning but appropriate arrangements must be in place. For example, either there must be a central system for cleaning or suitable materials must be supplied, both to encourage the action and to ensure that unsuitable cleaning methods or agents are not used. A central system for cleaning facilitates the carrying out of checks, maintenance and repairs. This maintains the level of protection and helps to prolong the life of the PPE. The use of disposable PPE reduces the need for maintenance, but it will still be necessary, for example, to maintain dispensers and to dispose of contaminated clothing.

11.1.5. Information, instruction and training

The various individuals and groups normally involved in a system in which PPE is used should all receive adequate information, instruction or training. Their needs differ but may include the following, for example:

- The manager responsible for the system needs information on appropriate surveys, on the selection of suitable equipment and literature from the manufacturer of the equipment. Management skills are necessary to set up an appropriate system and to maintain its effectiveness in practice.

- Workers need instruction on the specific hazards of the workplace and the consequences of unprotected exposure. Their training should include where, when and how protective equipment is obtained, fitted, used and cleaned. They will also need to recognize faulty equipment and hazards which may arise from use of the equipment.

- Storekeepers need to know how to store and issue the correct equipment properly.

- Maintenance and cleaning staff need to be trained in how to clean equipment properly, how to assess damage and wear, and how to ensure effective repair or replacement. The potential exposure of cleaning staff must be taken into account.

- Supervisors need all of the above and clear instructions which define their responsibilities. They need to provide for refresher training and to ensure that recruits to the system receive appropriate and adequate initial information, instruction and training.

11.1.6. Management of a system of personal protective equipment

The effectiveness of PPE depends on good management, supervision and monitoring of the system. The system needs to be defined in written procedures with the full support and commitment of senior management. PPE may make work more difficult or more demanding and may not be popular with all workers. Managers and supervisors need to recognize this and to set an example by using personal protection whenever, and for however short a time, they enter areas in which the system is in place.

Supervisors need to monitor whether the protective equipment is being used correctly and consistently; whether it is being cleaned and maintained; and whether provisions for training are being utilized and are adequate. They also need to be alert to possible problems, such as changes in conditions that might render the PPE inadequate, or hazards which the PPE might create or exacerbate (see Section 11.6).

Supervisors and workers need to keep managers informed of changes in the workplace or processes and changes or improvements in available PPE. There must be clear guidelines for any disciplinary action(s) that would be taken against workers who do not comply with obligations under the system.

11.1.7. Designated areas

Whenever there is a potential for occupational exposure to ionizing radiation, a prior evaluation of the radiological risk is necessary in order to consider the need for classifying the working area. Workplaces are designated as controlled areas if specific protective measures or safety provisions are or could be required for:

(a) Controlling exposures or preventing the spread of contamination in normal working conditions, and

(b) Preventing or limiting the extent of potential exposures.

Although specific protection measures and safety provisions are not normally necessary, the working area is classified as a supervised area if it is not already designated as a controlled area but if the conditions of occupational exposure need to be kept under review.

The system of work for a designated area should include the use of PPE if its use would be reasonably practicable, and if it would potentially either reduce the doses to those who work in the area or prevent the dispersal of contamination from the designated area. If the protective equipment is essential, access to the area must be restricted and the PPE should be specified as a condition of entry, such as on a written permit to work in the area. Under these circumstances barrier discipline is essential.

Routine and task related monitoring should be performed as described in the Manual on Workplace Monitoring for Radiation and Contamination (IAEA-PRTM-1) [13]. The Manual on Individual Monitoring (IAEA-PRTM-2) [39] describes methods to verify the effectiveness of the practices for control of radiation.

The validity of using PPE and the possibility of replacing it with more suitable engineering controls or redesigned processes should be considered in regular assessments.

11.2. PROTECTIVE SUITS

One piece suits, coveralls, overalls or ‘slicker suits’ are used at industrial workplaces to protect against radioactive contamination of the parts of the body covered by the clothing.

Suits are available with or without integrated head cover or hood to allow use with different types of RPE (see later sections). Elasticated hoods and arm and leg cuffs give more comfort and ensure that body surfaces remain covered.

Permeable suits are most comfortable for long term wear. Woven garments retain contamination, minimizing resuspension. For more severe conditions, impermeable suits made of rubber or plastic coated or non-woven fabrics are available. Products vary in durability, in their resistance to chemicals, flames and heat, in comfort, in cost, and so on. They also tend to cause and retain perspiration. Some products are more comfortable and flexible, although they may have lower protection factors. Suits are ventilated through sleeves, seams, valves, filters or sometimes several small holes, possibly concealed. Fully encapsulating, impermeable, pressurized suits provide the highest level of protection.

The suits can be decontaminated before removal, if this is practicable without further hazard, to avoid transferring or resuspending contamination when removing them. Alternatively, they might be sprayed with a fixative, removed and retained inside a designated area pending specialist decontamination. Seams in particular should be checked carefully to ensure that they are decontaminated. Minor damage to suits should be repaired, as appropriate, in accordance with the manufacturer’s instructions.

11.2.1. Choosing a protective suit

Protective clothing normally displays or is labelled with a trademark or other means of identifying the manufacturer, the product type and the intended purpose. The latter may be in the form of a pictogram or symbol with an indication of the suit’s intended level of performance. Manufacturers also typically supply information relating to the care and use of the PPE, and may be willing to discuss the tests applied and performance data. A list of performance levels, preferably in a table of performance, helps in choosing the most appropriate suit for the intended work. Table 13 is not specific to any particular manufacturer or recognized standard, and is intended only as general guidance for choosing protective suits.

TABLE 13. PERFORMANCE LEVELS [14]

Suit type	Expected surface contamination				Expected airborne contamination			
	Solid		Liquid		Aerosol		Gas	
	Low	High	Low	High	Weak	High	Weak	High
A. Non-ventilated, non-pressurized, permeable fabric or non-woven	✓ + R				✓ + R			
B. Non-ventilated, non-pressurized, impermeable	✓ + R	✓ + R	✓ + R	✓ + R	✓ + R		✓ + R	
C. Ventilated, impermeable	✓	✓	✓	✓	✓	✓		
D. Ventilated, impermeable	✓	✓	✓	✓	✓	✓	✓	✓

Notes

✓ = Type of garment is suitable.
+ R = Use together with appropriate RPE depending on specific conditions.
Type C = Air escapes freely through sleeves and seams.
Type D = Exhaust devices such as valves or filters are fitted; pressurized.

Type A suits (Fig. 28) are unventilated and are made of permeable fabric or of non-woven material. Type B suits are unventilated but impermeable. Types C and D suits are ventilated and impermeable.

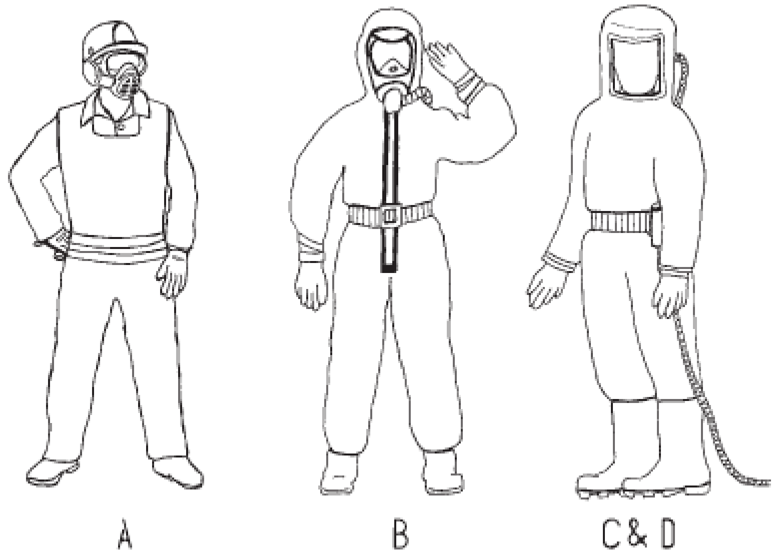

FIG. 28. Industrial suits of different types provide varying degrees of protection

11.3. GLOVES

Protective gloves range from lightweight disposable polythene gloves to gloves made of other synthetic materials, various fabrics and elastomers, leather, mineral fibres, glass fibre and so on, or from a mixture of materials. They may be available in different sizes or as stretch to fit; as long gauntlets extending above the elbows or small handpads and mitts covering just the fingers and thumbs; or as separate items, or a fixed or detachable part of a protective suit.

Gloves should be selected to provide the necessary protection while allowing sufficient dexterity. A lightweight polyvinyl chloride (PVC) or thin natural rubber latex (NRL) surgeon's glove may be suitable for laboratory use where maximum sensitivity and flexibility and a good grip are necessary for accurate work. Heavyweight PVC gloves are more appropriate in a harsh industrial environment. They need to form a barrier against contamination as well as protect against any other harmful agents present such as solvents, chemicals, physical hazards and severe climate. Some users of NRL products suffer allergic reaction after contact with either the glove or the glove powder. Symptoms may range from localized skin and eye irritations to asthmatic reactions and, in extreme cases, systemic shock. Using a different powder or cream or wearing gloves of a different material under the protective gloves can help.

Elasticated sleeves pulled down over the gloves or tape around the cuffs prevent the wrists from being exposed to contamination. Gloves that become contaminated or damaged should be discarded. This is not feasible when the glove is an integral part of a suit, which is an advantage for gloves that mechanically lock onto the suit. Gloves that are not disposable may need to be properly decontaminated in special facilities.

11.3.1. Procedure for removing contaminated gloves

Gloves are likely to become contaminated more easily than other protective clothing. Procedures should be practised to deal with problems that can arise without spreading the contamination to unaffected surfaces or areas.

Contamination may not be easily removable from the gloves, but having paper tissues or paper towels ready to hand will enable tools, monitoring instruments, gas and power controls, handles, communication aids and other essential items to be manipulated through the clean paper.

At an appropriate time and place, gloves should be removed without allowing the contaminated external surfaces of the gloves to make contact with an unprotected hand. This is normally achieved by gripping the outside of the cuff of one glove and pulling the glove inside out but without fully removing it. The fingers inside the turned out glove can then grip the other glove and pull it inside out and off. The partially removed glove is then fully removed turning it fully inside out. The contamination is safely contained on the inside of the turned out gloves.

11.4. FOOTWEAR

Protective footwear includes overshoes, ‘booties’, shoes and boots (see Fig. 29).

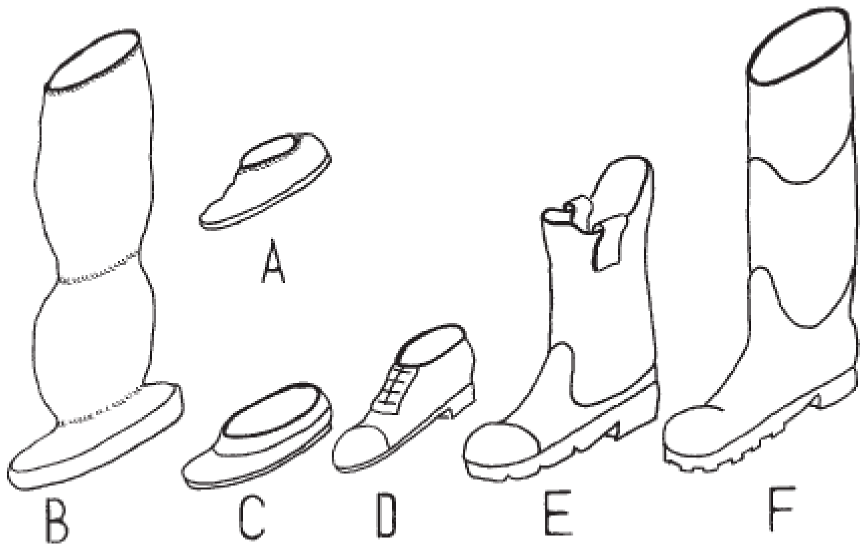

FIG. 29. Footwear of different types provides protection against radioactive contamination

Overshoes allow personal footwear to be worn in areas where there is a risk of a minor spill or drips contaminating the floor. In their simplest form, overshoes are disposable, single size, foot shaped plastic bags with elasticated openings. More expensive and durable but possibly less effective are outsized plastic shoes (C). These do not fully cover the personal footwear and may not provide a tight fit over it, especially over heels. Fabric overshoes (A) with hard soles and booties (B) and fabric overshoes with legging supported at the knee by elastic or drawstrings provide further inexpensive options.

In an industrial environment, where safety shoes (D) or ‘rigger’ boots (E) with steel toecaps are needed, colour coded footwear of the type is often issued for entry to designated areas. Rubber, rather than leather, safety boots (F) may be preferred to facilitate decontamination or to carry out wet work. Trouser cuffs, preferably elasticated, should be pulled down over the bootleg to complete the protection. Fully encapsulating, impermeable suits incorporate appropriate footwear.

Fabric overshoes can be decontaminated by allowing a period for radioactive decay and soaking and/or laundering before reuse. Boots and shoes may need deodorizing and hard brushing or grinding to remove impacted contamination.

11.4.1. Barrier procedures for protective footwear

The reason for using protective footwear is primarily to contain any floor or ground contamination within the designated area. In this respect protective footwear differs from other PPE which has a more direct effect in reducing doses to the worker. Ordinary, personal footwear could be worn where there is only a small risk of potential contamination, but the inconvenience of having to decontaminate or confiscate footwear may be unacceptable.

Barrier discipline is imperative to the effectiveness of protective footwear. A physical barrier should be set up between clean areas and the designated 'dirty' area (see Fig. 30). After placing personal footwear in appropriate storage in the clean area, clean overshoes may be donned before stepping over the barrier. On return, after removing other protective garments, the worker approaches and sits on the barrier. The worker removes one overshoe before immediately swinging the shoeless foot over the barrier. The other foot may then be lifted to remove the second overshoe and again swinging the leg over the barrier without the shoeless foot touching the dirty area floor. Dirty overshoes may not leave the dirty area.

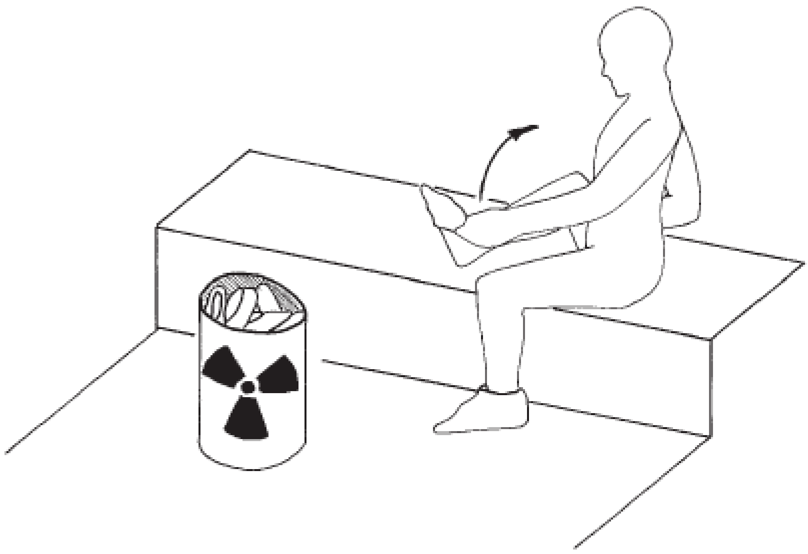

FIG. 30. Procedure for removing contaminated footwear

11.5. RESPIRATORY PROTECTIVE EQUIPMENT

11.5.1. Types of equipment

There are two categories of RPE with several subdivisions in each category (see following sections):

(i) *Respirators* purify the air by filtering out particulate materials such as dust or low concentrations of gas or vapour. The most common types are:

  (a) Filtering face piece respirators;

  (b) Half mask respirators;

(c) Full face mask respirators;

(d) Powered respirators fitted with a fan and filter(s) to supply air to a half mask, full face mask, visor, hood or helmet, blouse, half suit or full suit.

(ii) *Breathing equipment* provides clean air or oxygen from an independent, uncontaminated source. The most common types are:

(a) Fresh air hose equipment,

(b) Constant flow compressed air equipment,

(c) Breathing apparatus which includes full face masks and full suits supplied either from compressed air lines or self-contained cylinders of compressed air.

RPE and some other types of PPE can have an assigned protection factor (APF) defined by national standards and referred to in national regulations. In a typical system, RPE is performance tested to determine the inward leakage (IL) as the ratio of the concentration of the test particles inside the RPE (or PPE) to the challenge concentration of test particles in the test chamber. This is expressed as a percentage, the challenge concentration corresponding to 100%. The manufacturer may quote the inverse (100:IL), called the nominal protection factor (NPF), which is the expected ratio of the concentration of contaminant in the ambient atmosphere to the concentration of the contaminant inside the RPE (or PPE).

The effectiveness of a respirator in minimizing inward leakage depends on two parameters:

(i) The integrity of the face seal,

(ii) The filtration capability of the selected canister or filter medium (see Section 11.5.4).

Changing either or both of these factors can have a significant effect on the degree of protection actually achieved.

11.5.2. Selection of equipment

Several types of RPE might have the necessary APF/NPF to conform to the predicted contamination and/or measurements (see Section 11.1.7) taken to determine the physical form and concentration of contamination in the workplace. The choice could include all types of RPE to protect against low concentrations of a particulate contamination. Radioactive vapours and gases would restrict the choice to certain types of respirator or breathing equipment or, for adequate protection against contaminants at high concentrations in the ambient atmosphere, breathing equipment may be the only possibility. Radon gas has a high diffusivity and necessitates special considerations to prevent its inhalation.

The APF/NPF indicates the theoretical best protection that can be achieved. If, in addition to RPE, protective clothing is to be used, then the total ensemble has to provide the necessary protection factor. The specified protection factor might not be achieved in practice for various reasons. For example, if equipment that relies on a face seal does not fit the size and shape of a worker’s face, the necessary seal will not be possible. Facial hair, even growth over the working day, will lift some masks, possibly by enough to allow inward leakage of contaminated air. In these circumstances, or perhaps to permit prescription spectacles to be worn, RPE such as hoods, visors, blouses or suits would be a better alternative. The problem of facial hair also may be addressed by means of administrative requirements for all potential male users of RPE to be clean shaven.

Although APF and NPF are used interchangeably in this section, there can be significant differences depending on national regulations and standards. For the selection of a specific type of RPE as described above, for example, a regulatory authority may specify and enforce the use of RPE with an NPF of 3 for work in situations of low hazards, but may require the use of RPE with a higher factor of at least 100 for continuous use as a standard general purpose respirator for work with radioactive substances.

11.5.3. Filtering face piece respirators

Filtering face piece (FFP) respirators are made wholly or substantially of filter material (P) which covers the nose and mouth (see Fig. 31). The face piece is held in place by straps and a nose clip (N), which helps to complete the seal. Air is drawn through the material by underpressure when the wearer inhales. Some models incorporate an exhalation valve (V). FFP respirators are mainly used for protection against low to moderately hazardous particles. They should not be confused with nuisance dust masks which only filter larger, low hazard dust particles. Some models are capable of filtering malodorous (but not toxic) gases and vapours.

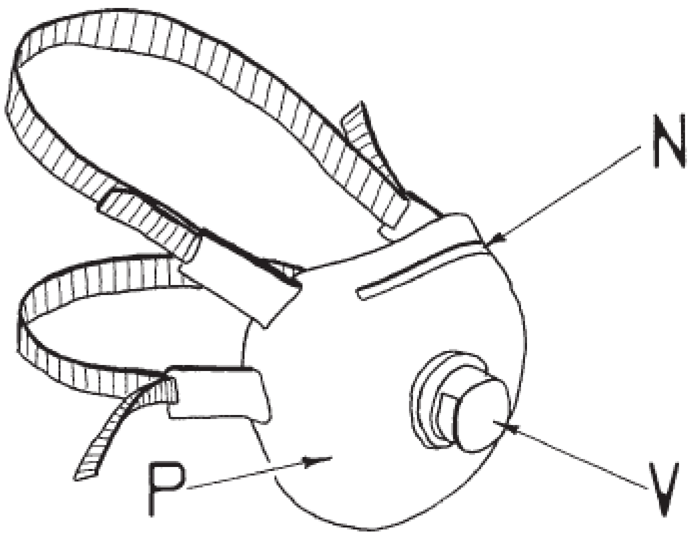

FIG. 31. A filtering face piece respirator (FFP)

The nominal protection factor of FFP respirators is relatively low, but the highest retention efficiency filters, class FFP3, provide adequate protection for either low risk and limited risk areas or for short exposures within the specified limits. Their use helps to keep contaminated gloves away from the mouth area but they provide no protection for the eyes and should not be used where skin contamination is a hazard. FFP respirators are easy to use and relatively inexpensive. They are usually described as disposable, for a single shift or single use only, and they should not be reused. They may retain contamination that can be monitored as an aid to assessing working conditions.

11.5.4. Half mask respirators

The elastomer half mask or orinasal respirator (Fig. 32) is a face piece (P) of rubber or plastic moulded to cover the nose and mouth and is held in place by adjustable straps. Air is drawn through one or more filters (F) and, where fitted, an inhalation valve (I). The filters are contained in one or more cartridges (canisters). Exhaled air is discharged to atmosphere through an exhalation valve (V) in the face piece.

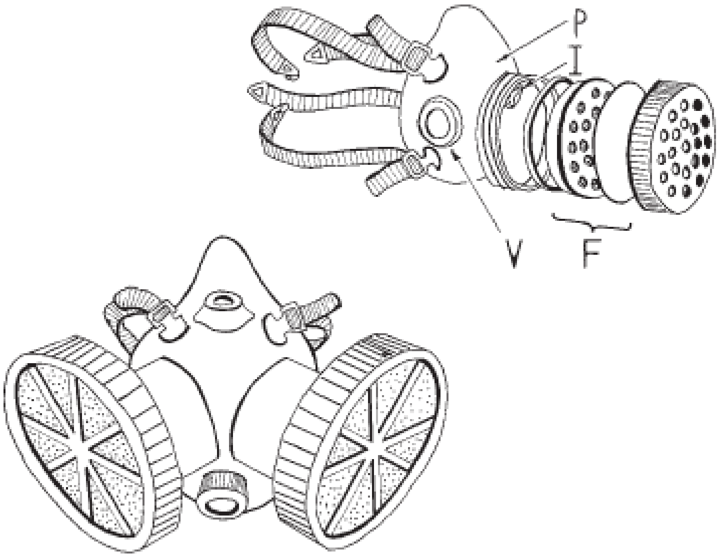

FIG. 32. Half mask respirators with single and multiple cartridges

Replaceable filters are available for particulate contaminants, gases and vapours. Their NPFs are usually much higher than for disposable FFP respirators but their real advantage is that the filter cartridges have a higher absorption capacity for gases and vapours and provide safe containment for subsequent disposal of the contaminant.

Specified gases and vapours are usually absorbed in a bed of activated carbon (charcoal) which may be impregnated with suitable chemicals to enhance the capacity to absorb or react with certain classes of chemicals such as acidic gases. If the contaminant is in the form of an aerosol, both particles and gases and/or vapours may be present in the workplace air and a combination of particulate and activated charcoal filters has to be used.

Half mask respirators provide no protection for the eyes and should not be used where skin contamination is a hazard.

11.5.5. Full face mask respirators

A moulded face mask of rubber or plastic covers the entire face from just below the hairline to beneath the chin and is held in place with an adjustable head harness (Fig. 33). Air is drawn through one or more filters and, where fitted, inhalation valves. Exhaled air is discharged through an exhalation valve (E) in the mask. Various models are manufactured, with either a single panoramic visor or individual eyepieces. The inner nose cup mask minimizes the possibility of misting (‘fogging’) and prevents the buildup of carbon dioxide. To prevent fogging due to moisture in exhaled air, antifogging compounds should be applied to the inside of the visor or the full face mask. The face mask can incorporate a speech diaphragm or microphone and provision for prescription corrective lenses.

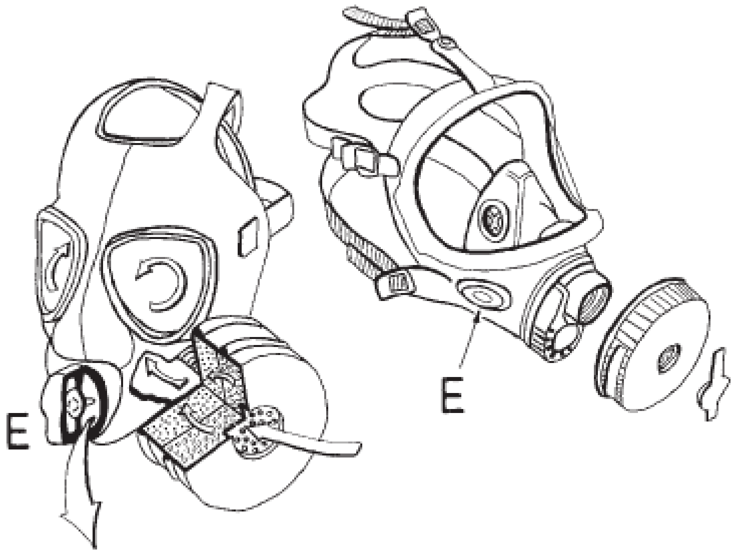

FIG. 33. Full face mask respirators with visor or individual eyepieces

The range of available filters is described in Section 11.5.4. The larger or multiple cartridges (canisters) can be used, with more comfort than is provided by the half mask, to extend the duration of use. The low inward leakage at the face seal enables the use of high efficiency particulate air (HEPA) filters, which would be over specified for filtering half masks.

Particulate filters indicate the end of their useful lifetime by the increase in resistance to breathing. A noticeable loss of resistance may indicate a hole or leak in the filter, face seal or cartridge (canister) gasket. Carbon (charcoal) filters cannot be tested and there is no feasible method to establish the residual capacity of a filter when it has once been used. The NPF offered against particles by a properly fitted full face mask respirator could be high. The wearer has to monitor the apparent protection being provided by RPE and has to leave the designated area if there is any noticeable deterioration.

11.5.6. Powered air purifying respirators with masks

Powered air purifying respirators (Fig. 34) provide a continuous flow of air into the mask in order to minimize inward leakage of contaminated air around an incomplete face seal. Ideally, the NPFs are then only determined by the filter characteristics and are higher than the NPFs of non-powered respirators.

Contaminated air is drawn through one or more filters by a battery powered fan and the filtered air is delivered to the mask. The ventilator is usually mounted on a belt but it may be incorporated into the mask. Half masks or full masks may be used but the latter are preferred. Exhaled air is discharged to atmosphere through valves of various designs in the mask. Filters are available for particulate contaminants, gases and vapours. These respirators use approximately three times as many filters as their non-powered counterparts because of the increased airflow.

FIG. 34. Powered respirator with full face mask

Powered air purifying respirators are desirable under conditions of increased workload because they make breathing easier. If the ventilator fails, the face mask gives the wearer enough time to escape a contaminated area.

11.5.7. Ventilated visors and helmets

Powered ventilated visors and helmets (Fig. 35) normally comprise a head covering, which may be a soft hood or a helmet to provide physical protection. A clear visor covers the face and an elasticated 'skirt' may enclose the area between the bottom of the visor and the neck or face.

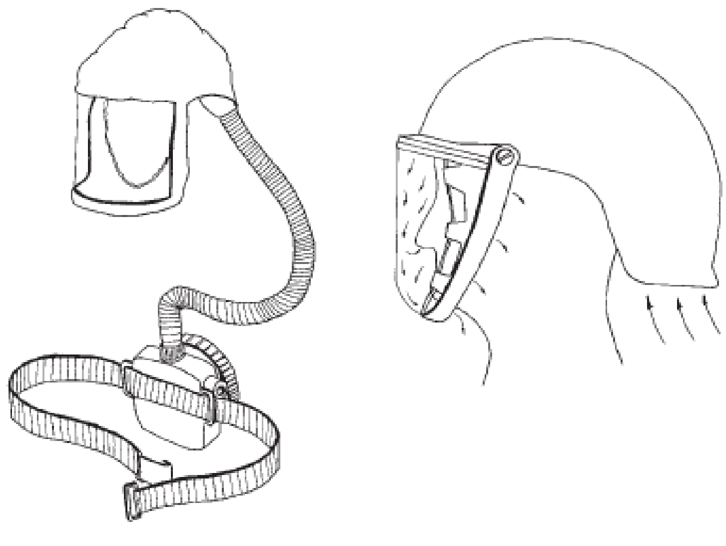

FIG. 35. Ventilated visor and helmet

Contaminated air is drawn through one or more filters by a battery powered fan and the filtered air is directed downwards over the face. The ventilator, incorporating the fan and filter(s), may be mounted on a belt or fitted inside the helmet between the head harness and the helmet shell. The equipment is less dependent on a face seal to achieve the NPF and provides a high degree of comfort for the wearer. In some situations metal helmets may be more suitable because they provide better protection against beta irradiation resulting from surface contamination.

The protection factors depend significantly on the type and circumstances of the task. Such equipment is normally used for protection against dust and other particulates but some models are available for protection against gases and vapours. Ventilated visors can offer high NPFs but some helmets offer quite low protection. If the ventilator fails there is a possibility of exposure as a result of the drastically reduced protection. They are therefore best for use in low hazard situations or where prompt egress from a contaminated area is possible.

11.5.8. Powered hoods, blouses and suits

Powered hoods (Fig. 36) completely cover the head and are made partially or totally of transparent material that offers minimum distortion or interruption of the wearer’s vision. Blouses cover the upper half of the body and seal at the wrists and waist. Suits cover the whole body and may incorporate boots and/or gloves.

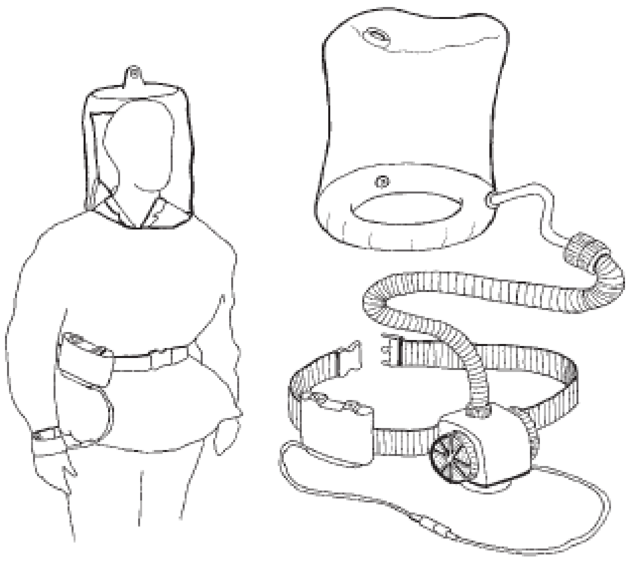

FIG. 36. Powered hood and blouses

Contaminated air is drawn through one or more filters by a battery powered fan and the filtered air is fed directly into the hood, blouse or suit and is exhausted usually by leakage from the protective clothing or through exhaust valves. The ventilator is usually mounted on a belt. Filters, as described above, are available for dusts, gases and vapours. The shelf life of the filter canisters is limited but, provided that the seal is not broken, they can remain effective for years.

Workers will need more extensive practical training to use hoods, blouses and suits than is necessary for the RPE previously described. They should be prepared for being dependent on the equipment to provide an air supply. They may need assistance to don and remove the RPE. The inner surfaces of the equipment must be disinfected hygienically and the outer surfaces monitored and, if necessary, decontaminated before reuse.

11.5.9. Fresh air hose breathing equipment

Fresh air hose breathing equipment (Fig. 37) comprises either a half or full face mask. The inlet of the hose contains a strainer and is secured by a spike or other means outside the contaminated atmosphere. Air is supplied by either normal breathing (unassisted ventilation), manually operated bellows (forced ventilation) or a powered fan unit (powered ventilation). A large diameter air hose is necessary which, for unassisted ventilation, should not be longer than about 9 m. Such equipment is vulnerable, heavy and more cumbersome to use than compressed air line equipment (see Section 11.5.10). It is not suitable for use in nuclear facilities.

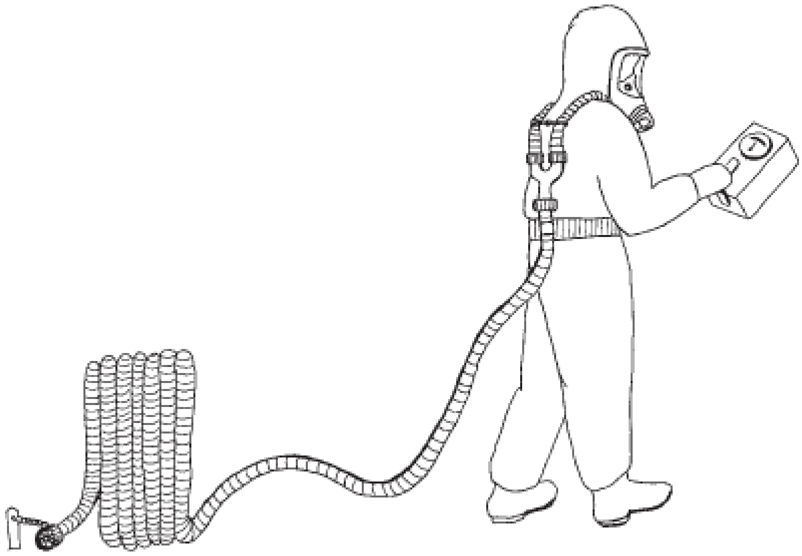

FIG. 37. Fresh air hose supplying a full face mask

11.5.10. Breathing equipment with a compressed air line

A compressed air line may be used to supply a face mask, a hood or a blouse (Fig. 38). The air may be supplied from a compressor or from compressed air cylinders that are outside the contaminated area. In using compressors, the air intake needs to be properly located to prevent the contaminant becoming entrained in the air supply. In-line filters and traps to remove oil, dust, condensate and odour from compressed gases should be provided as necessary to yield breathable air of an acceptable quality. Large compressors or cylinders are necessary, which may affect measures for atmospheric control in some locations such as vented rooms at subatmospheric pressure.

A face mask is connected through a belt mounted flow control valve to the compressed air line. To save air, especially when using compressed air cylinders, the flow control valve may be replaced by a lung demand valve, preferably of the positive pressure type, which provides a higher protection factor. It can reduce the air flow requirements by a factor of three, which also improves the quality of voice communication. High airflows cause noise and wearer discomfort (cooling or dehydration). With an adequate airflow, an effective positive pressure can be maintained in the mask to provide a high NPF. Some masks are also provided with a filter (F) for emergency escapes and to allow the worker movement through air locks.

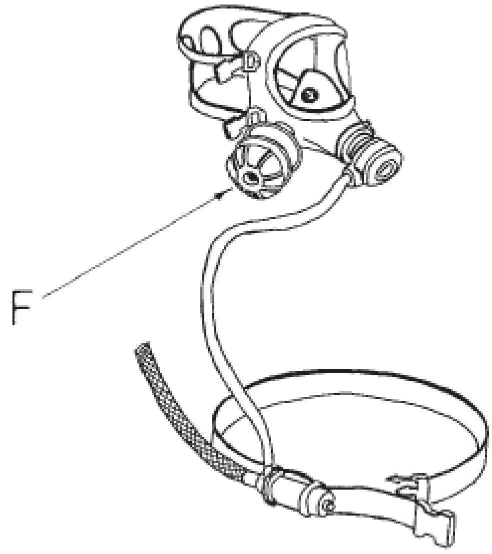

FIG. 38. Full face mask with compressed air line and auxiliary filter

A hood or blouse is connected to the compressed air line attached to a belt and may incorporate a valve by which the wearer can increase the flow rate of the supplied air above the necessary minimum. The wearer's comfort is relatively high in combination with moderately high protection. An auxiliary respiratory protection system, for example a filter, may also need to be worn if the wearer has to disconnect the air line to pass through air locks.

11.5.11. Self-contained breathing apparatus

A self-contained breathing apparatus (SCBA, Fig. 39) consists of a full face mask supplied with air or oxygen from compressed gas cylinders carried by the worker. Air is supplied to the mask through a positive pressure demand valve. Alternatively, oxygen is supplied at a constant low flow rate (4 L/ min) to replace the oxygen consumed. This is achieved in a closed system that collects the exhaled gases, routes them through a soda lime cartridge to remove the carbon dioxide, and then adds oxygen to make up the fresh gas. Both types can be obtained with positive pressure regulators.

An SCBA provides mobility but is bulky and heavy. Compressed air apparatus protects for up to 45 min and oxygen apparatus for up to four hours. Extensive training is necessary for the wearers and for those who maintain the equipment. An SCBA is difficult to decontaminate and should be worn under a protective suit when used in contaminated areas.

A type of SCBA that generates oxygen chemically can be used in emergency situations for up to one hour. It is less bulky than compressed oxygen cylinders and has a long shelf life. Oxygen is generated from sodium chlorate or potassium superoxide. The latter is more expensive but has the advantage of releasing oxygen in amounts equal to the exhaled carbon dioxide absorbed.

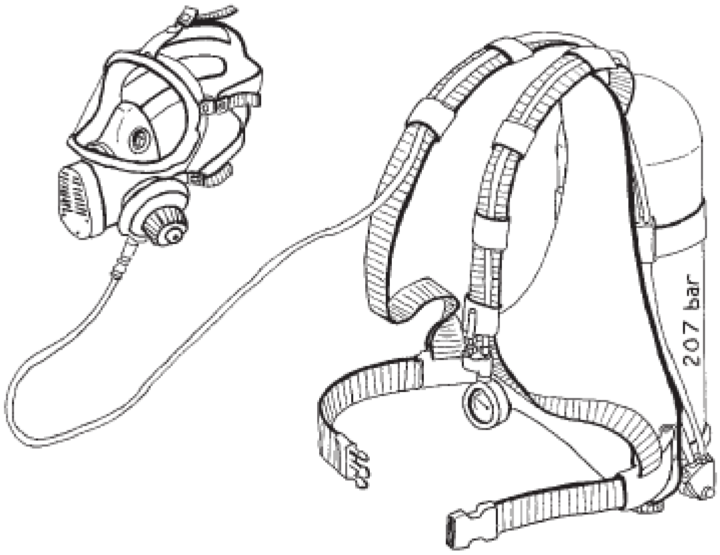

FIG. 39. Self contained breathing apparatus (SCBA) with a demand valve

11.5.12. Compressed air line with full suit

A ventilated pressurized suit enclosing the whole body (arms and legs) may be in one or two parts. Halved suits are sealed together at the waist. Full suits may have a gas tight zipper. The hood has at least the front section transparent, offering minimum distortion or interruption to the wearer's vision. The compressed air supply hose is attached to a belt to withstand the stresses of being dragged. A valve may be attached to the belt to allow the wearer to control the air supply, either to the whole suit or to the hood, according to the design. Exhaust gases are discharged through exhaust valves in the suit body. Part of the air supply may cool the suit.

Full suits (Fig. 40) offer among the highest NPFs of all PPE. Higher air flow rates provide cooling if necessary and, if no face mask is incorporated, exhaled carbon dioxide needs to be flushed out to maintain its concentration in inhaled air below acceptable levels (less than 1 vol% carbon dioxide). High overpressures of the suit cannot be achieved. Some substances can permeate or diffuse through the material, making the NPF dependent on the properties of the material and the flushing rate of the suit. An additional respirator should be worn under the suit if it is likely that a suit may become damaged.

There are usually sufficient reserves of air in a suit to allow the worker to egress through air locks after disconnection of the air supply, but for lengthy decontamination procedures breathing equipment may be necessary. Some suits are provided with an emergency breathing device to be used for escape purposes in the event of failure of the primary air supply.

FIG. 40. A full suit supplied by compressed air line

11.6. OTHER HAZARDS

In addition to radiological risks, there may be other hazards in the area(s) in which PPE is used. PPE can also create other problems and exacerbate hazards. For example, a worker’s field of vision may be reduced while wearing respiratory protection, vocal communication may be severely restricted or a hood may impair hearing. Such conditions increase the worker’s vulnerability to normal hazards and necessitate increased awareness and care.

Several types of PPE may be necessary to work safely. To protect against physical injury, head, eye and toe protection may be necessary. A safety helmet may be worn when wearing enclosed suits or hoods. Safety goggles may be worn inside ventilated suits. It is an advantage if the PPE used incorporates all necessary protection such as the ventilated helmet; if a respirator has eyepieces made from polycarbonate; or if integral boots have protective toecaps. Use of an eye shield with a respirator will severely limit the already restricted vision. Welding in a radioactive environment necessitates specially modified PPE, with the hoods of ventilated garments fitted with a welder’s mask, eye protection and an outer protective apron to protect against hot debris.

Suits made from aluminized fire resistant materials are available to protect against extreme radiant heat and, in hot environments, a cooled suit should be used. Suits resistant to attack by specific chemicals should be assessed before use in respect of their contamination control.

11.7. WARNING SIGNS AND NOTICES

The designated areas in which PPE needs to be worn must be identified, clearly demarcated and described in written procedures with details of the PPE to be used.

As a reminder to workers who are familiar with the conditions for the use of PPE, and as a warning to visitors, suitable notices in the local language to deny unauthorized access should be posted at the barriers around the designated areas. It is preferable for the notices to display signs and symbols, which do not depend on the observer’s literacy. A system of signs using distinctive and meaningful shapes, colours and idealized symbols has been developed.

A trefoil symbol on a yellow background within a black triangle indicates the potential presence of ionizing radiation. It could be accompanied by the words ‘Radioactive Contamination’. A sign with a person in silhouette on a white background within a red circle and a diagonal red bar prohibits unauthorized entry. Other signs with a blue background may display a symbol indicating the type of PPE that has to be worn by those about to enter the area. A head wearing a full face mask respirator indicates that RPE has to be worn by those about to enter the area and a symbol depicting boots indicates that the footwear used has to have protective toecaps.

12. NORM IN THE OIL AND GAS INDUSTRY

12.1. GENERAL ASPECTS OF NORM

Naturally occurring radionuclides have two types of origin:

(i) Primordial (^{238}U, ^{235}U and ^{232}Th decay series, ^{40}K, ^{87}Rb);

(ii) Cosmic ray interactions (^{3}H, ^{14}C, ^{7}Be).

All minerals and raw materials contain the primordial radionuclides of natural, terrestrial origin. The ^{238}U and ^{232}Th decay series (see Tables 4 and 5) and ^{40}K are the main radionuclides of interest. The activity concentrations of these radionuclides in normal rocks and soil are variable but generally low (see Tables 14 and 15).

TABLE 14. TYPICAL CONCENTRATIONS OF NATURAL RADIONUCLIDES IN SOIL

	Activity concentration (Bq/g)		
	^{40}K	^{226}Ra (= ^{238}U+)	^{228}Ra (= ^{232}Th+)
Sand and silt	0.004–0.03	0.6–1.2	0.005–0.02
Clay	0.6–1.3	0.02–0.12	0.025–0.08
Moraine	0.9–1.3	0.02–0.08	0.02–0.08
Soil with Al-shale	0.06–1	0.1–1	0.02–0.08

TABLE 15. TYPICAL CONCENTRATIONS OF NATURAL RADIONUCLIDES IN ROCKS

		Activity concentration (Bq/g)	
		^{226}Ra (= ^{238}U+)	^{228}Ra (= ^{232}Th+)
Acid intrusive:	Granite	0.001–0.37	0.0004–0.103
Basic intrusive:	Basalt	0.0004–0.041	0.0002–0.036
Chemical sedimentary:	Limestone	0.0004–0.34	0.0001–0.54
Detrital sedimentary:	Clay, shale	0.001–0.99	0.0008–0.147
Metamorphic igneous:	Gneiss	0.001–1.8	0.0004–0.42
Metamorphic sedimentary:	Schist	0.001–0.66	0.0004–0.37

Certain minerals, including some that are commercially exploited, contain uranium and/or thorium series radionuclides at significantly elevated activity concentrations (see, for instance, the data for the components of heavy-mineral sands in Table 16). Furthermore, during the extraction of minerals from the earth's crust and subsequent physical and/or chemical processing, the radionuclides may become unevenly distributed between the various materials arising from the process, and selective mobilization of radionuclides can disrupt the original decay chain equilibrium. As a result, radionuclide concentrations in materials arising from a process may exceed those in the original mineral or raw material, sometimes by orders of magnitude. As the various industrial processes differ, so the distributions of radionuclides in process materials differ accordingly (see Table 17).

TABLE 16. EXAMPLES OF CONCENTRATIONS OF NATURAL RADIONUCLIDES IN THE COMPONENTS OF HEAVY-MINERAL SANDS

	Activity concentration (Bq/g)	
	^{226}Ra (= ^{238}U+)	^{228}Ra (= ^{232}Th+)
Ilmenite	<0.1-0.4	0.6-6
Leucoxene	0.25-0.6	0.04-0.35
Rutile	<0.1-0.25	<0.6-4
Zircon	0.2-0.4	2-3
Monazite	10-40	600-900
Xenotime	50	180
Average soil and rock, for comparison	0.04	0.04

TABLE 17. EXAMPLES OF DISTRIBUTION OF RADIOACTIVITY IN THE PROCESSING OF MINERALS AND RAW MATERIALS

Industry	Main mineral or raw material	Radionuclide distribution
TiO_2 pigment production	Rutile	Activity migrates to residues
Elemental phosphorus production	Phosphate rock	Volatile ^{210}Po, ^{210}Pb in furnace dust; other radionuclides in slag
Phosphate fertilizer production	Phosphate rock	Radium-rich scales; ^{226}Ra in phosphogypsum; ^{238}U in phosphoric acid
Rare earths production	Heavy mineral sands	Activity migrates to residues
Brick production	Clay	Volatile ^{210}Po
Iron and steel production	Iron ore, cokes, limestone	Volatile ^{210}Po, ^{210}Pb
Oil and gas production		Activity migrates to scales and sludges

Any mining operation or other industrial activity involving a mineral or raw material has the potential to increase the effective dose received by individuals from natural sources, as a result of exposure to radionuclides of natural origin contained in or released from such material. Where this increase in dose is significant, radiation protection measures may be needed to protect workers or members of the public. This can occur in two types of situation:

(1) Where the radionuclide concentration in any material associated with the process is significantly higher than in normal rocks and soil, whether as a result of the process or not, protective measures may need to be considered with regard to:

   (a) External exposure to radiation (primarily gamma radiation) emitted by the material;

   (b) Intake of material (primarily through inhalation of radionuclides in dust);

   (c) Inhalation of radon (and sometimes thoron) released from the material into the air and their decay products.

   Material that is designated as being subject to regulatory control in this regard is referred to as naturally occurring radioactive material (NORM).

(2) Where the radionuclide concentrations in the materials associated with the process are not significantly higher than in normal soil, measures may still be needed to protect workers against exposure to radon if the workplace conditions are conducive to the buildup of radon gas in the air—in underground mines, for instance, radon may become concentrated in the mine atmosphere due to emanation from the rock or from water entering the workings.

A considerable body of knowledge and experience has already been built up concerning operations involving minerals and raw materials that may lead to an increase in exposure to natural sources. The following industry sectors have been identified as being the most likely to require some form of regulatory consideration:

(i) Uranium mining and milling;

(ii) Extraction of rare earth elements;

(iii) Production and use of thorium and its compounds;

(iv) Production of niobium and ferro-niobium;

(v) Mining of ores other than uranium ore;

(vi) Production of oil and gas;

(vii) Manufacture of titanium dioxide pigments;

(viii) The phosphate industry;

(ix) The zircon and zirconia industries;

(x) Production of tin, copper, aluminium, zinc, lead, and iron and steel;

(xi) Combustion of coal;

(xii) Water treatment.

A key question is “at what level of activity concentration does it become necessary to regulate?” Decisions therefore have to be made on what to regulate and how. The IAEA Safety Standards provide the basis on which to make such decisions [3–5, 18]. More information on how to regulate NORM can be found in IAEA Safety Reports Series No. 49 [10].

12.2. ORIGIN AND TYPES OF NORM IN THE OIL AND GAS INDUSTRY

The first reports of NORM associated with mineral oil and natural gases appeared in 1904 [40]. Later reports describe the occurrence of ^{226}Ra in reservoir water from oil and gas fields [41, 42] and in the 1970s and 1980s several observations prompted renewed interest [43 –51]. The radiological aspects of these phenomena, the results of monitoring and analyses and the development of guidelines for radiation safety have now been reported extensively [52–56].

12.2.1. Mobilization from reservoir rock and deposition

The radionuclides identified in oil and gas streams belong to the decay chains of the naturally occurring primordial radionuclides ^{238}U (and ^{235}U) and ^{232}Th but do not include the parents. These elements are not mobilized from the reservoir rock that contains the oil, gas and formation water. The formation water contains cations of calcium, strontium, barium and radium dissolved from the reservoir rock. As a consequence, formation water contains the radium isotopes ^{226}Ra from the ^{238}U series and ^{228}Ra and ^{224}Ra from the ^{232}Th series. All three radium isotopes, but not their parents, thus appear in the water co-produced with the oil or gas. They are referred to as ‘unsupported’ because their long lived parents ^{238}U and ^{232}Th and also ^{228}Th remain in the reservoir (see Figs 41 and 42).

When the ions of the Group II elements, including radium, are present in the produced water, drops in pressure and temperature can lead to the solubility products of their mixed sulphates and carbonates being exceeded. This causes their precipitation as sulphate and carbonate scales on the inner walls of production tubulars (T, see Fig. 43), wellheads (W), valves (V), pumps (P), separators (S), water treatment vessels (H), gas treatment (G) and oil storage tanks (O). Deposition occurs where turbulent flow, centripetal forces and nucleation sites provide the opportunities. Particles of clay or sand co-produced from the reservoir may also act as surfaces initiating scale deposition or may adsorb the cations. If seawater, used to enhance oil recovery, mixes with the formation water, it will increase the sulphate concentration of the produced water and enhance scale deposition. Mixing may occur in the formation if ‘breakthrough’ occurs, which will result in scale deposits in the well completion, or the waters may be combined from different producing wells and mixed in topside plant and equipment.

The mixed stream of oil, gas and water also carries the noble gas ^{222}Rn that is generated in the reservoir rock through decay of ^{226}Ra. This radioactive gas from the production zone travels with the gas/water stream and then follows preferentially the dry export gases. Consequently, equipment from gas treatment and transport facilities may accumulate a very thin film of ^{210}Pb formed by the decay of short lived progeny of ^{222}Rn adhering to the inner surfaces of gas lines. These ^{210}Pb deposits are also encountered in liquefied natural gas processing plants [40–44].

A quite different mechanism results in the mobilization, from the reservoir rock, of stable lead that contains relatively high concentrations of the radionuclide ^{210}Pb. This mechanism, although not well understood [56], has been observed in a number of gas production fields and results in the deposition of thin, active lead films on the internal surfaces of production equipment and the appearance of stable lead and ^{210}Pb in sludge. Condensates, extracted as liquids from natural gas, may contain relatively high levels of ^{222}Rn and unsupported ^{210}Pb. In addition, ^{210}Po is observed at levels in excess of its grandparent ^{210}Pb, indicating direct emanation from the reservoir (Fig 41).

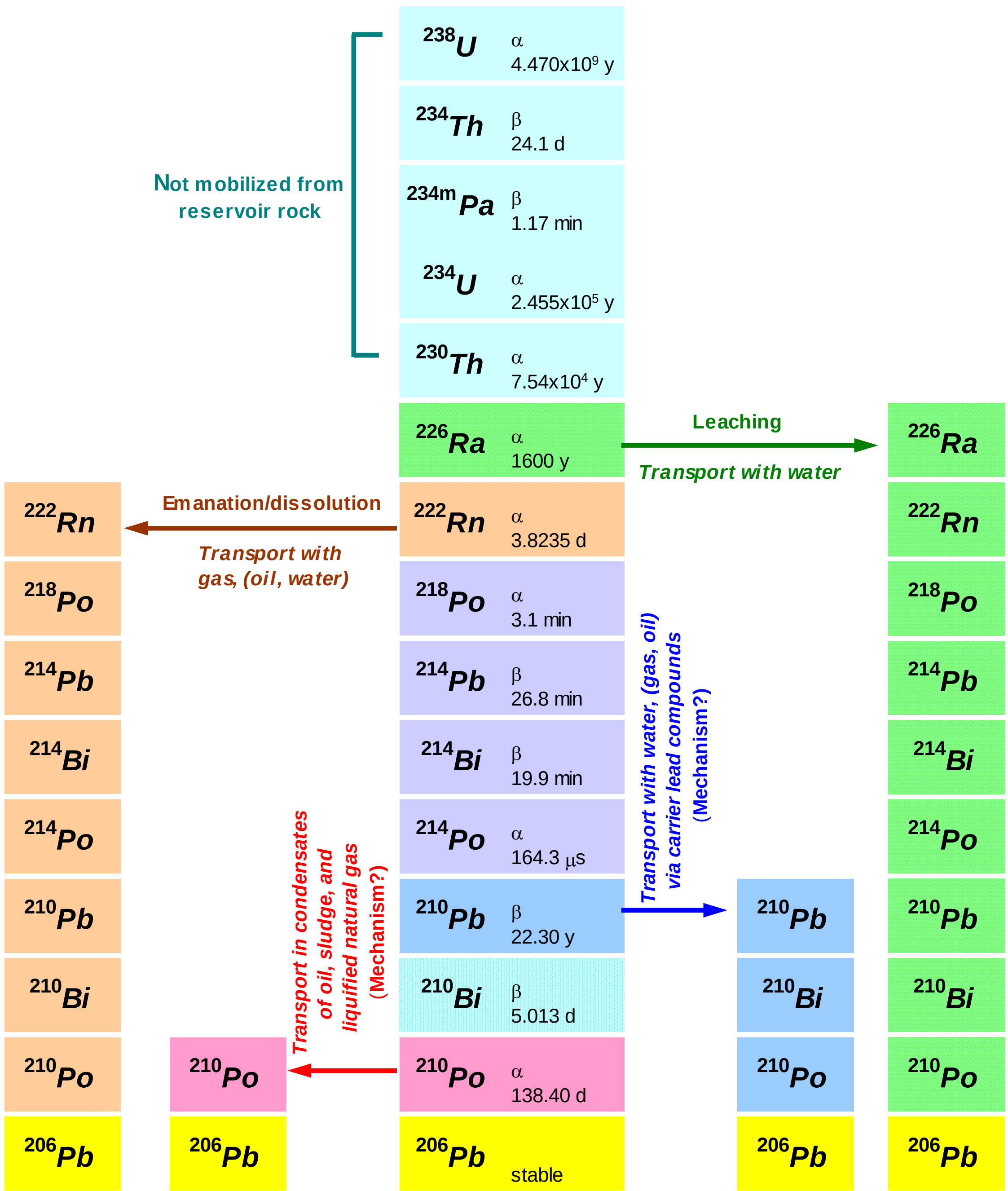

FIG. 41. Transport of ^{238}U progeny in oil and gas production

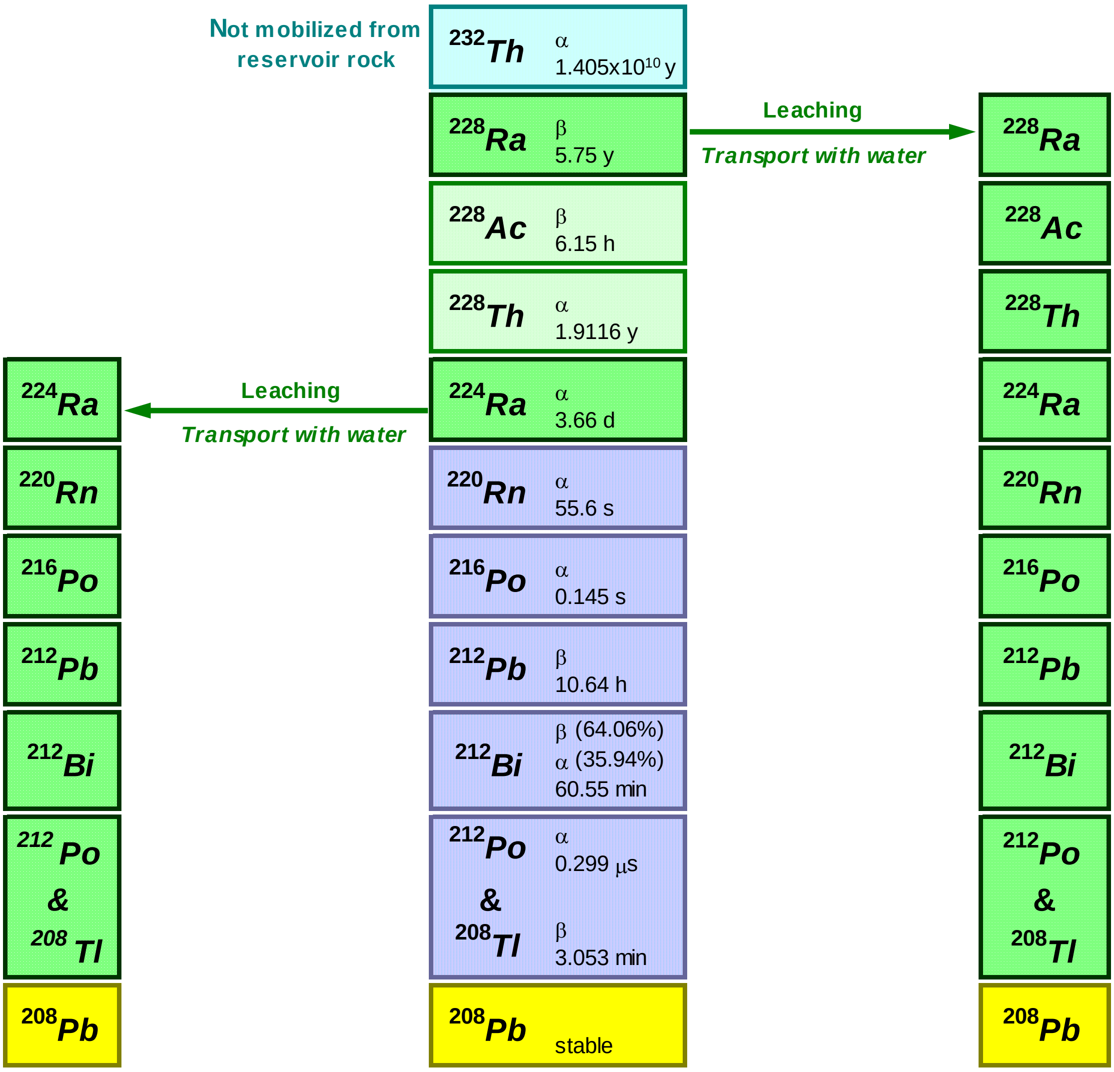

FIG. 42. Transport of ^{232}Th progeny in oil and gas production

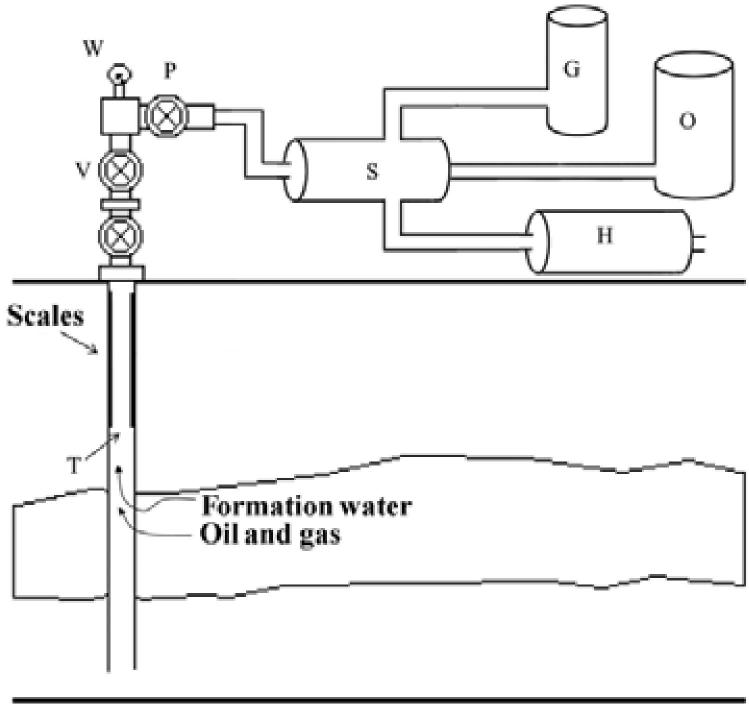

FIG. 43. Precipitation of scales in production plant and equipment

12.2.2. Main forms of appearance

The main forms of appearance of NORM in the oil and gas industry are presented in Table 18.

An additional type of NORM associated with oil production has been reported recently [57]. Biofouling/corrosion deposits occurring within various parts of seawater injection systems, including injection wells and cross-country pipelines, have been found to contain significantly enhanced concentrations of uranium originating from the seawater (where it is present in concentrations of a few parts per billion) as a result of the action of sulphate-reducing bacteria under anaerobic conditions.

Scale deposition interferes in the long term with the production process by blocking transport through the pay zone, flow lines and produced water lines, and may interfere with the safe operation of the installation. Operators try to prevent deposition of scales through the application of chemical scale inhibitors in the seawater injection system, in the topside equipment located downstream from the wellhead, or in the producing well [58]. To the extent that these chemicals prevent the deposition of the sulphate and carbonate scales, the radium isotopes will pass through the production system and be released with the produced water. Methods of chemical descaling are applied in situ using scale dissolvers when scaling interferes with production and mechanical removal is not the method of choice [59, 60].

The extent of mobilization of radionuclides from reservoirs and their appearance in produced water and production equipment varies greatly between installations and between individual wells. In general, heavier scaling is encountered more frequently in oil producing installations than in gas production facilities.

TABLE 18. NORM IN OIL AND GAS PRODUCTION

	Radionuclides	Characteristics	Occurrence
Ra scales	^{226}Ra, ^{228}Ra, ^{224}Ra + progeny	Hard deposits of Ca, Sr, Ba sulphates and carbonates	Wet parts of production installations Well completions
Ra sludge	^{226}Ra, ^{228}Ra, ^{224}Ra + progeny	Sand, clay, paraffins, heavy metals	Separators, skimmer tanks
Pb deposits	^{210}Pb + progeny	Stable lead deposits	Wet parts of gas production installations Well completions
Pb films	^{210}Pb + progeny	Very thin films	Oil and gas treatment and transport
Po films	^{210}Po	Very thin films	Condensates treatment facilities
Condensates	^{210}Po	Unsupported	Gas production
Natural gas	^{222}Rn ^{210}Pb, ^{210}Po	Noble gas Plated on surfaces	Consumers domain Gas treatment and transport systems
Produced water	^{226}Ra, ^{228}Ra, ^{224}Ra and/or ^{210}Pb	More or less saline, large volumes in oil production	Each production facility

In the separation of natural gas by liquefaction, radon can become concentrated with gases that have similar liquefaction temperatures. It is expected that ^{210}Po and ^{210}Pb would also become concentrated in certain parts of the process [43].

12.2.3. Radionuclide concentrations

Over the production lifetime, the produced water may become increasingly more saline, indicating the co-production of brine. This may enhance the dissolution of the Group II elements — including radium — from the reservoir rock in a manner similar to the effect of seawater injection when it is used to enhance recovery. Therefore, over the lifetime of a well, NORM may be virtually absent at first but then start to appear later. The mobilization of lead with ^{210}Pb is also variable. The extent to which sludge is produced and the need to remove it regularly from separators and systems handling produced water also vary strongly between reservoirs, individual wells, installations and production conditions. As a consequence, there are neither typical concentrations of radionuclides in NORM from oil and gas production, nor typical amounts of scales and sludge being produced annually or over the lifetime of a well.

As can be seen in Table 19, the concentrations of ^{226}Ra, ^{228}Ra and ^{224}Ra in scales and sludge range from less than 0.1 Bq/g up to 15 000 Bq/g [56]. Generally, the activity concentrations of radium isotopes are lower in sludge than in scales. The opposite applies to ^{210}Pb, which usually has a relatively low concentration in hard scales but may reach a concentration of more than 1000 Bq/g in lead deposits and sludge. Examples of activity concentrations in scales and sludge are given in Figs 44 and 45. Although thorium isotopes are not mobilized from the reservoir, the decay product ^{228}Th starts to grow in from ^{228}Ra after deposition of the latter. As a result, when scales containing ^{228}Ra grow older, the concentration of ^{228}Th increases to a level of up to 1.5 times the concentration of ^{228}Ra still present (see Figs 46 and 47).

TABLE 19. CONCENTRATIONS OF NORM IN OIL, GAS AND BY-PRODUCTS [56]

Radio-nuclide	Crude oil Bq/g	Natural gas Bq/m^3	Produced water Bq/L	Hard scale Bq/g	Sludge Bq/g
^{238}U	<0.01	—	0.0003–0.1	0.001–0.5	0.005–0.01
^{226}Ra	0.000–0.04	—	0.002–1200	0.1–15 000	0.05–800
^{210}Po	0–0.01	0.002–0.08	—	0.02–1.5	0.004–160
^{210}Pb	—	0.005–0.02	0.05–190	0.02–75	0.1–1300
^{222}Rn	—	5–200 000	—	—	—
^{232}Th	0.000 03–0.002	—	0.0003–0.001	0.001–0.002	0.002–0.01
^{228}Ra	—	—	0.3–180	0.0 –2800	0.5–50
^{224}Ra	—	—	0.5–40	—	—

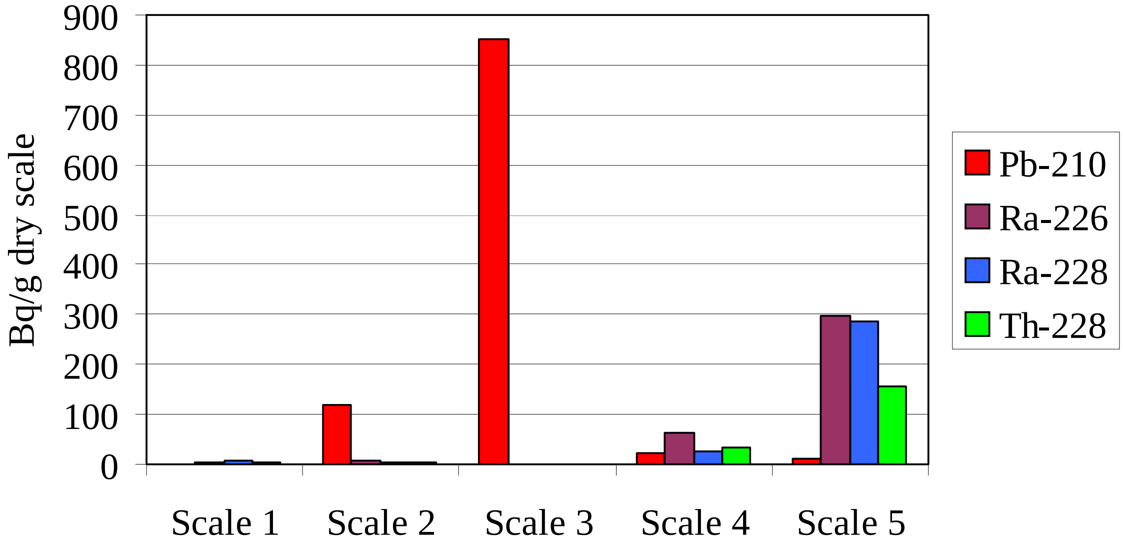

FIG. 44. Examples of the variation of activity concentrations in scales

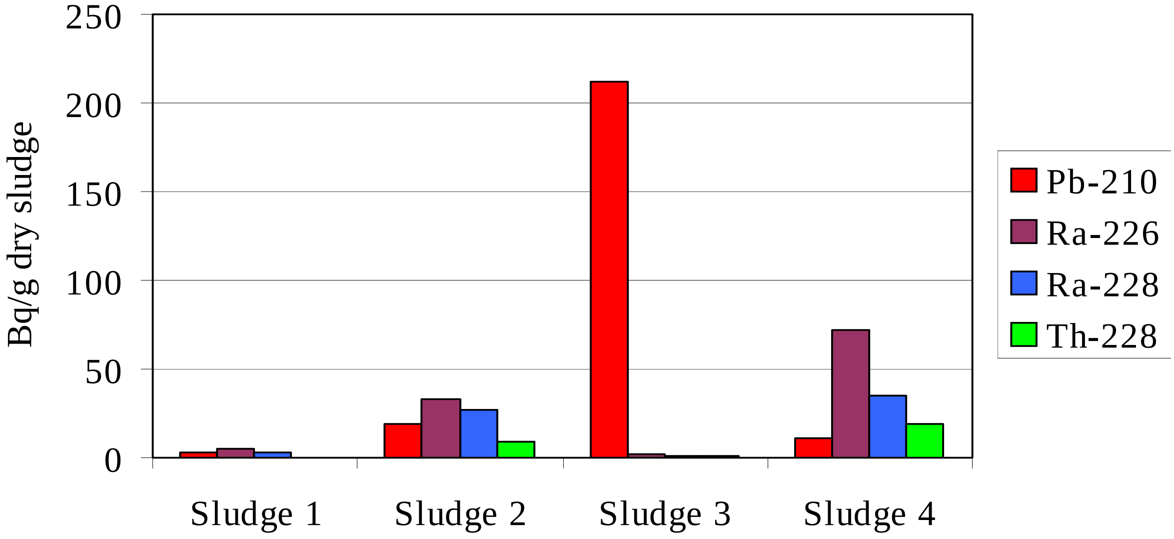

FIG. 45. Examples of the variation of activity concentrations in sludge

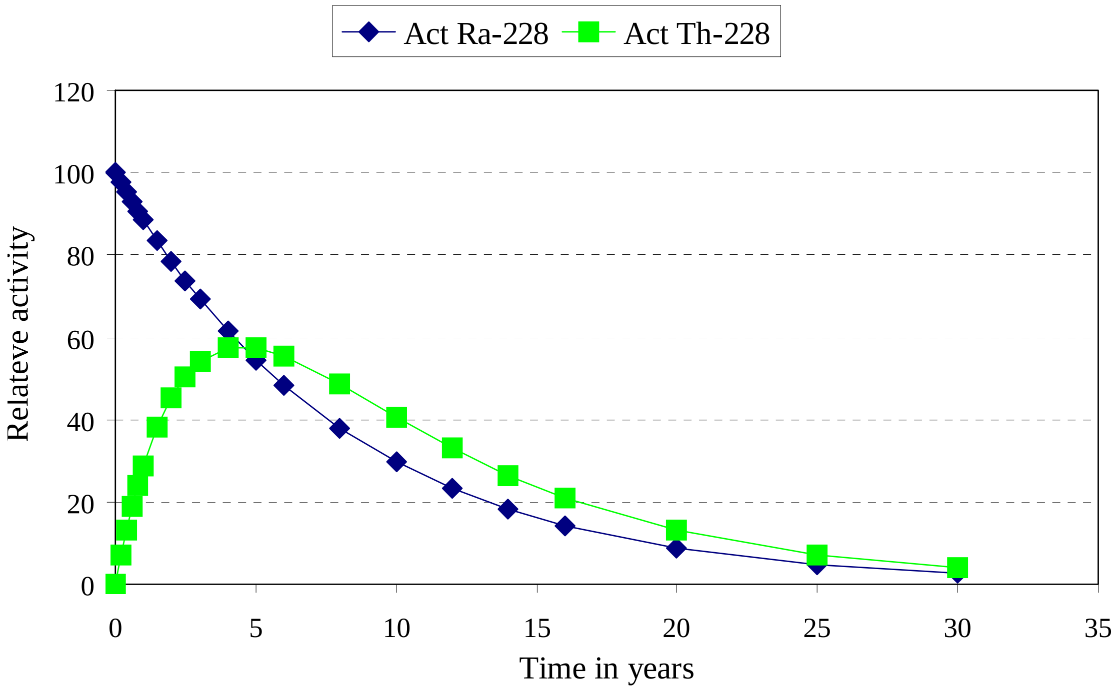

FIG. 46. Ingrowth of ^{228}Th in ^{228}Ra-bearing scale

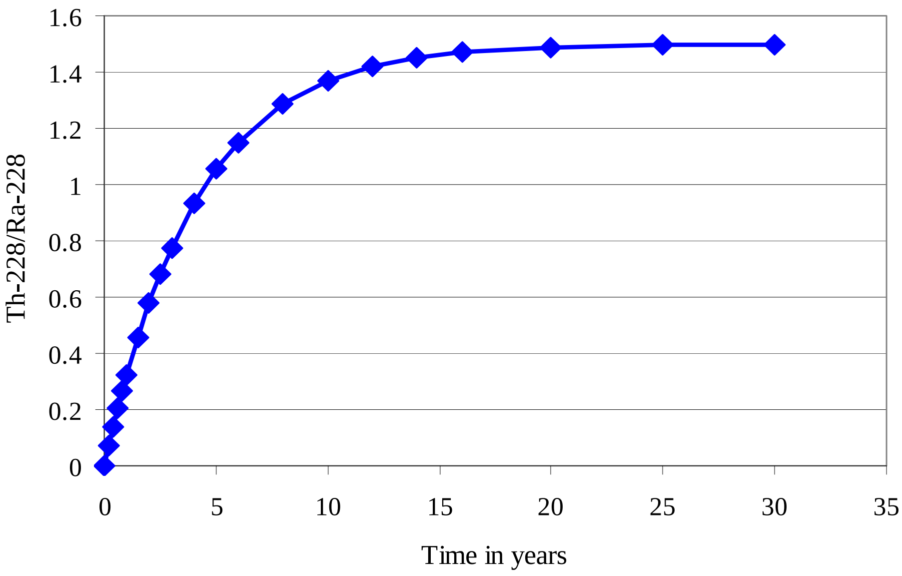

FIG. 47. ^{228}Th:^{228}Ra activity ratio for unsupported ^{228}Ra

12.3. RADIATION PROTECTION ASPECTS OF NORM

In the absence of suitable radiation protection measures, NORM in the oil and gas industry could cause external exposure during production due to accumulations of gamma emitting radionuclides and internal exposures of workers and other persons, particularly during maintenance, the transport of waste and contaminated equipment, the decontamination of equipment, and the processing and disposal of waste. Exposures of a similar nature may arise also during the decommissioning of oil and gas production facilities and their associated waste management facilities.

12.3.1. External exposure

The deposition of contaminated scales and sludge in pipes and vessels may produce significant dose rates inside and outside these components (Table 20). Short lived progeny of the radium isotopes, in particular ^{226}Ra, emit gamma radiation capable of penetrating the walls of these components, and the high energy photon emitted by ^{208}Tl (one of the progeny of ^{228}Th) can contribute significantly to the dose rate on outside surfaces when scale has been accumulating over several months. The dose rates depend on the amount and activity concentrations of radionuclides present inside and the shielding provided by pipe or vessel walls. Maximum dose rates are usually up to a few microsieverts per hour. In exceptional cases, dose rates measured directly on the outside surfaces of production equipment have reached several hundred microsieverts per hour [56, 61], which is about 1000 times greater than normal background values due to cosmic and terrestrial radiation. The build-up of radium scales can be monitored without opening plant and equipment (Fig. 48). Where scales are present, opening the system for maintenance or other purposes will increase dose rates. External exposure can be restricted only by maximizing the distance from, and minimizing time during exposure to, the components involved. In practice, restrictions on access and occupancy time are found to be effective in limiting annual doses to low values.

TABLE 20. EXTERNAL GAMMA DOSE RATES OBSERVED IN SOME OIL PRODUCTION AND PROCESSING FACILITIES

	Dose rate (µSv/h)
Down hole tubing, safety valves (internal)	up to 300
Wellheads, production manifold	0.1–22.5
Production lines	0.3–4
Separator scale (measured internally)	up to 200
Separator scale (measured externally)	up to 15
Water outlets	0.2–0.5

FIG. 48. Monitoring the outside of plant and equipment using a dose rate meter (Courtesy: HPA-RPD, UK)

Deposits of almost exclusively ^{210}Pb cannot be assessed by measurements outside closed plant and equipment. Neither the low energy gamma of ^{210}Pb nor the beta particles emitted penetrate the steel walls. Therefore ^{210}Pb does not contribute significantly to external dose and its presence can be assessed only when components are opened.

12.3.2. Internal exposure

Internal exposure to NORM may result from the ingestion or inhalation of radionuclides. This may occur while working on or in open plant and equipment, handling waste materials and surface contaminated objects, and during the cleaning of contaminated equipment. Ingestion can also occur if precautions are not taken prior to eating, drinking, smoking, etc. More detail on this issue is provided in section 12.3.3.2.

Effective precautions are needed during the aforementioned operations to contain the radioactive contamination and prevent its transfer to areas where other persons also might be exposed. The non-radioactive characteristics of scales and sludge also demand conventional safety measures, and therefore the risk of ingesting NORM is likely to be very low indeed. However, cleaning contaminated surfaces during repair, replacement, refurbishment or other work may generate airborne radioactive material, particularly if dry abrasive techniques are used. The exposure from inhalation could become significant if effective personal protective equipment (including respiratory protection) and/or engineered controls are not used.

The potential committed dose from inhalation depends on both the physical and chemical characteristics of NORM. It is important to consider the radionuclide composition and activity concentrations, the activity aerodynamic size distribution of the particles (quantified by the activity median aerodynamic diameter, or AMAD), and the chemical forms of the elements and the corresponding lung absorption types. Table II-V (Schedule II) of the BSS quotes the following lung absorption types for the elements of interest for dose calculations:

- Radium (all compounds): Medium (M)
- Lead (all compounds): Fast (F)
- Polonium (all unspecified compounds): Fast (F)
  (oxides, hydroxides, nitrates): Medium (M)
- Bismuth (nitrate): Fast (F)
  (all unspecified compounds): Medium (M)
- Thorium (all unspecified compounds): Medium (M)
  (oxides, hydroxides): Slow (S).

Table 21 gives the effective dose per unit intake of dust particles of 5 μm AMAD (the default size distribution for normal work situations) and 1 μm AMAD (a size distribution that may be more appropriate for work situations such as those involving the use of high temperature cutting torches). For each case, values are quoted for the slowest lung absorption type listed in the BSS (S for thorium, M for radium, polonium and bismuth, and F for lead — as noted above). In addition, values for 5 μm AMAD calculated by Silk [62] are quoted, based on a more conservative assumption that all radionuclides are of lung absorption type S.

Table 21 indicates that the inhalation of particles of 5 μm AMAD incorporating ^{226}Ra (with its complete decay chain in equilibrium), ^{228}Ra, and ^{224}Ra (with its complete decay chain in equilibrium), each at a concentration of 10 Bq/g, would deliver a committed effective dose per unit intake of about 0.1 to 1 mSv/g, the exact value depending on the extent of ingrowth of ^{228}Th from ^{228}Ra and the lung absorption types assumed. For 1 μm AMAD particles, the committed effective dose per unit intake would be about 25–30% higher (based on the slowest lung absorption types listed in the BSS).

Radium-containing sulphate scales are very insoluble which could bring them into lung absorption type S (Slow). In addition these scales are characterized by very low radon emanation rates. These two characteristics could increase the dose coefficient for inhalation of ^{226}Ra in sulphate scale significantly above the values provided in BSS for particles of type M.

Consequently, the dose per unit mass intake could be considerably higher than 1 mSv/g at a concentration of 10 Bq/g.

TABLE 21. DOSE PER UNIT INTAKE FOR INHALATION OF RADIONUCLIDES IN PARTICLES OF NORM SCALE

	Committed effective dose per unit intake, Sv/Bq		
	5 μm AMAD		1 μm AMAD
	Slowest lung absorption type listed in BSS	Slow (S) absorption type [62]	Slowest lung absorption type listed in BSS
^{226}Ra	2.2×10^{-6}	3.8×10^{-5}	3.2×10^{-6}
^{210}Pb	1.1×10^{-6}	4.5×10^{-6}	8.9×10^{-7}
^{210}Po	2.2×10^{-6}	2.8×10^{-6}	3.0×10^{-6}
^{228}Ra	1.7×10^{-6}	1.2×10^{-5}	2.6×10^{-6}
^{228}Th	3.2×10^{-5}	3.2×10^{-5}	3.9×10^{-5}
^{224}Ra	2.4×10^{-6}	2.8×10^{-6}	2.9×10^{-6}

12.3.3. Practical radiation protection measures

The requirements for radiation protection and safety established in the BSS apply to NORM associated with installations in the oil and gas industry. The common goal in all situations is to keep radiation doses as low as reasonably achievable, economic and social factors being taken into account (ALARA), and below regulatory dose limits for workers. The practical measures to reach these goals differ principally for the two types of radiation exposure: through external radiation and internal contamination.

12.3.3.1. Measures against external exposure

The presence of NORM in installations is unlikely to cause external exposures approaching or exceeding annual dose limits for workers. External dose rates from NORM encountered in practice are usually so low that protective measures are not needed. In exceptional cases where there are significant but localized dose rates, the following basic rules can be applied to minimize any external exposure and its contribution to total dose:

- Minimize the duration of any necessary external exposure;
- Ensure that optimum distances are maintained between any accumulation of NORM (installation part) and exposed people;
- Maintain shielding material or equipment between the NORM and potentially exposed people.

The first two measures in practice involve the designation of supervised or controlled areas to which access is limited or excluded. The use of shielding material is an effective means of reducing dose rates around radiation sources but it is not likely that shielding can be added to shield a bulk accumulation of NORM. However, the principle may be applied by ensuring that NORM remains enclosed within (and behind) the thick steel wall(s) of plant or equipment such as a vessel for as long as feasible while preparations are made for the disposal of the material. If large amounts of NORM waste of high specific activity are stored, some form of localized shielding with lower activity wastes or materials may be required to reduce gamma dose rates to acceptably low levels on the exterior of the waste storage facility.

12.3.3.2. Measures against internal exposure

In the absence of suitable control measures, internal exposure may result from the ingestion or inhalation of NORM while working with uncontained material or as a consequence of the uncontrolled dispersal of radioactive contamination. The risk of ingesting or inhaling any radioactive contamination present is minimized by complying with the following basic rules, whereby workers:

- Use protective clothing in the correct manner to reduce the risk of transferring contamination;
- Refrain from smoking, drinking, eating, chewing (e.g. gum), applying cosmetics (including medical or barrier creams, etc.), licking labels, etc. or any other actions that increase the risk of transferring radioactive materials to the face during work;
- Use suitable respiratory protective equipment as appropriate to prevent inhalation of any likely airborne radioactive contamination (Fig. 49);
- Apply, where practicable, only those work methods that keep NORM contamination wet or that confine it to prevent airborne contamination;
- Implement good housekeeping practices to prevent the spread of NORM contamination;
- Observe industrial hygiene rules such as careful washing of protective clothing and hands after finishing the work.

FIG.49. Workers with personal protective equipment (Courtesy: Atomic Energy Commission of Syria)

12.4. ANALYTICAL ASPECTS OF NORM AND NORM WASTE

12.4.1. General considerations

Only under certain conditions can reliable estimates of the activity concentration of gamma emitting nuclides be obtained from the known composition and the readings of dose rate or contamination monitors on the outside of the waste container. Usually, the radiological characterization of NORM waste will demand nuclide-specific analysis by high-resolution gamma spectrometry at a qualified laboratory. The method requires sophisticated equipment, comprising well calibrated high-purity germanium detectors of the thin window N-type, operated by experienced analysts. Quality assurance systems and reporting requirements have to satisfy the regulatory body. The method allows the determination of NORM nuclides as summarized in Table 22. The use of a small flat geometry is required in combination with a thin window N type high purity germanium detector for measurement of the low energy photons of ^{210}Pb emitted by the sample and by the ^{210}Pb source to be used for self-absorption correction. A gas tight geometry is required if the Rn emanation from the sample material cannot be assumed to be very low and ^{226}Ra is to be measured by the short-lived progeny of ^{222}Rn.

TABLE 22. DETERMINATION OF NATURAL RADIONUCLIDES

Nuclide to be measured	Nuclide to be used from the gamma spectrum	Remarks
^{226}Ra	^{226}Ra (186 keV)	If no interference from ^{235}U is expected
^{226}Ra	^{214}Pb (352 keV)	If interference from ^{235}U is expected. Use gas-tight geometry if ^{222}Rn emanates from matrix
^{210}Pb	^{210}Pb (46.5 keV)	Correction needed for self absorption
^{228}Ra	^{228}Ac (911 keV)	—
^{228}Th	^{208}Tl (583 keV)	Correction needed for decay chain branching

Difficult-to-resolve systematic errors are caused by coincidence phenomena associated with many photons of different energy emitted in cascade by the same radionuclide. This can be solved most efficiently and reliably by deriving calibration factors from counting reference material in the same geometry as the samples to be measured. Reference material such as IAEA-RGU-1 and IAEA-RGTh-1 can be obtained from IAEA [63]. Sample pretreatment of produced water for significant reduction of detection limits will also require skilled laboratory personnel.

12.4.2. Scales and sludges

Samples of sludges and scales need only drying and homogenizing for the preparation of counting samples. Even this simple sample treatment may cause problems with sludges containing glycol or oily residues.

Interference of ^{235}U with the determination of ^{226}Ra is rather unlikely. With both sludges and scales emanation rates of Rn can be expected to be very low, which will allow reduction of the detection limit for ^{226}Ra by measuring its gamma emitting short-lived progeny ^{214}Pb and/or ^{214}Bi. If interference of the 186 keV photon from ^{235}U cannot be excluded and a low emanation rate of Rn cannot be assumed, ^{226}Ra has to be measured by the short lived progeny mentioned after confinement of the Rn in a gas tight geometry until secular equilibrium is attained.

Assessment of the concentration of ^{210}Pb in sludges and scale will require correction for self-absorption of the 46.5 keV photons in the sample matrix. This use of a flat cylindrical geometry allows such transmission measurements with a ^{210}Pb source over the sample and over the same but empty sample holder.

Estimation of ^{210}Po activity concentrations will need time-consuming special analysis involving complete dissolution of the sample matrix, chemical separation and alpha spectrometry. In practice, secular equilibrium between ^{210}Pb and ^{210}Po in most sludges and scales is assumed in order to obtain an estimate of the concentration of ^{210}Po from the gamma spectrometric analysis of ^{210}Pb. This assumption will not hold, for instance, for the condensates fraction of natural gas.

Analyses of wastes have to be expressed in a format acceptable to the regulatory body.

12.4.3. Produced water

Methods applicable to the radiological characterization of produced water depend on the sensitivity needed and on the radionuclides to be detected. Secular equilibrium between ^{210}Pb and ^{210}Pb cannot necessarily be assumed.

12.4.3.1. Without pre-concentration

Activity concentrations in produced water are much lower than in sludges and scales from the same installations. They may range from less than 0.1 Bq/L to over 50 Bq/L. At activity concentrations greater than 10 Bq/L produced water samples can be counted without pre-concentration provided the counting system is adequately calibrated, and taking the following into account:

- Determination of ^{226}Ra on the basis of the count rate of gamma photons of its progeny ^{214}Pb and ^{214}Bi can introduce large uncertainties caused by coincidence losses that are not easily quantifiable and by ^{222}Rn escaping from the water sample as well as from the sample holder.
- The uncertainties caused by coincidence losses in measuring ^{214}Pb and/or ^{214}Bi can be avoided if the calibration sources are prepared from the reference material IAEA-RGU-1 or from a certified ^{226}Ra solution (in a gas-tight geometry). The calibration factor derived after secular equilibrium has been obtained is insensitive to coincidences.
- Because of the large difference between the emission probabilities of the 186 keV photon from ^{226}Ra (3.5%) and those of the 352 keV and 609 keV photons from ^{214}Pb (35%) and ^{214}Bi (45%) respectively, the use of the ^{226}Ra photon for determining ^{226}Ra means improving the sensitivity by a factor of about 10. The sample vessel has to be gas tight and equilibrium has to be established before any determination is attempted.
- The method is inherently insensitive when used for determining ^{210}Pb because of the high self-absorption of its low energy photon (46 keV).
- When counting liquid samples of produced water, there is a risk of undissolved matter settling on the bottom of the sample holder closer to the detector. This can be avoided by gelling the sample with, for instance, wallpaper glue. Highly saline samples cannot be gelled.

12.4.3.2. With pre-concentration

At activity concentrations below 1 Bq/L, the counting efficiency for direct measurement of ^{226}Ra and ^{228}Ra in produced water will not usually be sufficient. Consequently, pre-concentration will be needed to reduce uncertainties to acceptable levels while maintaining reasonable counting times. High sensitivities can be obtained using a radium separation technique that involves the addition of a barium carrier and the co-precipitation of radium and barium as insoluble sulphate. The activity of samples of several litres can then be concentrated in a small amount of solid material that can be counted in a small volume sample geometry close to the detector. At the same time, the precipitation leaves ^{40}K in the stripped water sample, which reduces the background count rate of the solids containing the radium isotopes. This procedure also enables the determination of ^{210}Pb at levels less than 1 Bq/L if a stable lead carrier, in addition to the barium carrier, is added to separate ^{210}Pb by precipitation of insoluble lead sulphate. Self-absorption correction with a ^{210}Pb source can be carried out as described for scales and sludges, provided a flat cylindrical geometry is used for counting the precipitate. The use of a small, flat, gas tight geometry implies that a thin window N-type high purity germanium detector will be used for measurement of the low energy photons of ^{210}Pb emitted by the sample and by the ^{210}Pb source used for self-absorption correction.

12.5. DECONTAMINATION AND NORM WASTE

Decontamination of plant and equipment gives rise to different waste streams depending on the type of contaminating material and the decontamination method applied. For instance, in situ descaling produces water containing the chemicals applied as well as the matrix and the radionuclides of the scale. Mechanical decontamination by dry methods will produce the dry scale as waste. Dry waste also arises from filter systems used to remove radioactive aerosols from venting systems. Dry abrasive decontamination without the use of filters is to be avoided, as airborne dispersal of the contaminant may give rise to an additional waste stream that is difficult to control. The types of waste stream generated by decontamination processes are summarized below:

- Sludges removed from pipes, vessels and tanks;
- Solid scale suspended in water;
- Liquids containing dissolved scale and chemicals used for chemical decontamination;
- Solid scale recovered from wet or dry abrasive decontamination processes;
- Waste water resulting from removal of scale by sedimentation and/or filtration of water used for wet abrasive methods, in particular high pressure water jetting;
- Filters used to remove airborne particulates generated by dry abrasive decontamination methods;
- Slag from melting facilities;
- Flue dust and off-gas (containing the more volatile naturally occurring radionuclides) from melting facilities.

In practice, these waste streams contain not only naturally occurring radionuclides but other constituents as well. These other constituents include the compounds from chemical mixes used for decontamination, solid or liquid organic residues from oil and gas purification and heavy metals. In particular, mercury, lead and zinc are encountered frequently in combination with NORM from oil and gas production. These other components in waste streams from decontamination will demand adoption of additional safety measures and may impose constraints on disposal options. Also, the volatility of the heavy metals mentioned above will limit the practicability of melting as a decontamination option.

The removal of NORM-containing scales and sludges from plant and equipment, whether for production and safety reasons or during decommissioning, needs to be carried out with adequate radiation protection measures having been taken and with due regard for other relevant safety, waste management and environmental aspects. In addition to the obvious industrial and fire hazards, the presence of other contaminants such as hydrogen sulphide, mercury and hydrocarbons (including benzene) may necessitate the introduction of supplementary safety measures.

On-site decontamination is the method preferred by operators when the accumulation of scales and sludges interferes with the rate and safety of oil and gas production, especially when the components cannot be reasonably removed and replaced or when they need no other treatment before continued use. The work may be carried out by the operator's workers but is usually contracted out to service companies. It will necessitate arrangements, such as the construction of temporary habitats, being made to contain any spillage of hazardous material and to prevent the spread of contamination from the area designated for the decontamination work. Decontamination work has to be performed off the site where:

- On-site decontamination cannot be performed effectively and/or in a radiologically safe manner;
- The plant or equipment has to be refurbished by specialists prior to reinstallation;
- The plant or equipment needs to be decontaminated to allow clearance from regulatory control for purposes of reuse, recycling or disposal as normal waste.

Service companies hired to perform decontamination work need to be made fully aware of the potential hazards and the rationale behind the necessary precautions, and may need to be supervised by a qualified person. The service companies may be able to provide specific facilities and equipment for the safe conduct of the decontamination operations, for example a converted freight container on the site (Fig. 50) or a designated area dedicated to the task (Fig. 51). Personal protective measures will comprise protective clothing and, in the case of handling dry scale, respiratory protection as well.

The regulatory body needs to set down conditions for:

- Protection of workers, the public and the environment;
- Safe disposal of solid wastes;
- Discharge of contaminated water;
- Conditional or unconditional release of the decontaminated components.

12.5.1. Decontamination

Various decontamination methods are being applied on and off site, the choice of method depending on the type and size of the components and the characteristics of the contaminating material. Methods range from removal of bulk sludge from vessels (Fig. 52) followed by rinsing with water to the application of chemical or mechanical abrasive techniques. The methods of specific operational importance are summarized briefly below.

FIG. 50. Workers wearing personal protective equipment decontaminating a valve inside an on-site facility (Courtesy: HPA-RPD, UK)

FIG. 51. Barrier designating a controlled area to restrict access to NORM-contaminated equipment stored outside a decontamination facility (Courtesy: HPA-RPD, UK)

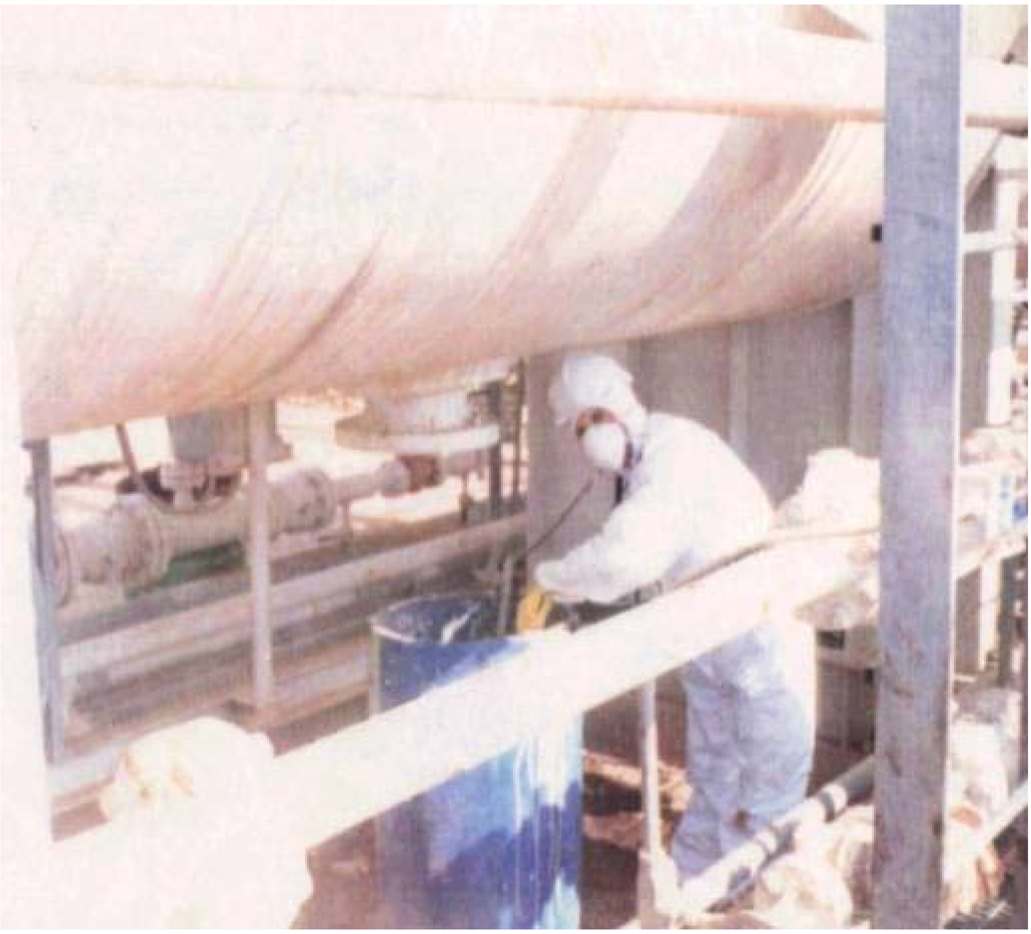

FIG. 52. Removal of bulk sludge from a vessel (Courtesy: Atomic Energy Commission of Syria)

12.5.1.1. Manual cleaning and vacuuming

The method does not involve any machinery or involves simple machinery only and may be as simple as hand washing or shovelling. It is commonly used for removing sand and sludge from topside equipment. Vacuuming can be used wet or dry to remove loose particle contamination or to transfer slurries of solids from topside equipment into transport or storage tanks.

12.5.1.2. Mechanical removal

Drilling or reaming is commonly used to remove scale (hard deposits) from tubulars and other types of surface contaminated equipment. If dry drilling processes are used, extractors should be installed in a closed system to avoid spreading of radioactive dust (Fig. 53). Wet drilling processes will reduce or prevent the generation of radioactive dust. The wet process should also be enclosed to contain the contaminants and wash water should be filtered to remove scale.

FIG. 53. Dry drilling of tubulars with a closed extractor system to remove contaminated dust (Courtesy: Atomic Energy Commission of Syria)

12.5.1.3. Chemical descaling

Chemical methods are applied and are being developed further for downhole scale removal and scale prevention [59, 60, 64–66]. If scale prevention has failed and the extent of scaling interferes with production and/or safety, chemical methods are also applied for removal of scale from the production system. The chemicals used are based on mixtures of acids or on combinations of acids and complexing agents. Usually, the primary reason for in situ descaling is to restore or maintain the production rate rather than to remove radioactive contamination. Nevertheless, effective prevention of scaling causes radionuclides mobilized from the reservoir to be carried by the produced water through the production system rather than being deposited.

Chemical methods have to be applied when the surfaces to be decontaminated are not accessible for mechanical treatment, when mechanical treatment would cause unacceptable damage to the components being refurbished, and when the contaminating material is not amenable to mechanical removal. Usually, components have to be degreased by organic or hot alkaline solvents prior to chemical decontamination. The chemicals used are acids, alkalis and complexing agents, which are usually applied in agitated baths.

Chemical decontamination results in a liquid waste stream containing the dissolving and complexing chemicals, and the matrix and radionuclides of the contaminating material. In many cases, some dissolution of the metal of the component being decontaminated cannot be avoided.

12.5.1.4. Abrasive methods

Dry and wet abrasive methods employing hand held devices can be applied to remove scale from easily accessible surfaces of components. Dry gritting, milling, grinding and polishing is normally to be avoided because of the risks of spreading radioactive air contamination. With wet abrasive methods, this risk is reduced considerably. Consequently, the application of dry abrasive methods needs extensive protective measures for workers and the environment, which can in practice only be provided by specialized companies or organizations.

High pressure water jetting (HPWJ) has been shown to be effective for decontamination of components from oil and gas production (Figs 54 and 55). Water pressures of 10–250 MPa are used, which need special pumps and safety measures. In principle it can be applied on site, offshore as well as onshore, but its effective and radiologically safe application needs special expertise and provisions to obtain the right impact of the jet, to contain the recoiling mist and to collect and dispose of the water as well as the scale. HPWJ is usually applied at a limited number of specialized establishments and service companies that are authorized to operate decontamination facilities [61]. Decontamination of tubulars is carried out with the aid of long HPWJ lances with special nozzles that are moved through the whole length of a tubular while the water with the scale is collected at the open ends (Fig. 56). It is relatively easy to contain the recoiling water from tubulars. The application of HPWJ on outer surfaces of components, however, is strongly complicated by the mist produced by the impact and recoil of the jet causing spread of contamination in the open air and strongly reduced visibility in dedicated enclosed spaces.

FIG. 54. Worker using a HPWJ lance (overhead extractor removes airborne contamination) (Courtesy: Atomic Energy Commission of Syria)

FIG. 55. Worker using a HPWJ lance (Courtesy: Atomic Energy Commission of Syria)

FIG. 56. Facility for tubular decontamination by HPWJ (Courtesy: Atomic Energy Commission of Syria)

12.5.1.5. Melting

The melting of metallic components contaminated with NORM will separate the metals from the NORM nuclides. The latter end up in the slag or in the off-gas dust and fume.

Decontamination by melting is being applied at dedicated melting facilities (Fig. 57). The typical processes involved in the melting of scrap steel are the following:

- Transport to the recycling facility by road, rail or sea, using cranes to load and offload;
- Segmenting, by mechanical or thermal means, into sizes suitable for melting;
- Loading by crane or conveyor into an electric arc furnace, induction furnace or converter together with iron, fluxes and coke;
- Casting of the molten product steel into ingots and mechanized removal of the slag for disposal or reuse;
- Recovery and disposal of dust from the off-gas filters.

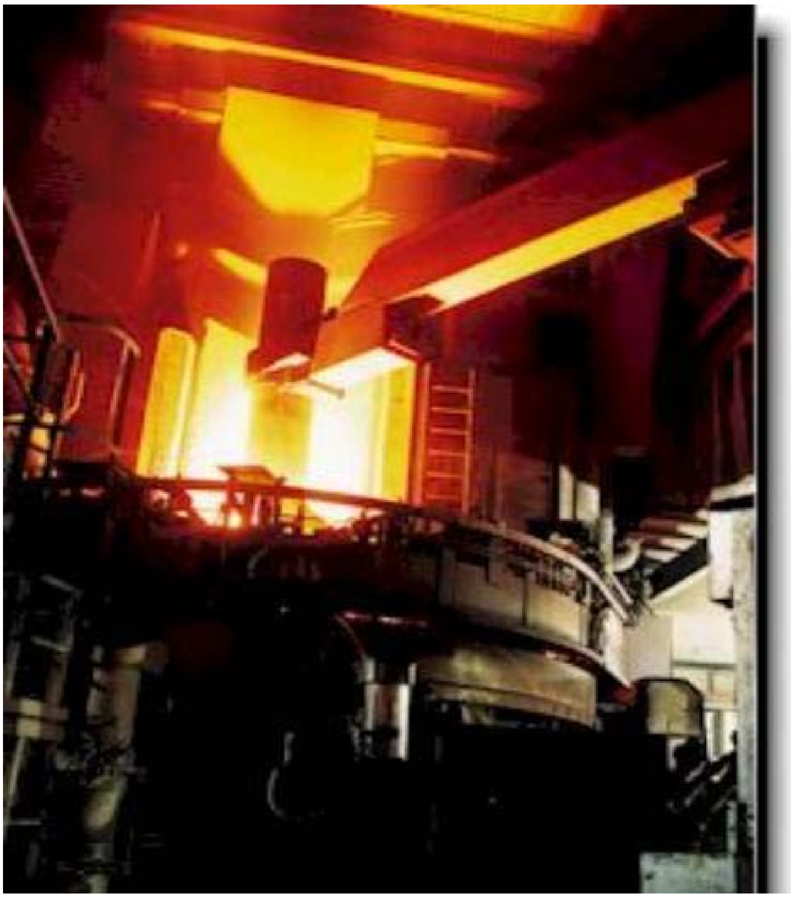

FIG. 57. Melting facility for NORM contaminated materials

12.5.2. NORM waste volumes and activity concentrations

Solid and liquid wastes are generated in significant quantities during the operating lives of oil and gas facilities. Additional quantities of other (mostly solid) wastes may be produced during decontamination activities and during the decommissioning and rehabilitation of the production facility and associated waste management and treatment facilities. These wastes contain naturally occurring radionuclides. Depending on the activity concentrations, they may have radiological impacts on workers, as well as on members of the public who may be exposed if the wastes are dispersed into the environment. These radiological impacts are in addition to any impacts resulting from the chemical composition of the wastes.

Various types of NORM wastes are generated during oil and gas industry operations, including:

- Produced water;
- Sludges and scales;
- Contaminated items;
- Wastes arising from waste treatment activities;
- Wastes arising from decommissioning activities.

12.5.2.1 Volumes and activity concentrations of produced water

Produced water volumes vary considerably between installations and over the lifetime of a field, with a typical range of 2400–40 000 m^3/d for oil producing facilities and 1.5–30 m^3/d for gas production [67]. Produced water may contain ^{226}Ra, ^{228}Ra, ^{224}Ra and ^{210}Pb in concentrations of up to a few hundred becquerels per litre but is virtually free of ^{228}Th. Mean concentrations of 4.1 Bq/L of ^{226}Ra and 2.1 Bq/L of ^{228}Ra were recorded from a recent survey of Norwegian offshore oil production installations [68] but concentrations at individual facilities may well reach levels 50 times higher. Ratios between the concentrations of the radionuclides mentioned vary considerably. As a consequence, the dominant radionuclide may be ^{226}Ra or ^{228}Ra or ^{210}Pb.

Produced water contains formation water from the reservoir and/or (with gas production) condensed water. If injection of seawater is used to maintain reservoir pressure in oil production it might break through to production wells and appear in the produced water. Produced water contains dissolved hydrocarbons such as monocyclic aromatics and dispersed oil. The concentration of dissolved species, in particular Cl^- and Na^+, can be very high when brine from the reservoir is co-produced. Other constituents comprise organic chemicals introduced into the production system by the operator for production or for technical reasons such as scale and corrosion inhibition. A wide range of inorganic compounds, in widely differing concentrations, occurs in produced water. They comprise not only the elements of low potential toxicity: Na, K, Ca, Ba, Sr and Mg, but also the more toxic elements Pb, Zn, Cd and Hg. The health implications of the last two are the focus of particular attention by regulatory bodies and international conventions.

12.5.2.2. Volumes and activity concentrations of solid waste

Solid NORM wastes include sludge, mud, sand and hard porous deposits and scales from the decontamination of tubulars and different types of topside equipment. The activity concentrations of ^{226}Ra, ^{228}Ra, ^{224}Ra and their decay products in deposits and sludge may vary over a wide range, from less than 1 Bq/g to more than 1000 Bq/g [41]. For comparison, the average concentration of radionuclides in the ^{238}U decay series (including ^{226}Ra) in soils is about 0.03 Bq/g [17]. A production facility may generate quantities of scales and sludge ranging from less than 1 t/a to more than 10 t/a, depending on its size and other characteristics [69, 70]. Decontamination of equipment will produce solid and/or liquid waste, the latter also being contaminated with nonradioactive material if chemical methods have been used (Section 12.5.1.3).

The deposition of hard sulphate and carbonate scales in gas production tubulars, valves, pumps and transport pipes is sometimes accompanied by the trapping of elemental mercury mobilized from the reservoir rock. Deposits of ^{210}Pb have very high concentrations of stable lead mobilized from the reservoir rock. They appear as metallic lead and as sulphides, oxides and hydroxides.

Sludges removed from oil and gas production facilities contain not only sand, silt and clay from the reservoir but also non-radioactive hazardous material. Therefore, their waste characteristics are not limited to the radioactive constituents. In all sludges in which ^{210}Pb is the dominant radionuclide the stable lead concentration is also high. Sludges also contain:

- Non-volatile hydrocarbons, including waxes;
- Polycyclic aromatic hydrocarbons, xylene, toluene and benzene;
- Varying and sometimes high concentrations of the heavy metals Pb, Zn and Hg.

In sludges from certain gas fields in Western Europe, mercury concentrations of more than 3% (dry weight) are not uncommon.

12.6. WASTE MANAGEMENT

12.6.1. Waste management strategy and programme

Radioactive waste management comprises managerial, administrative and technical steps associated with the safe handling and management of radioactive waste, from generation to release from further regulatory control or to its acceptance at a storage or disposal facility. It is important that the NORM waste management strategy forms an integral part of the overall waste management strategy for the operation — non-radiological waste aspects such as chemical toxicity also need to be considered, since these will influence the selection of the optimal waste management options for the radioactive waste streams. For sludges in particular, the constraints on waste disposal or processing options imposed by non-radioactive contaminants will in many cases be greater than those imposed by radioactive components.

In view of the range of NORM waste types that can be generated in the industry at different times and the possibility of changes occurring in the ways in which they are generated and managed, particular attention needs to be given to the radiation protection issues which may arise in their management and regulatory control. Because of the nature of the industry, and the fact that the volumes and/or activity concentrations are relatively small, there is often limited knowledge among the staff about the radiation protection aspects of waste management. While the safety principles [2] are the same for managing any amount of radioactive waste regardless of its origin, there may be significant differences in the practical focus of waste management programmes [32]. Good operating practice will focus on ways in which the amount of radioactive waste can be minimized.

12.6.1.1. Risk assessment

Part of the waste management programme is a waste management risk assessment. This is a quantitative process that considers all the relevant radiological and non-radiological issues associated with developing a waste management strategy. The overall aim is to ensure that human health and the environment are afforded an acceptable level of protection in line with current international standards [2, 3]. Prior to any detailed risk assessment, there will be an overall assessment of waste management options that will not be based only on radiological criteria. At the detailed risk assessment stage, the following radiological considerations are addressed in a quantitative manner:

(a) Identification and characterization of radioactive waste source terms;

(b) Occupational and public exposures associated with the various waste management steps from waste generation through to disposal;

(c) Long term radiological impact of the disposal method on humans and on the environment;

(d) All phases of the operation from construction to decommissioning;

(e) Optimal design of waste management facilities;

(f) All significant scenarios and pathways by which workers, the public and the environment may be subject to radiological (and non-radiological) hazards.

The results of the assessment are then compared with criteria specified by the regulatory body. These criteria normally include annual dose limits for workers exposed during operations and for members of the public exposed to radioactive discharges during operation and after closure. The regulatory body may specify, in addition, derived levels and limits related to activity concentration and surface contamination. These derived values are usually situation specific and may relate to materials, items or areas that qualify for clearance from regulatory control.

12.6.1.2. Safety implications of waste disposal methods

Disposal methods are discussed in Sections 12.6.3.1 and 12.6.3.2. Where appropriate, key safety issues and waste management concerns are also listed, since the adoption of a method without the appropriate risk assessment and regulatory approval can lead to significant environmental impacts and associated remediation costs. Particular examples include the disposal of produced water in seepage ponds (Section 12.6.3.1(c)) and the shallow land burial of scales and sludges (Section 12.6.3.2(e)). Ultimately, the acceptability of a particular disposal method for a specific type of NORM waste has to be decided on the basis of a site specific risk assessment. Since the characteristics of particular types of NORM waste (i.e. solid or liquid) arising from different facilities are not necessarily uniform, it cannot be assumed that the disposal methods described are suitable for general application, i.e. at any location.

Waste characteristics such as the radionuclides present, their activity concentrations, and the physical and chemical forms and half-life of the dominant radionuclide can have a major impact on the suitability of a particular disposal method. Site specific factors such as geology, climate, and groundwater and surface water characteristics will also influence strongly the local suitability of a particular disposal method. Only by considering all the relevant factors in the risk assessment can a considered decision be made regarding the optimal local disposal option.

12.6.1.3. Significant non-radiological aspects

The selected disposal method, in addition to meeting the fundamental principles of radioactive waste management [2], also has to take account of the environmental impact of the significant non-radiological hazards associated with the wastes. This applies in particular to sludges that contain hydrocarbons and heavy metals. Discussion of these non-radiological hazards may constitute a dominant aspect in the selection of a disposal method.

12.6.1.4. Storage of solid radioactive wastes

There may be a need to accumulate and store solid NORM wastes (such as scales) and contaminated objects (such as pipes) prior to taking further steps leading to disposal. The regulatory body has the responsibility for authorizing facilities for storage of radioactive waste, including storage of contaminated objects. A well-designed storage facility will have clear markings to identify its purpose, contain the waste material adequately, provide suitable warnings, and restrict access.

The regulatory body will normally require the waste to be encapsulated or otherwise isolated to an approved standard and the dose rate on the outside of the storage facility to be kept within values acceptable to the regulatory body. The regulatory body will probably also impose specific requirements for record keeping of the stored waste.

12.6.2. Regulatory approaches

It is important that the regulatory body achieve a consistent regulatory approach for protection against the hazards associated with NORM wastes in line with international waste management principles [2] and the BSS [3]. Regulatory bodies unfamiliar with control over radioactive wastes in the oil and gas industry need to develop a technical and administrative framework in order to address appropriately the radiation protection and waste management issues specific to that industry.

Regulatory frameworks for the control of radioactive wastes generated in the oil and gas industry are under development in several countries. For example, the management of NORM residues from industrial processes (including the oil and gas industry) by Member States of the European Union is subject to the requirements of Article 40 of the Council Directive 96/29/Euratom of 13 May 1996 [71]. Implementation of this involves the identification of work activities that may give rise to significant exposures of workers or members of the public and, for those identified industries, the development of national radiation protection regulations in accordance with some or all of the relevant Articles of the Directive. One of the regulatory instruments is the setting of activity concentration clearance levels for industrial residues below which the regulator regards these residues of no regulatory concern.

Waste characterization and classification are important elements at all stages of waste management, from waste generation to disposal. Their uses and applications include:

(a) Identification of hazards;

(b) Planning and design of waste management facilities;

(c) Selection of the most appropriate waste management option;

(d) Selection of the most appropriate processing, treatment, packaging, storage and/or disposal methods.

It is important that records be compiled and retained for an appropriate period of time. Practical guidance on methods of NORM waste characterization (from a radiological point of view only) is provided in Section 12.4.

12.6.3. Disposal options

Various disposal methods for liquid and solid NORM wastes are described in the following sections. The use of these methods by the oil and gas industry is not necessarily an indication that such methods constitute international best practice. Regulatory review, inspection, oversight and control over these disposal activities and methods have been generally lacking in the past. The issue of NORM waste management — and particularly disposal — has been identified in recent years as an area of radiation protection and safety that needs to be formally addressed by national regulatory bodies wherever oil and gas production facilities are operating.

The process of selecting and developing a disposal method for NORM wastes forms an essential part of the formal radioactive waste management programme for a production facility, although the process is generally not conducted at the level of individual production facilities but at company level or at the level of associations of companies. In addition, it is important to commence selection of the optimal waste disposal method at an early stage of the project. In developing a waste management strategy the overall aims are to:

(a) Maximize the reduction of risks to humans and to the environment associated with a particular disposal method in a cost effective manner;

(b) Comply with occupational and public dose limits and minimize doses in accordance with the ALARA principle;

(c) Comply with all relevant national and international laws and treaties;

(d) Comply with all national regulatory requirements.

Disposal methods for NORM wastes fall into four main categories:

(i) Dilution and dispersal of the waste into the environment, e.g. liquid or gaseous discharges;

(ii) Concentration and containment of the waste at authorized waste disposal facilities;

(iii) Processing of the waste with other chemical waste by incineration or other methods;

(iv) Disposal of the waste by returning it back to the initial source of the material (reinjection into the reservoir).

NORM wastes meeting the clearance criteria specified by the regulatory body [5] may be disposed of as normal (non-radioactive) waste.

For any proposed disposal method requiring regulatory authorization, the owner/operator will need to address the minimization of risks to humans and the environment in a cost effective manner, and must conduct a risk assessment and submit it to the regulatory body for review. In deciding on the acceptability of the proposed method, the regulatory body must base its decision on the risk assessment and must be satisfied that the method meets all relevant national and international legal and regulatory requirements and long term safety requirements.

12.6.3.1. Disposal methods for produced water

The large volumes of produced water preclude storage and treatment as a practicable disposal method. The impracticability of treatment applies to both radioactive and non-radioactive contaminants, although some form of treatment is usually needed to meet the requirements set by regulatory bodies with respect to non-radioactive contaminants such as dissolved and dispersed hydrocarbons.There are three methods for disposal of produced water: reinjection into the reservoir, discharge into marine waters, and discharge into seepage ponds.

(a) Reinjection into the reservoir

This method is commonly used onshore and offshore. There are some technical constraints such as the potential for breakthrough into production wells. No added radiological risks would seem to be associated with this disposal method as long as the radioactive material carried by the produced water is returned in the same or lower concentration to the formations from which it was derived (the confirmation of which might entail taking some measurements). Should this not be the case, it is important that any regulatory decision on this method of disposal be supported by an appropriate risk assessment.

(b) Discharge into marine waters

Many production installations on the continental shelf discharge their produced water into estuaries and the sea. Regulatory requirements with respect to the discharge of NORM in this way differ between countries; in some cases there are no requirements at all and in others authorizations are required if activity concentrations exceed the discharge criteria set by the regulatory bodies. Some discharges may be subject to international maritime conventions such as the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (the London Convention) and the Convention for the Protection of the Marine Environment of the North-East Atlantic, 1992 (the OSPAR Convention). Various reports that address the fate of radionuclides and the radiological risks associated with discharges of NORM-containing produced waters pertain to discharges in coastal and offshore areas of the Gulf of Mexico and are based partly on monitoring results [72–77]. Risk assessments of discharges from platforms on the Dutch and Norwegian continental shelf are based on modelling of dispersion and exposure pathways [78, 79]. These risk assessments show that the calculated level of risk to humans is strongly dependent on local conditions (estuary, coastal or open sea) and on the degree of conservatism applied in the dispersion and exposure pathway modelling. It is important that risk assessments such as these are carried out and used as the basis for regulatory requirements with respect to this method of disposal.

(c) Discharge into seepage ponds

At several onshore oil field locations, the produced water is discharged to form artificial lagoons, ponds or seepage pits (Fig. 58). Subsequently, the released waters drain to ground leaving radioactive deposits associated with the soil that eventually require remedial action in accordance with radiation protection principles [80–82] (Fig. 59). It has been estimated that 30 000 contaminated waste pits and bottom sediment sites exist in coastal Louisiana, United States of America [83]. A key factor in determining the acceptability of this method is the radiological impact of the contaminated water on local surface water and groundwater and the potential accumulation of radionuclides in local biota. The degree of impact depends on several factors, including:

- The radionuclide activity levels in the produced water,
- The proportion of the activity contained in the deposited salts,
- The degree of dilution into local surface water and groundwater,
- The volumes produced.

FIG. 58. Lagoons of produced water (Courtesy: Atomic Energy Commission of Syria)

FIG. 59. Remediation of contaminated land after drying the lagoon (Courtesy: Atomic Energy Commission of Syria)

Risk assessments incorporating mathematical modelling can be used to estimate the local contamination and the resulting doses received by the critical group. The regulatory body will then have to make a decision regarding the acceptability of the disposal method.

This method can be considered as a form of waste treatment (concentrate and contain) in that the dissolved radionuclides are converted into solid deposits. The solid waste materials, including soil contaminated by the downward migration of radionuclides, will have to be collected, packaged and disposed of in a manner similar to those specified for scales and sludges (Section 12.6.3.2), or transported in bulk to a burial site that will isolate the waste more effectively than the original seepage pond area. The land areas require remediation and radiation surveys of residual contamination to be undertaken in order to obtain clearance from the regulatory body for future unrestricted use of the land. The regulatory body needs to specify the clearance levels to which the land must be decontaminated.

In considering this disposal method, the following aspects need to be addressed:

- Selection of a suitable site;
- Controls to prevent public access to the area;
- Risk assessments to determine the human and environmental impacts, including long term implications, arising from contamination of soil, groundwater and surface water;
- Possible need for occupational risk assessments and radiation protection programmes for certain activities or areas, to control exposures and limit the spread of contamination into public areas;
- Quality assurance (QA) and record keeping programmes such as those for waste inventories;
- Transport costs and compliance with transport regulations [27];
- Cleanup and remediation costs;
- Disposal of the solid residues as radioactive wastes.

12.6.3.2. Disposal methods for scales and sludges

Various disposal methods are in regular use: discharge from offshore facilities into marine waters (subject to international maritime conventions such as the London Convention and the OSPAR Convention), injection into hydraulically fractured formations, disposal in abandoned wells, and dispersal on land. Disposal by shallow land burial and (for contaminated scrap metal) decontamination by melting is practised on a limited scale. Deep underground disposal is not presently practised, but has been considered as a potential disposal method.

(a) Discharge from offshore facilities into marine waters

The discharge of solid NORM wastes from offshore platforms is an allowed practice on the continental shelf of the United Kingdom and Norway [61, 84]. Limits are set on residual hydrocarbons and particle diameter. As regards the UK, operators are required to obtain authorization for these discharges and to keep records. Intentional discharge of solid NORM wastes with produced water is not allowed on the Dutch continental shelf. This method of disposal can result in the buildup of localized concentrations of scales around offshore rigs over a period of years, and the following aspects need to be addressed:

- The need for risk assessments to determine the human and environmental impacts;
- The possible need for occupational risk assessments and radiation protection programmes for certain activities or areas, to control exposures and limit the spread of contamination into public areas;
- The need for QA and record keeping programmes such as waste inventories.

(b) Injection into hydraulically fractured formations

Methods of disposal that employ hydraulic fracturing have been developed and used for offshore generated solid NORM wastes in the Gulf of Mexico [85, 86]. Hydraulic fracturing is also considered in the generic radiological dose assessments carried out for various NORM disposal options [87] and for a Class II well[3] [88]. In considering this disposal method, the following aspects need to be addressed:

- Site selection in relation to the long term stability of the surrounding geological structures and the required depth of emplacement;
- The possible need for encapsulation or stabilization (e.g. in concrete) of the solid wastes;
- The need for risk assessments to determine the human and environmental impacts;
- The possible need for occupational risk assessments and radiation protection programmes for certain activities or areas, to control exposures and limit the spread of contamination to public areas;
- The need for QA and record keeping programmes such as those for waste inventories.

(c) Disposal in abandoned wells

Disposal in abandoned wells involves the emplacement of NORM solids, whether encapsulated or not, between plugs in the casings of abandoned wells. The method has been the subject of radiological dose assessments [87] and has been described as a preferred option for onshore disposal of scales and mercury-containing sludges [89]. In considering this disposal method, the following aspects need to be addressed:

- Site selection with respect to the long term stability of the surrounding geological structures and the required depth of emplacement. This should be viewed in relation to the half life of the longest lived radionuclide ^{226}Ra (1600 years). It should also be borne in mind that long term stability of an abandoned and plugged well will be required in any case to eliminate the risk of a blow-out.
- Possible need for encapsulation and the associated costs.
- Need for risk assessments to determine the human and environmental impacts, including long term implications, arising from groundwater contamination.
- Possible need for occupational risk assessments and radiation protection programmes for certain activities or areas, to control exposures and limit the spread of contamination into public areas.
- Need for QA and record keeping programmes such as those for waste inventories.

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[3] Class II injection wells are a specific category of injection well used by the oil and gas industry to dispose of salt water produced in conjunction with oil or gas, to inject fluids to enhance oil recovery, or to store hydrocarbon liquids.

Proof of long term performance of the isolation of the waste is likely to be more difficult to provide in the case of non-radioactive constituents (which do not disappear by decay) than in the case of radioactive constituents. The Dutch Government requires 'proof of retrievability' for sludges disposed of in abandoned wells.

(d) Dispersal on land

Land dispersal (also known as 'landspreading' or 'landfarming'), with or without dilution, has been described as "a long standing waste disposal method that has been available to the petroleum industry" [90], but its acceptability for the disposal of sludges is doubtful because of the presence of heavy metals and toxic hydrocarbons. The study cited addresses potential radiation doses to workers and the public, as well as addressing regulatory aspects. The following aspects need to be addressed:

- The need for risk assessments to determine the human and environmental impacts, including long term implications, arising from groundwater contamination;
- The possible need for occupational risk assessments and radiation protection programmes for certain activities or areas, to control exposures and limit the spread of contamination into public areas;
- The need for QA and record keeping programmes such as those for waste inventories;
- Transport costs and compliance with transport regulations [27].

(e) Disposal by shallow land burial

Shallow land burial is discussed as one of the NORM waste disposal options in a study made by the American Petroleum Institute [91] and is described as being practised on a limited scale in Texas [92] and in three other states in the USA [70, 93]. Remediation problems caused by earthen pit disposal of scale and sludge appear to be considerable [94]. The presence of non-radioactive contaminants is one of the more important factors to be considered, and makes this method of disposal an unlikely option for sludges. The radiological assessment of NORM waste disposal in non-hazardous waste landfills is discussed in Ref. [95]. Operational guidance on possible shallow ground disposal methods is available in Ref. [96]. The following aspects need to be addressed:

(i) Selection of a suitable site requiring minimum depth of emplacement. It is particularly important that a suitable site be selected for such a waste management facility. The site selection process should focus on taking maximum advantage of desirable characteristics with regard to minimizing the impact of wastes and ensuring the long term stability of the facility. The various options and the final decision will be subject to economic, technical and practical constraints. Factors that need to be considered in the site selection process include:

    - Anticipated duration of the facility, i.e. temporary or final;
    - Climate and meteorology;
    - Hydrology and flooding;
    - Geography;
    - Geology, geochemistry and geomorphology;
    - Seismicity;
    - Mineralogy;

- Demography and land use;
- Biota;
- Amenability to decommissioning and the permanent disposal of wastes.

(ii) Institutional control issues.

(iii) Long term stability of the facility.

(iv) Need for risk assessments to determine the human and environmental impacts, including long term implications, arising from groundwater contamination.

(v) Possible need for occupational risk assessments and radiation protection programmes for certain activities or areas, to control exposures and limit the spread of contamination into public areas.

(vi) Need for QA and record keeping programmes such as those for waste inventories.

(vii) Transport costs and compliance with transport regulations [27].

(f) Recycling by melting of contaminated scrap metal

The recycling, by melting, of scrap metal contaminated with NORM can be regarded as a potential disposal method as well as a decontamination method. The NORM contamination is mostly concentrated and contained in the slag [61], with low residual activity being diluted and dispersed throughout the product or steel billet. However, volatile radionuclides (^{210}Pb and ^{210}Po) become concentrated in the off-gas dust and fume and may constitute an exposure or waste management issue.

A recycling plant dedicated to NORM-contaminated scrap is operated in Germany [97] and represents one option in the approach to recycling by melting. A preferred option would seem to be the melting of contaminated scrap with larger quantities of uncontaminated scrap, which — together with added iron and other inputs — results in a throughput of NORM-contaminated scrap that is small compared with the throughput of uncontaminated materials [98]. The addition of uncontaminated scrap, together with iron and other inputs, results in sufficient dilution of the contaminated scrap to ensure that the activity concentrations of natural radionuclides in the slag and in the emissions to the atmosphere are not enhanced significantly. The most significant radiological aspect is likely to be the occupational exposure associated with segmentation of the scrap by cutting or shearing to satisfy the size limitations imposed by the melting operation.

The feasibility of this method of disposal and the associated economic, regulatory and policy issues are discussed in Ref. [99]. The radiological aspects are presented in more detail in Refs [87, 98]. Issues that need to be addressed include:

- The possible need for dilution of the contaminated scrap metal with uncontaminated scrap metal to achieve clearance of the steel billets from regulatory control. This will depend on contamination levels; the regulatory body will have to specify appropriate clearance levels for the radionuclides of concern.
- The partitioning behaviour of the main radioactive elements associated with different NORM types; Th (from the decay of ^{228}Ra) and Ra partition to the slag, while Po and Pb are emitted with, or recovered from, the off-gas.
- The safe disposal of the contaminated slag and other wastes such as flue dust.

- The need for risk assessments to determine the human and environmental impacts and possible need for radiation protection programmes for certain activities or areas, and to control exposures and limit the spread of contamination into public areas.
- The need for QA and record keeping programmes such as those for waste inventories and activity levels in the slag and product.

The recycling of radioactively contaminated scrap metal has been increasingly restricted in recent times because of the potential legal liabilities of metal dealers and scrap merchants [100], [101]. Consequently, almost all large metal dealers and scrap steel smelting operations have installed portal gamma radiation monitors at their premises for the purposes of identifying and rejecting consignments of scrap metals contaminated with radioactive materials, sealed radiation sources and NORM. Consignments tend to be rejected, perhaps unnecessarily, even when it is proven that the portal monitor alarm has been triggered only by NORM.

(g) Deep underground disposal

Deep underground disposal is a well-studied method for disposal of high and intermediate level radioactive wastes from the nuclear fuel cycle. Disposal in salt caverns has been described as a potential method for NORM waste from the oil and gas industry [102]. Other possibilities include deep disposal in nearby disused metal mines. The practical potential of these methods depends strongly on the availability of suitable non-operating mines close to the oil and gas production regions. Transport costs could have a significant impact on the practicability of this option as suitable sites may be located far away from the oil and gas production areas. The following aspects would need to be addressed in considering this disposal method:

- The costs of setting up, operating and maintaining such a repository in comparison with the costs associated with other disposal methods;
- The repository location in relation to the oil and gas producing areas;
- The selection of a suitable site requiring minimum depth of emplacement;
- Waste treatment, handling and packaging;
- Institutional control issues;
- The long term stability of the facility;
- Transport costs and compliance with transport regulations [27];
- The need for risk assessments to determine the impacts on the public and on the environment;
- The possible need for occupational risk assessments and radiation protection programmes for certain activities or areas, to control exposures and limit the spread of contamination into public areas;
- The need for QA and record keeping programmes such as waste inventories.

12.6.3.3. Issues common to various disposal options

In addition to the issues mentioned above that need to be considered for specific disposal options, there are certain issues common to various disposal options for produced water and for scales and sludges:

(i) Most disposal options require an appropriate risk assessment for human/environmental impacts and a quality assurance and record keeping programme[4]; furthermore, an occupational exposure assessment and even a radiation protection programme to control exposures and/or contamination may sometimes be required, for instance when rig workers, divers or fisherman are exposed as a result of discharges of scales and sludges to the marine environment.

(ii) The costs of transport and compliance with transport regulations have to be taken into account when considering disposal of solid wastes by shallow land burial, land dispersal, deep underground disposal, or melting of scrap, and when considering the remediation of seepage pits used for the disposal of produced water.

(iii) Disposal into a hydraulically fractured formation, abandoned well, shallow land burial facility, and deep underground repository all require consideration to be given to the long term stability of the facility and to the minimum depth of emplacement. In addition:

- The shallow land burial and deep underground disposal options require consideration of the need for institutional controls (including the costs involved);
- Injection into hydraulically fractured formations and disposal in abandoned wells may need some consideration to be given to the encapsulation and/or stabilization of the waste (including the costs involved).

A summary of these common considerations is given in Table 23.

[4] Disposal options unlikely to require a risk assessment and QA/record-keeping programme are the reinjection of produced water into the reservoir and, possibly, discharge of produced water into the marine environment.

TABLE 23. CONSIDERATIONS FOR WASTE MANAGEMENT

Disposal option		Human and environmental impact assessment	Occupational exposure assessment	Radiation protection programme	QA, record keeping	Transport costs and regulatory compliance	Long term stability of disposal facility	Minimum depth of emplacement	Encapsulation or stabilization including costs	Institutional control including costs
Water	Reinject to reservoir									
	Discharge to sea	x								
	Seepage ponds	**X**	x	x	**X X**					
Scales and sludges	Discharge to sea	**X**	x		**X**					
	Hydraulic fractures	**X**	x	x	**X**		**X X**		x	
	Abandoned wells	**X**	x	x	**X**		**X X**		x	
	Land dispersal	**X**	x	x	**X X**					
	Shallow burial	**X**	x	x	**X X**		**X**	**X**		**X**
	Melting of scrap	**X**	x	x	**X X**					
	Deep underground	**X**	x	x	**X X**		**X**	**X**		**X**

X = consideration;
x = possible consideration

13. RADIATION MONITORING IN THE WORKPLACE

13.1. MEASUREMENT PRINCIPLES AND INSTRUMENTS

13.1.1. Principles

A wide range of instruments is manufactured to carry out workplace monitoring for ionizing radiation and radioactive contamination (Fig. 60). Instruments have not been developed specifically for use at oil and gas production and processing facilities and no single instrument is capable of detecting all types and energies of the radiation used in the industry. It is important to select and make available instruments that are appropriate and efficient for the different applications. Intrinsic safety for use in flammable atmospheres may be an important requirement for the instruments used.

FIG. 60. Various instruments suitable for workplace monitoring

Radiation measuring instruments are usually designed to quantify only one of the two types of potential exposure:

- External exposure to penetrating radiation emitted by sources outside the human body: Such exposures are associated with sealed sources, open sources such as radiotracers (whether they are contained or not), bulk quantities of NORM, and radiation generators or machines.
- Internal exposure associated with radioactive materials that are in a form capable of being inhaled, ingested or otherwise entering and interacting with the human body: Open sources used as radiotracers, radioactive material that has leaked from a sealed source and NORM are potentially capable of causing internal exposure. Special attention is to be drawn to the radioactive noble gas radon which may accumulate near the exit points of sludges, water, mud and other drilling fluids.

142

Dose rate meters are used to measure the potential external exposure, and dosimeters to indicate the cumulative external exposure. Surface contamination meters indicate the potential internal exposure when the radioactive material is distributed over a surface; airborne contamination meters and gas monitors indicate the potential internal exposure when a radioactive material is distributed within the atmosphere.

13.1.2. Dose rate meters

A suitable and efficient dose rate meter that is matched to the specific task is capable of measuring external exposure directly, indicating readings of the equivalent dose rate in microsieverts per hour. Dose rates of this magnitude are measured for safety purposes in most situations such as around source stores, installed level gauges or near accumulated NORM. For other purposes, such as making measurements at the external surfaces of a transport package, it is necessary to be able to measure up to several thousand microsieverts per hour and an instrument capable of measuring in millisieverts per hour is desirable. For some situations, such as implementing an emergency plan to recover an unshielded radiography source, a high dose rate range instrument capable of a continued response where there are tens of millisieverts per hour is needed. In such hazardous situations it is important that the instrument does not exceed the maximum of its range or, worse still, overload and give a zero reading. There are many wide-range or multi-range instruments (see for example Fig. 61) covering dose rates up to several millisieverts per hour and, particularly when working in remote locations, these may be supplemented by specialized high range instruments (indicating in sieverts per hour) assigned to the emergency kit.

FIG. 61. Ion chamber dose rate meter

Instruments with sensitive probes capable of measuring low dose rate gamma radiation fields such as the background value at sea level (40–60 nSv/h) are useful (see for example Figs 62 and 63). They can be used for monitoring mud returns when it is suspected that a sealed source might have ruptured downhole or when it is necessary to monitor over a wide area to find a lost source or equipment that contains a gamma source. This type of instrument may be used also to monitor the outside of equipment to detect the enhanced dose rates that would indicate the presence of accumulated sludge or scales containing radium. As the shielding provided by the scale or sludge mass itself and that of the wall of the equipment can be substantial, it is usually not possible to convert reliably the measured dose rates either into areal inner surface contamination or the activity per unit mass of scale or sludge. Internal contamination by ^{210}Pb will not be detected by dose rate meters because all low energy gamma radiation, beta particles and alpha particles from this nuclide and its progeny are shielded by the intervening metal. Sensitive detectors are available that incorporate both a dose rate measuring capability and gamma spectrometry. Gamma spectrometry enables the radiation that produces the dose rate to be analysed in terms of the radiation energies present. This characterizes unequivocally the nature of the radioactive material (identifying it as ^{137}Cs, ^{226}Ra, etc.) emitting the gamma radiation.

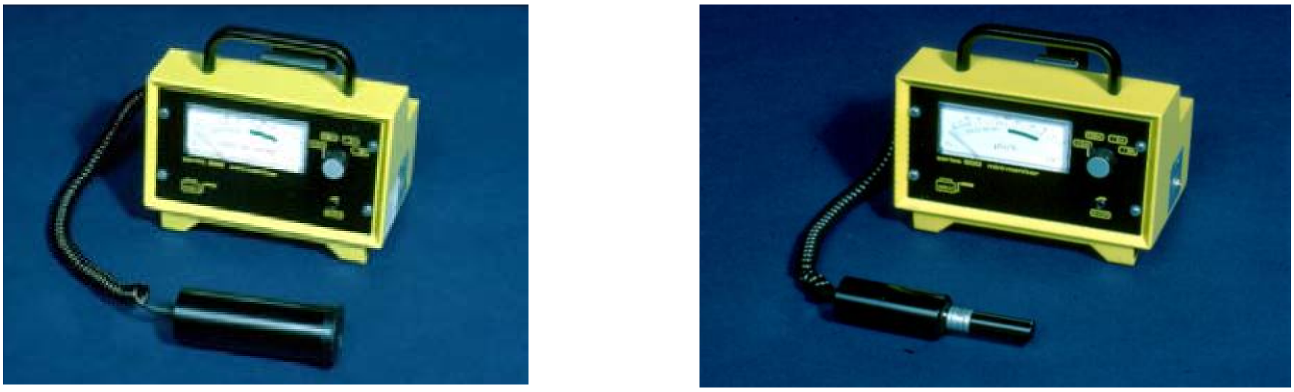


FIG. 62. Compensated and end window dose rate meters

FIG 63. Dose rate meters

The response of any dose rate meter is dependent on the characteristics of the detector it contains and in particular its detection efficiency at the energy (or energies) of the radiation to which it is exposed. An instrument may have a good detection efficiency over a range of radiation energies, reducing to zero (or nearly zero) efficiency at certain radiation energies perhaps at the range extremes. If the detection efficiency is poor the instrument will indicate zero readings whatever actual dose rate those radiations may be producing. For example, an instrument that provides an accurate indication of dose rates due to ^{137}Cs gamma radiation (of an energy of 662 keV) may measure less accurately the dose rates due to ^{241}Am gamma radiation (of an energy of approximately 60 keV). A specific detector may be able to detect radiation of only a certain type or of energy greater than some threshold value. The neutron sources used in well logging, typically ^{241}Am–Be, emit both gamma and neutron radiation that cannot be measured using a single instrument. Well logging service companies therefore need both gamma and neutron dose rate meters and to sum the separate measurements to fully determine external exposure (see for example Figs 64–66). However, for the routine occasions when repetitive measurements are made, the gamma measuring instrument alone will normally suffice to provide adequate confirmation of the whereabouts of the source, the general condition of the shielded container, etc. The gamma measurement can be used with a gamma–neutron ratio to obtain the total dose rate under known exposure conditions. Dose rate measurements should be averaged over a suitable interval, for example 1 min or longer, depending on whether the prevailing dose rate is apparently constant or transient.

FIG. 64. Intrinsically safe dose rate meter

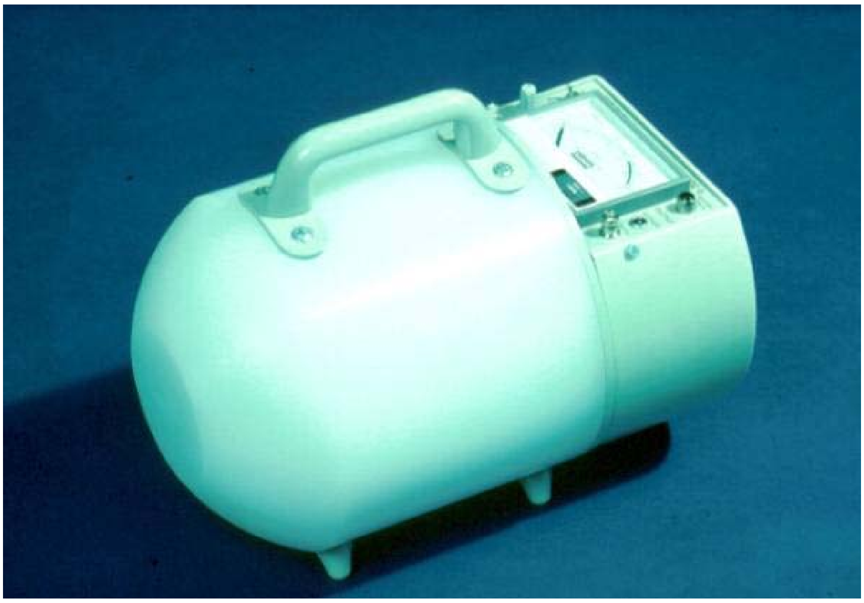


FIG. 65. Neutron dose rate meter (17 MeV energy response)

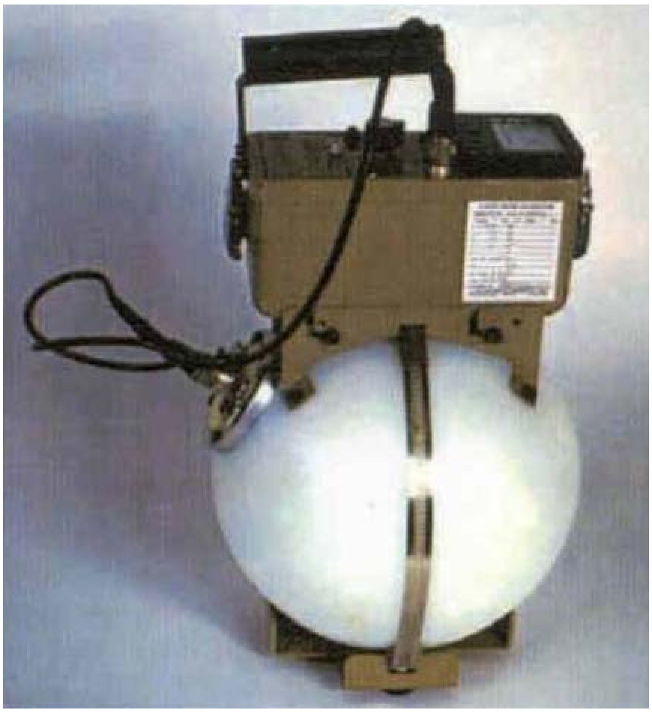
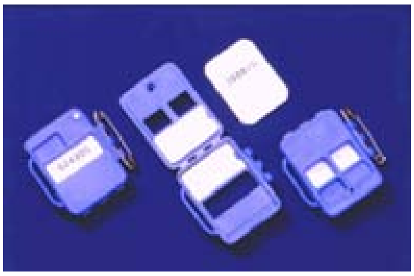


FIG. 66. Neutron survey meter (10 MeV energy response)

13.1.3. Dosimeters

There are many situations in which workers are exposed to transient dose rates that change rapidly with time, for example when a logging source is being transferred from the shield to the tool, or when a radiography source is being projected from the exposure container along the projection sheath. It is not feasible to measure a single dose rate in such circumstances. In order to assess these situations and provide advice on optimizing radiation protection measures (applying the ALARA principle), a specialist in radiation protection may need to make 'time averaged' dose rate measurements. For these an 'integrating dose rate meter' is used to assess each exposure and average the dose over a longer period of time, for example a working day. There are different types of dosimeters [39] for individual monitoring, generally designed to be pinned or clipped to clothing, that register the total dose accumulated over the period of exposure. Individuals involved in well logging or other tasks that involve the use of neutron sources need to wear dosimeters that will measure both gamma and neutron radiation so that the total cumulative exposure can be assessed. Occupationally exposed workers must wear a suitable dosimeter (Fig. 67) and where high dose rates are possible, such as in radiography, a direct reading dosimeter in addition (Fig. 68). Direct reading dosimeters provide an alarm to indicate a high dose or dose rate in the event of accidental exposure. The circumstances of the accident would necessitate further investigation and remedial actions [24].

Thermoluminescent



Film badge

Neutron badge

FIG. 67. Personal dosimeters

FIG.68. Direct reading dosimeters: quartz fibre electrometer (left) and electronic dosimeters (right)

13.1.4. Surface contamination monitors

Surface contamination monitors usually are designed to measure a specific type of radiation and often have optimum detection efficiency over a limited range of radiation energies. For example the detector may respond only to alpha particles or gamma radiation or beta and gamma radiation. It may perform better in detecting high energy beta particles rather than those of low energy; or it may be designed to detect low energy gamma radiation but not high energy. It is important to select an instrument that has a detection efficiency optimized for the radiation (or isotope) of interest. Most surface contamination monitors indicate in counts/s (or s^{-1}) or counts/min and the instrument needs to be calibrated for the particular radiation being detected to enable the indicated reading to be converted into meaningful units such as becquerels per square centimetre (Fig. 69). Some instruments are designed to allow either the calibration response factor to be programmed into the instrument or the isotope being used, perhaps as a radiotracer, to be selected from a list on the instrument so that response is automatically corrected and the reading is displayed directly in becquerels per square centimetre.

FIG. 69. Two types of surface contamination monitor

One difficulty in quantifying the contamination due to NORM on a surface is that sludge and scales in which NORM is present contain a mixture of radioactive material that are seldom present in the same proportions. Assumptions need to be made about the NORM that is likely to be measured so that the likely response of the instrument may be determined in a laboratory. This may include examining how the monitor responds to an actual sample of the material.

Another difficulty is that the various substances emit radiation that differs widely in its ability to penetrate matter. NORM usually emits alpha particles but these are potentially stopped from reaching the detector depending on the condition of the surface being investigated. NORM incorporating radium generally emits beta particles and gamma radiation. The beta particles are significantly attenuated but even at their reduced energy are likely to be detected using an appropriate instrument. Gamma radiation has a much greater range in matter but an instrument used to measure it would always display a significant background gamma radiation component, particularly if the surface of interest is close to other accumulations of NORM.

Surface contamination monitors that incorporate either a beta detector or a combination of separate alpha and beta detectors offer the best options to monitor thin layers of NORM on surfaces (Fig. 70). Care should be taken as most beta detectors are sensitive to gamma radiation — the presence of ambient gamma radiation that might originate from inside a vessel could in such cases be misinterpreted as contamination. The use of a beta detector allows assumptions that are necessary to provide a calibration for the instrument, discriminating against any detectable alpha particles that may be present when the NORM contains radium and its progeny. While an instrument that has a combined response to alpha and beta particles may be calibrated for NORM constituents, interpreting the measurement may be problematic, depending on the condition of the surface being investigated.

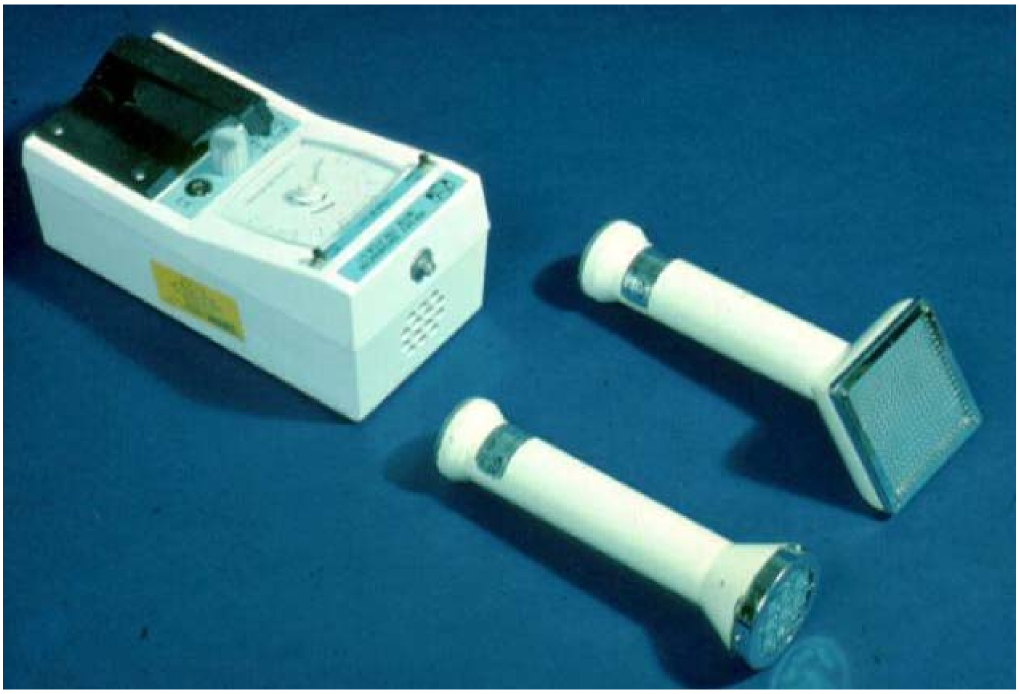


FIG. 70. Portable contamination rate meter with beta probe and alpha–beta dual probe

Alpha contamination monitors are intrinsically sensitive to NORM because they do not respond to gamma radiation and consequently have no background count rate. However, they are vulnerable to mechanical damage and cannot be used reliably to measure surface contamination where the surface is irregular (for example, uneven or curved) or covered in a thick layer of NORM bearing material (which self-absorbs the radiation) or wet (with degrees of moisture producing variable self-absorption).

A beta contamination monitor will indicate whether NORM is present within a facility only after access is provided to internal surfaces (Fig. 71) because the particles do not penetrate structural materials such as the steel walls of tubulars and vessels. If beta contamination is detected outside a system, then the contaminant must be on the external surface of the object being investigated. It is unlikely that a beta contamination monitor will provide accurate quantitative measurements of the surface contamination (in becquerels per square centimetre) because assumptions made about the radioactive constituents of the contaminant may not be entirely correct and significant self-absorption of the beta radiation occurs in all but thin layers of contamination. At best, beta contamination measurements provide a reliable indication of the need for radiation protection measures and further investigation by sampling and radionuclide analysis. Specially designed instruments may be used in specific circumstances to monitor NORM surface contamination; for example, there are intrinsically safe instruments for use in potentially flammable atmospheres and a cylindrical form of beta detector may be drawn through the inside of whole tubulars to check for internal NORM contamination (Fig. 72).

FIG. 71. NORM contamination within a vessel being measured using a surface contamination measuring instrument (Courtesy: HPA-RPD, UK)

FIG. 72.Checking tubulars for NORM contamination (Courtesy: HPA-RPD, UK)

Gamma radiation detectors (either sensitive dose rate meters or contamination meters) may be used to detect accumulations of NORM within plant and equipment and, with appropriate calibration, to measure thick deposits of NORM surface contamination. Rugged gamma spectrometers may be used in the field, but it is more likely that samples of the contaminating material will need to be submitted to a laboratory for gamma spectrometry to identify and determine the NORM activity concentrations (in becquerels per gram).

13.1.5. Contamination monitors for airborne radioactivity

Instruments for measuring airborne contamination are used where there is the need to monitor a risk of radioactive material being either released into the atmosphere or resuspended from contaminated surfaces. The instruments normally draw potentially contaminated air at a constant rate through a filter mainly to monitor airborne alpha emitters, including radon progeny. 'Active detectors' are capable of detecting the accumulated radioactive material on the filter and initiating an alarm. Rugged, portable, lightweight personal instruments exist that measure radon levels and provide an acoustic warning with short reaction times. Samples of natural gas may be taken and measured at a laboratory to determine the radon content using the Lucas cell method. Personal air samplers based on the use of a filter may also serve as personal dosimeters, but like many of the installed versions, the filter needs to be assessed elsewhere. These so-called 'passive detectors' provide only retrospective assessments of the working conditions. The filter papers need to be handled carefully to ensure that they are kept flat, undamaged and not contaminated by contact. These factors, and the need for specialist assessment of the filters after sampling, limit the usefulness of these instruments in the oil and gas industry.

13.2. MONITORING STRATEGIES

A sufficient number of suitable and efficient radiation monitoring instruments need to be provided and used whenever work involves the production, processing, handling, use, holding, storage, moving, transport or disposal of radiation sources or radioactive material. They are to be used according to an overall monitoring strategy. Three levels of expertise generally may be recognized: task, routine and special monitoring [4]. Further guidance on monitoring can be found in Refs. [37, 38].

13.2.1. Task monitoring

The worker who has day-to-day use of the radiation source or works with open sources or NORM performs task monitoring. It is important that the worker (possibly called a qualified operator) be adequately trained to use the instruments and interpret the measurements as part of a standard procedure, particularly when operations may involve an increased hazard. For example, a radiation-measuring instrument should be used by:

- A radiographer to check that a radioactive source has safely returned to its shielded container after an exposure;
- The user of a mobile gauge to check that a shutter has closed after using the gauge;
- a well logging engineer to check the safe return of the sources after a logging tool returns from the well;
- A radiotracer technician to check for contamination around high pressure joints and mixer vessels after the injection of the radiotracer;
- A NORM worker to check for contamination on clothing before leaving an area where decontamination work is being carried out;
- A technician to monitor the radon level at the exit points of fluids and gases.

13.2.2. Routine monitoring

In order to oversee, supervise, maintain and keep under review a programme for monitoring in the workplace, the radiation protection officer (RPO) will normally carry out routine monitoring. Surveys are conducted at appropriate regular intervals but not necessarily to a predictable timetable. The measurements are intended to confirm the extent of any designated supervised and controlled areas, to prove the adequacy of measures against external and internal hazards and to reveal any deterioration in the standard of radiation protection. A record of the measurements may be kept for an appropriate period, for example two years from the date on which the surveys are carried out, which will provide confirmation of a safe working environment and indicate any trends in the standard of safety provided. Examples of routine monitoring include the following:

(a) The RPOs of radiography and well logging service companies monitor their shielded containers and storage conditions;

(b) The RPOs of radiography and well logging service companies monitor to ensure the correct placement of barriers demarcating controlled areas;

(c) The RPO responsible for installed gauges monitors them to ensure that they are adequately shielded, that they show no physical damage and to confirm that the shutter of a gauge has closed prior to clearing it for vessel entry;

(d) The RPO of a radiotracer laboratory monitors bench surfaces, waste disposal routes, storage facilities, etc.;

(e) The RPO monitors any transport package for compliance with dose rate and surface contamination limits prior to labelling the package and providing relevant documentation;

(f) The RPO of an injection company monitors disused packaging prior to its disposal by the appropriate route;

(g) The RPO responsible for facilities in which NORM accumulates measures external dose rates where accumulations occur, monitors the plant when it is opened for operational reasons and designates the workplace prior to authorizing entry of workers; an area monitoring diagram and an on-site measurements record may be used in these situations (Fig. 73);

(h) The RPO responsible for NORM decontamination confirms the success of measures to contain surface and airborne contamination within the designated areas;

(i) The RPO responsible for NORM decontamination monitors to determine whether an item meets clearance criteria prior to its certification and release.

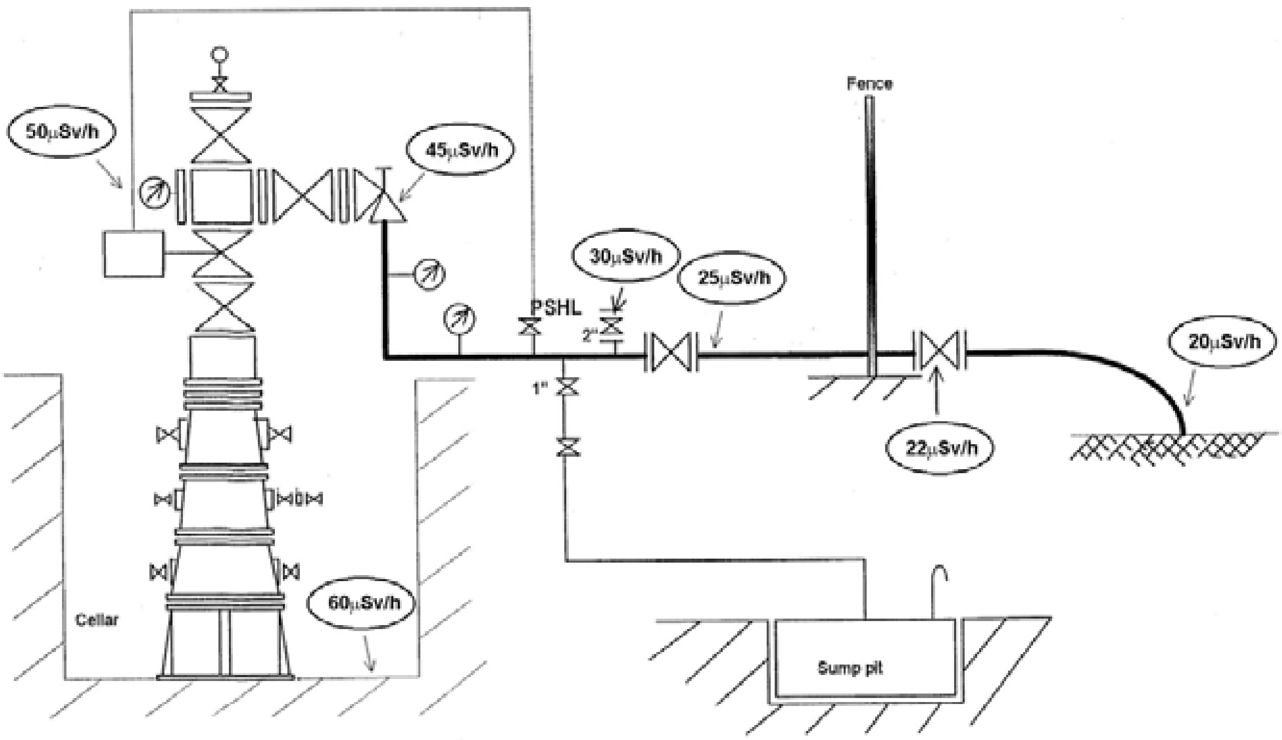


FIG. 73. *Example of a completed area monitoring diagram*

13.2.3. Special monitoring

Special monitoring will normally be carried out by qualified experts capable of using highly technical instrumentation, interpreting complex measurements or applying the results in computational methods in order to reach pertinent conclusions. A report has to be kept detailing the measurements, the conclusions and any recommendations that arise from them. Special monitoring might also refer to that carried out by a person such as a safety officer or inspector employed by the oil and gas operators or the regulatory bodies. The purpose of such monitoring would be to exercise a duty of care for the overall site or facility, to ensure that safe working practices are followed, and that there is compliance with regulatory requirements and relevant licence conditions. Examples of where special monitoring might be used include the following:

(a) The use of specialized monitoring instruments to assess external exposure and optimize protection against unusual radiation sources with low energy radiations, pulsed or transient emissions, narrow beams, etc.;

(b) Critical examinations, hazard evaluations and risk assessments of novel equipment and/or non-routine procedures;

(c) Reviews and measurements to determine shielding requirements and quality assurance assessments of equipment and facilities such as shielded containers, source storage facilities, transport packages, etc.;

(d) Audits and inspections of equipment, facilities, procedures and other arrangements for compliance with predefined company standards and regulatory requirements;

(e) Baseline surveys to assess whether NORM is present in an operating facility; where the survey is negative it may be repeated triennially or more frequently when changed operating conditions (e.g. changes in the salinity of produced water) or other factors indicate the need; a flow diagram for the assessment of closed systems internally contaminated with NORM material is shown in Fig. 74;

(f) Baseline surveys to establish the conditions at a location prior to its development as a radioactive waste disposal facility;

(g) Where NORM is present in operational plant, sampling and analysing produced waters, scales, sludge, natural gas, gas condensates etc., as appropriate for radionuclide and activity concentrations;

(h) Decommissioning surveys of redundant facilities;

(i) The location and recovery of lost sources, damaged sources, etc., following an incident;

(j) Investigation of accident conditions and providing specialized dosimetric methods to determine effective doses and acute partial body doses;

(k) Obtaining samples and measurements and analysing samples for presentation as evidence in a legal action.

13.2.4. Other considerations

Some radiation measuring instruments, particularly contamination monitoring probes, are not robust and may be more suited to the laboratory environment rather than that of an oil and gas facility. However, there are also rugged instruments available for on-site contamination measurements and dosimetry, especially for gamma emitting radionuclides and radon. Superficial repairs are effected easily in the field provided the necessary spare parts, such as cables and foils covering the face of the detector, are readily available. The instruments are normally battery powered and a plentiful supply of batteries is needed especially where, for example, an instrument may be in almost constant use during a facility shutdown and the work is in a remote location. The battery needs to be tested each time an instrument is switched on and regularly while it is in use. Units operated with rechargeable batteries or accumulators will demand regular loading cycles and performance testing. It is important to have:

- A test source of low activity available or a known location close to a shielded operational sealed source where the instrument may be placed prior to its use to confirm that it continues to provide a familiar response;
- Every instrument tested at intervals defined by the regulatory body, usually at least annually, and where appropriate calibrated by a qualified expert. The results of such tests are given on a certificate, a copy of which is made available to the user.

Work with a radiation source should not proceed without suitable and efficient radiation measuring instruments available. It is normally the responsibility of the service company that owns the radiation source to provide the instrument(s). However, the field operator may ensure that an adequate range and number of appropriate radiation measuring instruments are available or are provided when mobilizing service companies to undertake such work.

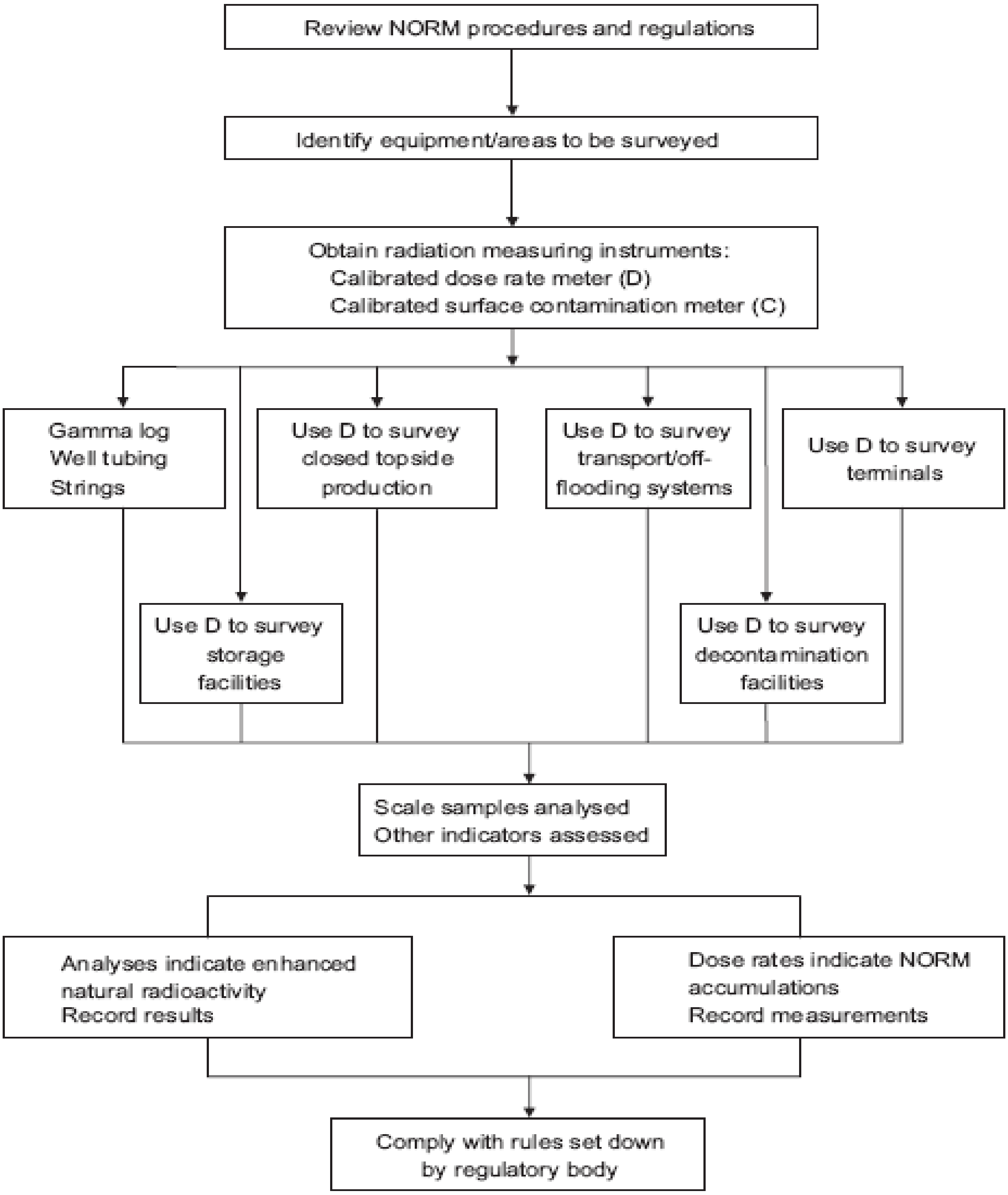


FIG. 74. Flow diagram for NORM assessments

It must be borne in mind that most radiation measuring instruments are electrical devices operating at high voltage. They may themselves constitute a risk in areas where there are flammable or explosive conditions. Some dose rate meters, but very few surface contamination meters, are intrinsically safe for use in these conditions and their use may need to be subject to prior authorization (a ‘hot work’ permit).

14. EMERGENCIES AND CONTINGENCY PLANNING

In all aspects of using radioactive material accidents can and do occur. This section discusses the various likely accidents that may occur and the need for written contingency or emergency plans. Most accidents that occur are the result of careless handling by individuals. Therefore, many accidents can be avoided by strict adherence to proper procedures and good management of employees. Requirements for documentation of the use of radioactive material will assist in keeping track of radioactive material on site. A good, well-enforced radiation safety programme is the best deterrent to accidents involving radioactive material.

However, even with a well-enforced radiation safety programme, accidents will occur. These accidents can range from small spills to accidents that result in high acute exposures to individuals and spills that require extensive and costly clean-up efforts. Although this section does not cover all accidents that may occur, it will give the reader a general overview of accidents and guidance on handling those accidents.

General guidance on the principles and the basic objectives of emergency preparedness and response for protection and safety, together with the principles for intervention that apply in taking actions to meet these objectives, is given in IAEA Safety Requirements [103] and Safety Guides [104, 105]. Guidance on occupational radiation protection in intervention and emergency situations is available in the Safety Guide on Occupational Radiation Protection [4].

14.1. ACCIDENTS INVOLVING SEALED SOURCES

14.1.1. High exposure and overexposure to radiation sources

Without suitable radiation protection measures, radiographic and well logging radiation sources could give rise to significant external doses particularly while they are being manipulated routinely out of their shielded containers. If appropriate action is not taken when, for instance, a typical radiographic source fails to return to the exposure container, a dose approaching or exceeding a regulatory limit could be received within minutes of exposure [106]. Improper handling of well logging sources and emergency situations such as extended exposure during a difficult removal of a source from the logging tool could result in significant doses being received by the engineer and technicians carrying out this type of work. The most likely cause of a significant dose being accidentally received is the failure to use a suitable radiation monitoring instrument to detect an unshielded source. When site radiography and well logging are carried out it is always necessary to have available the expertise and necessary equipment such as remote handling tongs to implement contingency plans quickly and efficiently. On offshore oil and gas platforms it may not be practicable to evacuate personnel to a safe area and it is therefore more urgent to implement the source recovery.

Installed gauges and most mobile gauging devices are unlikely to contain radiation sources capable, under normal circumstances, of delivering doses equivalent to a dose limit. Care is needed by the operator not to allow access to a vessel on which a source housing is mounted, until the radiation beam has been sufficiently shielded by a shutter within the housing locked in the closed position. This is particularly important where dip tube or suspended source(s) configurations are used within the vessel. Radiation monitoring must be carried out to confirm that shutters have actually closed and it is safe to enter a vessel or to manipulate a gauge source housing.

Significant exposure to radiation could result from improper handling of gauge sources if, for example, maintenance or leakage testing were to be carried out incorrectly. Significant exposure could also result from high output devices such as neutron generators if they were to be energized before lowering downhole or before providing adequate shielding by means of a calibration tank.

14.1.2. Lost or misplaced sources

Radiation sources used in the oil and gas industry are frequently transported between service company bases and points of use; they are sometimes transferred or redirected to new locations; and may be moved, removed for temporary storage or reallocated within a field or between sites. They are vulnerable to loss or theft or to simply being misplaced. Service companies and operators must keep detailed and accurate records to account for the whereabouts of sources at all times to prevent accidental occupational exposures or unauthorized disposal. For sources used on offshore platforms and rigs, the keeping of an up-to-date record at an appropriate onshore location would aid recovery of the sources in the event of a serious incident. An example of such a record system is given in Fig. 75.

INSTALLATION SOURCE REGISTER

Radioactive consignments, i.e. sealed sources and unsealed substances, arriving at and departing from the installation to be recorded. Use one line per consignment.

Service company	Source arrival date	Nuclide e.g. ^{192}Ir	Activity GBq	Physical form e.g. sealed, gas, liquid, powder	Source serial no .	Storage location	Source disposal date	Disposal route e.g. beach, well no., rig transfer	Audit date

FIG. 75. Example of a source record system

The likelihood of loss or damage is greater for portable or mobile sources (particularly small items such as smoke detectors and beta lights). Installed equipment is to be detailed on plant and equipment drawings. Every effort must be made to locate radiation sources that are not accounted for and the regulatory body must be notified promptly of any loss. Sources that are lost or orphaned present a radiological risk to the public and constitute a potentially serious hazard to any individual member of the public who attempts to remove a source from safe containment. They may become a significant economic burden and risk to the wider public if, for example, they are recycled with scrap metal.

Unnecessary risks that may result in the loss of a source ought to be avoided; for example, it is desirable that source containers are not lifted over the sea. When sources must be manipulated, and there is a risk of loss, suitable precautions need to be taken. A plate covering the annulus around a well logging tool, or a chain connecting the source to the handling rod while it is being inserted into the tool, is sufficient to prevent a disconnected source from falling into a well. A tarpaulin may be used to cover deck grating during an emergency procedure to recover a disconnected source from the projection tube of a radiographic exposure container.

14.1.3. Retrieval of disconnected sources from a well

When logging tools are placed in a well there is a risk that the radiation sources they contain, such as ^{137}Cs and ^{241}Am, may not be retrievable [107, 108]. The wireline support for tools may break or the tool may become snagged within an open (uncased) hole. If any radioactive source associated with well logging becomes stuck downhole, the licensee must immediately notify the regulatory body and advise the operator ensuring that every reasonable effort is made to recover the sources. Specialist service companies and equipment may be called upon to carry out ‘fishing’ operations to retrieve disconnected logging equipment. It is important that the manner in which the recovery is attempted does not compromise the integrity of the encapsulation of the radioactive material. Damage to the encapsulation could cause widespread radioactive contamination of the wellbore, drilling rig, fishing tools, mud tanks, mud pumps, and other equipment that comes into contact with the drilling fluids. During fishing operations, the logging engineer provides advice and monitors the mud returns for any evidence of damage to the source using instruments suitable for detecting the types and energies of the emissions from the radioactive source material. Any increase in radiation levels detected from the returned fluids would call for the operator to stop recovery operations immediately, pending an assessment to determine the source status. The specialist service companies and the operator must advise the regulatory body when fishing operations have been unsuccessful and obtain agreement to discontinue recovery operations. Appropriate measures will be needed to ensure that an abandoned source in a tool is not destroyed in any future drilling of the well. Usually the tool is cemented in, possibly using coloured cement, and a hard metal deflector may be placed on top of the cement plug. Later, drilling around the plug may continue, with a permanent plaque attached at the wellhead to provide details of the abandoned source and a clear warning.

14.1.4. Physical damage to sources, containers and other equipment

The containers in which radiation sources are transported, moved and stored are generally designed to provide adequate shielding and radiation safety in most climatic conditions. They demand a degree of maintenance that may need to be increased in more adverse working environments, for example in salty or sandy environments where corrosion and increased wear may be of concern (see Fig. 76). Installed gauges often remain in position for long periods of time and it is important that they are kept clean so that identification markings, labels or other safety markings — which some might consider to be cosmetic features — do not become illegible. Otherwise, in the longer term, the obvious profile, discernible relevant markings and even the source’s identity may be lost. The care and maintenance of ancillary equipment for controlling the radiation source (tubes and cables used for radiography and handling rods used for well logging) are similarly very important.

FIG. 76. Weathered nuclear gauge

Increased dose rates and unacceptable external exposures may result if the shielding of a radiation source container is damaged by mechanical, thermal or chemical means. Suitable precautions will normally include the following:

- Regular measurements of the shielding properties of radiation source containers;
- Monitoring of measured surface dose rates with control charts (see Fig. 77); the charts are likely to indicate even subtle deterioration in the standard of radiation safety;
- Source leakage tests (smear tests) at intervals advised by the source or equipment manufacturer or required by the regulatory body; sources that are at greatest risk of rupture when placed downhole may demand the most frequent testing, for example biannually.

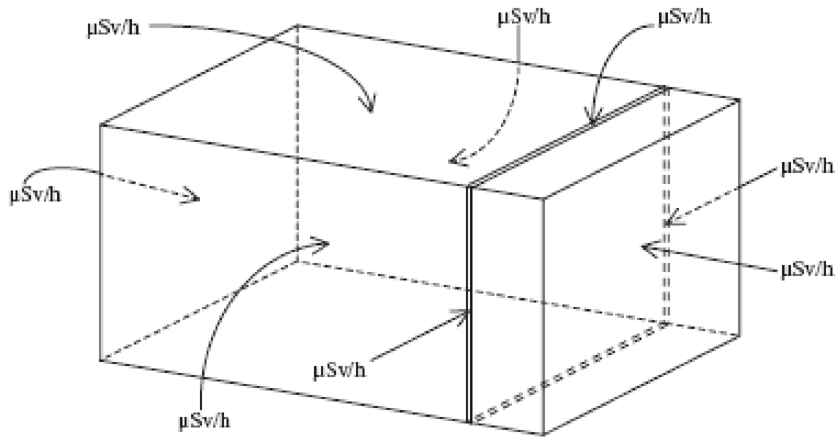
Sealed sources used in the oil and gas industry may become damaged or 'ruptured' to the extent that the radioactive material leaks or is released in loose form from the encapsulation. For instance, despite taking the necessary precautions there is always some risk of the integrity of the source encapsulation being compromised during attempts to retrieve a disconnected source from a well. Leakage may also result from mechanical, thermal or chemical conditions exceeding the specifications of the source (see Fig. 78) or from the unlikely situation of poor quality control by the manufacturer or improper encapsulation of the sealed radioactive material. Sealed sources are leak tested after manufacture and before transport, and additional tests may be arranged as required by the end user or to meet requirements of the regulatory body.

A ruptured industrial radiography source could create a severe immediate health threat to individuals [106]. The most common radioactive materials used, ^{192}Ir and ^{60}Co, are incorporated into sources with activities generally of several hundreds or thousands of gigabecquerels. Therefore, if the encapsulation becomes compromised, extensive contamination can result, with consequential extremely large internal and external doses to those exposed to the contamination.

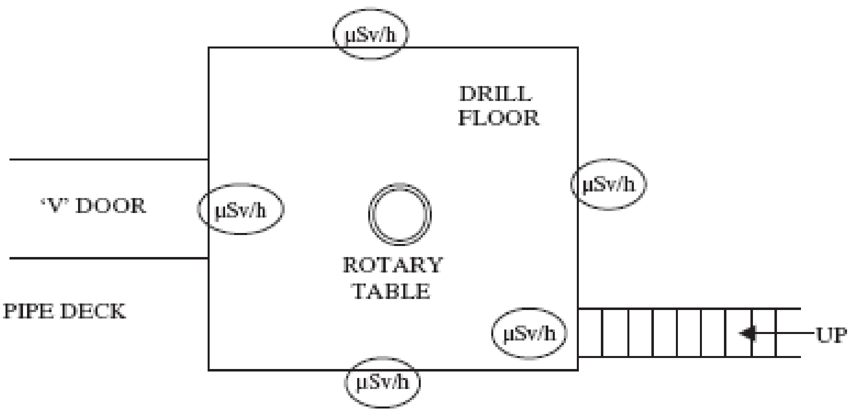
Date of measurements . . . .

Instrument used: Gamma meter . . . . Neutron meter . . . .

Radioactive sources storage container results



Controlled area results



RPO Signature . . . .

FIG. 77. Example of a radiation survey form

FIG. 78. Damaged radiography source after vehicle fire. The shielding was still intact and smear tests showed no apparent leakage of radioactivity.

If damage to a radiography source is identified in the early stages, widespread contamination can be avoided. A ruptured radiography source may be returned to the shielded position in the exposure container, or otherwise shielded to decrease the immediate health threat. Risks associated with a damaged radiography source can be further minimized by:

- Managing individuals who may be contaminated so that contamination is contained within a controlled area;
- Decontaminating any person who is found to be contaminated, in accordance with established procedures [109];
- Handling with care any potentially contaminated items, such as ancillary radiographic equipment, and if possible placing them in bags to prevent any spread of contamination;
- If there is any doubt whether contamination exists but there are elevated radiation readings, setting up cordons to prevent access to the area concerned;
- Treating any potentially contaminated item or area as contaminated until an assessment can be completed, i.e. the exposure device, any material used to shield the radioactive source, the area, and any equipment in the immediate vicinity [110];
- Performing leak tests of the radiography sources as soon as possible after any incident or other occurrence that could cause stress to the source encapsulation.

14.1.5. Site emergencies, natural disasters and strife

The highly combustible products of the oil and gas industry pose a constant risk of fire and explosion. Hazardous chemicals and explosives are also used routinely in the industry. The operator must minimize the possibilities of these non-radiation hazards compounding the risks associated with work involving radiation sources. Care is needed in storing hazardous materials to ensure that there is adequate separation between the different stores and other hazardous areas such as the wellhead. It is important for equipment and radiation sources to be secured against damage or loss in situations where natural disaster or strife is imminent.

14.2. EMERGENCIES RESULTING FROM ACCIDENTS WITH UNSEALED SOURCES

14.2.1. External overexposures

External exposures can occur while handling unsealed radioactive material. Should vials of radioactive materials not be returned to proper storage individuals in the area may receive high whole-body exposures; if proper techniques for transferring radioactive materials are not used, the technician can receive high exposures to the hand.

Once it has been established that an individual has received a high exposure, there must be a determination of whether any regulatory limits have been exceeded. If regulatory limits have been exceeded the regulatory body may have reporting requirements. The licensee must make proper notification to the individual that has received the exposure and comply with any reporting requirements to the proper authorities. The individual that receives high exposures may have his work with radioactive material restricted for the remainder of the year. Any report of an unusually high exposure to a worker should be investigated. A review of work habits and working conditions may reveal the need for worker training, changing of work habits, or working conditions that will allow the worker to maintain his exposure as low as reasonably achievable (ALARA).

14.2.2. Internal overexposures

Internal exposures can result from poor hygiene, spills, volatilization of material, poor ventilation, or general contamination. Once it is determined that an individual has internal contamination, any action taken should be based on the amount and type of internal contamination that is involved. To determine the amount of contamination, whole body counting or bioassay sampling may be required.

An investigation should be performed to determine the cause of the internal contamination. After an investigation has determined the cause of the exposure, actions should be taken to prevent recurrence. The actions can be training of employees, correcting ventilation programs, developing better procedures during handling of unsealed sources, or reducing contamination of areas. The investigation and any corrective actions taken should be well documented. Proper notification should be made to the individual(s) involved and to the regulatory body.

14.2.3. Spills

Accidental spills or unintentional releases of radioactive material may occur in the relatively controlled environment of a laboratory, or under the much less favourable conditions of a well site or on a public highway. The result is a presence of uncontrolled open radioactive material in restricted or unrestricted areas. The licensee’s emergency procedures address all reasonably foreseeable incidents and occurrences to minimize the risk of spreading contamination and establish good practices designed to minimize potential internal and external exposures. Immediate actions to be taken by the licensee include notifying the regulatory body and restricting access to the contaminated area. Guidance on assessing the severity of an incident, dealing with contaminated individuals and decontamination procedures can be found in [109, 110]. The licensee is responsible for ensuring adequate decontamination of any areas and/or items that have been contaminated by the incident. The licensee must either be authorized to perform the decontamination or employ an authorized entity to perform the decontamination. Materials will be generated during decontamination that must be handled as radioactive waste. After any decontamination efforts, a survey must be performed of the area and any items that will be released for unrestricted use to verify compliance with appropriate authorized clearance levels.

14.2.4. Lost material

As with sealed sources, unsealed sources can be lost. Proper inventories of unsealed sources must be performed and well documented. Inventories of unsealed sources must include material received, material used, disposal of material, and decay of material. Without good inventory records, it would be difficult to determine whether material was unaccounted for.

Once there is a determination that unsealed radioactive material is lost, the proper regulatory body should be notified. An investigation should be performed with the initial purpose being an attempt to locate the lost material. The investigation efforts should focus on locating the source until either the material is found or all possibilities have been exhausted and there is a minute likelihood of locating the material. At that time, the investigation should focus on determining the reasons for losing the source and procedures that could be implemented to prevent future occurrences of similar incidents.

14.3. EMERGENCY/CONTINGENCY PLANS

Written procedures that the licensee can implement in conjunction with the operator [110] need to be immediately available to deal with an emergency. An emergency would include any event involving the rupture of an industrial radiography or well logging source (including the rupture, during recovery attempts, of a well logging source that has become lodged downhole) and procedures should specify:

- Immediate notification of the regulatory body by the licensee in conjunction with the operator;
- Securing of the affected area in order to limit the spread of contamination and to prevent anyone from acquiring either an internal or external exposure from the ruptured source;
- Restrictions on access until a person is authorized, by reason of training and experience, to assess the problem, including the extent of the contamination, and decide on further actions such as decontamination procedures; in the case of damage occurring while attempting to retrieve a disconnected source from a well, the access restrictions apply to the area around the wellhead and any equipment used in the recovery operations;
- Accumulation of all contaminated items and storage of them in such a way as to prevent further exposures and the spread of contamination, pending their decontamination to authorized clearance levels or disposal as radioactive waste in accordance with the requirements of the regulatory body;
- Monitoring for internal contamination of those persons who were involved in the operations giving rise to the incident or who were in the immediate area when the incident occurred, and assessment of the total committed effective doses resulting from the internal and external exposures of those persons [37];
- Retention in the company records of the results of these assessments and copying of them to the companies that employ the workers involved.

Site emergency plans will need to include contingencies to deal with the potential radiation exposure of fire fighters and other personnel who need to deal with an incident, accident or other occurrence in an area where radiation sources are present. A contingency plan has to include standing instructions to specialist service companies to make safe any radiation source for which they are responsible in the event that a site emergency status is announced. The operator ensures that appropriate action will be taken to either make safe a source or implement suitable countermeasures in the event that a radiation worker is incapacitated by the emergency.

The contingency planning should recognize the need to advise first responders such as firefighters and traffic control authorities of the presence of radioactive material. The notification of the presence of radioactive material will enable the emergency workers to take the necessary precautions to prevent the further spread of contamination and also for the responders to implement the necessary precautions for their own protection against the radiological health hazards. In the case of transport accidents, the shipping documents will identify the radioactive material by nuclide, quantity and form of the material being transported. The documents should also identify the individual(s) responsible for assessing the hazards and providing assistance to the emergency workers. The licensee should:

(a) Notify the proper fire department or authority when radioactive material is being maintained at a location;

(b) Provide 24 hour emergency contact in case a fire occurs;

(c) Provide the first responders with relevant information concerning the proper procedures for minimizing the risks to health and for preventing the unnecessary spread of contamination.

In the case of fire, the possibility of volatilization of the radioactive material and consequently the possibility of internal exposure by ingestion exist. The first responders should be made aware of all exposure possibilities and informed as necessary to either stay upwind of the fire or use self-contained breathing apparatus.

15. CASE STUDY: A RUPTURED WELL LOGGING SOURCE[5]

15.1. BACKGROUND

A mixture of americium-241 and beryllium is used in sealed sources to produce neutrons. In logging oil wells, the sealed source is used in a tool which has a detector located at some point in the tool. This is referred to as a tool string. The tool string may also contain other equipment to perform resistively studies, gamma logs, and various other measurements. Generally, a neutron log is run during the initial completion of the well prior to casing the well. Later, a neutron log can be performed and compared to the initial log for information gathering.

The main problem in lowering a tool downhole is that the tool can become stuck during negotiating the bends and crevices in the well bore while either being lowered or raised. When a tool containing a radioactive source becomes stuck downhole, the company is required to notify the appropriate agencies. The licensee is required to notify the regulatory body when a source is stuck or lodged downhole and to make a reasonable effort to recover the lost or lodged source. The recovery operations must not be performed in a manner that could rupture the sealed source. If the source (Fig. 79) is not recoverable, the source can be abandoned downhole as specified by rule.

FIG. 79. Bull plug containing sealed source

15.2. THE INCIDENT

On 5 August 1995, a well service company moved a workover rig onto a well site and began workover operations on the well. The well had been completed to 2509 m and cased to the bottom. A screen and liner had been placed in the well from 2472 to 2502 m. The screen and liner have centralizers that help keep the liner centred in the casing. The centralizers used on the screen and liner in this well appeared to be large washers that had been cut in half and welded at 90° angles onto the liner (Fig. 80).

[5] This case study was made available by T. Cardwell, Texas Department of Health, Bureau of Radiation Control.

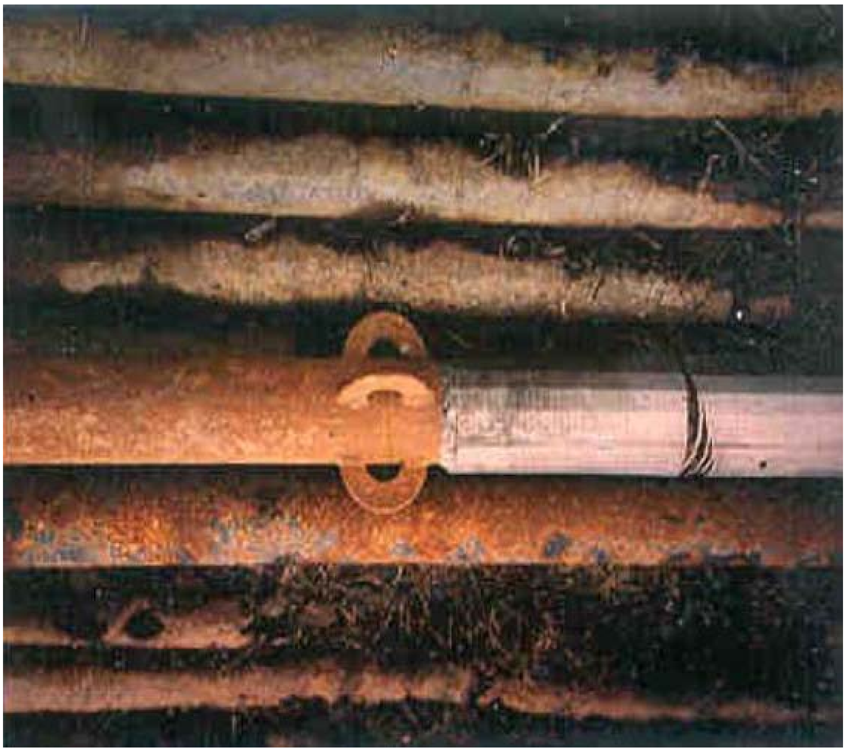


FIG. 80. Screen and liner

On 14 August 1995, the licensee notified the radiation control agency that a 111 GBq americium–241/beryllium source had become stuck in a wellbore on 11 August 1995. The licensee indicated that recovery operations would be attempted.

On 21 August 1995, after not receiving any further contact from the well operator, the original well service company left the well site. The licensee notified the radiation control agency that the source was still downhole but plans were to attempt further recovery operations.

On 6 September 1995, a second well service company moved onto the site and began source recovery operations. The operating company and the well service company believed that the source came loose from the tool string and fell to the bottom of the screen and liner. If this were the case, by pulling the screen and liner from the well, the source would be recovered inside the screen and liner. The well service company unsuccessfully fished for the screen and liner for several days. At the objection of the licensee, a milling bit was rotated on top of the screen and liner in an attempt to free the screen and liner. On 13 September 1995, the well service company, using oil jars, recovered the screen and liner but not the source. Oil jars are devices used to actually jar equipment free from a wellbore. The source apparently had been wedged between the liner and the wellbore casing and when the screen and liner were removed, the source fell to the bottom of the wellbore. On 15 September 1995, the well service company recovered the source using a tool called a junk snatcher.

The licensee notified the agency on 19 September 1995, that the source had been recovered and was not leaking. Later that day however, the agency was notified by a consultant that a wipe from the source indicated a radiation level of 10 mGy/h. The leaking source (Fig. 81) had been taken to the licensee's facility and placed in downhole storage. A possibly contaminated mud pump used to circulate drilling fluids had been removed from the site and taken to the well service company's facility a few miles from the well site. The well service company had already set the new screen and liner and installed tubing and gas lift valves. An inspector arrived at the site and informed the operating company and the well service company that the source had been damaged and was leaking radioactive material. The well head and equipment were surveyed and found to be contaminated (Fig. 82).

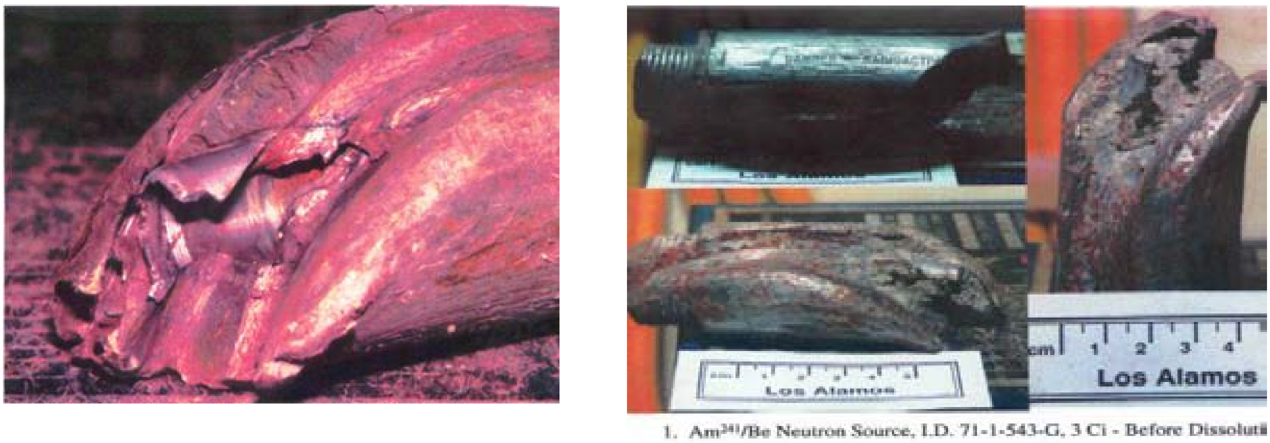


FIG. 81. Ruptured source

FIG. 82. Contaminated well head and equipment

15.3. SURVEYS

Radiation surveys were performed at employees' homes, at the licensee's facility, and at the well service company's facility. A few items at the employees' residences were found to be contaminated and were returned to the well site. Surveys of the mud pump at the well service facility indicated that the pump was internally contaminated. The inlet and outlet ports of the mud pump were covered and taped to prevent further spread of contamination. The licensee's facility was determined to be contaminated. The well site was determined to be generally contaminated out to a 15 m radius. The concentrations ranged from a high of 300 Bq/g in the immediate vicinity of the well head to approximately 370 mBq/g at 15 m from the wellhead. Local contamination was indicated at a distance of 30.5 m from the wellhead with a high concentration of approximately 925 mBq/g (Figs 83 and 84). The drilling rig was contaminated to levels of 367 Bq per 100 cm^2 (Fig. 85). The survey indicated general levels of contamination from several becquerels to approximately 200 Bq per 100 cm^2. A frac tank with a total capacity of 180 barrels was approximately one third full of fluid and mud and both the fluid and mud had concentrations of 37 Bq/g. Other ancillary equipment was contaminated to comparable levels.

FIG. 83. Restricted area, including the office building, downhole, storage, and well logging truck

FIG. 84. Contamination at the office entrance (left) and inside (centre)) and near the truck (right)

FIG. 85. Contaminated drilling rig

15.4. THE PROBLEMS

Emergency orders were issued to the responsible parties requiring site characterization and decontamination of the land and equipment and requiring the responsible parties to provide the name of an authorized licensee who would perform the required surveys and decontamination.

On 10 October 1995, after not receiving any information from the involved companies, the agency held a management conference with the affected parties including the landowner and two other regulatory agencies with some responsibility concerning oil production and environmental issues. During the meeting the agencies were informed that the licensee, a small one-man operation, did not have the resources to decontaminate the facility owned and controlled by the licensee, much less the well site and associated equipment. The other involved companies indicated that they were also small companies without the resources to perform decontamination. No commitments were received from the companies to perform site characterization. Another meeting was held with the affected parties on 25 October 1995. The parties were informed that they were required to submit survey and sampling methodology, a plan for decontamination, waste disposal options and the name of an authorized person who would perform the activities. Subsequently, the radiation control agency did receive surveys of the drilling rig and the well site. However, plans for decontamination and waste disposal have not been received. The affected companies were notified that they were in violation of the agency’s orders and that if action was not taken, the incident would be forwarded for legal remedy. The licensee does not meet the criteria under the decommissioning rule for submitting decommissioning plans and financial security.

Meanwhile, the company contracted to perform the site characterization survey reported that cattle had been inside the contaminated area and that faecal material from the cattle had been analysed and indicated 9.0 Bq/g. The radiation control agency visited the site and determined that cattle did have access to the contaminated property by crossing a drainage canal. A survey of the bovine faecal material inside the restricted area did not indicate elevated radiation levels. Four faecal samples were collected from the contaminated area and analysed. Three of the faecal samples were below minimum detectable limits. One sample indicated a concentration of 51 mBq/g. Grass samples from the most highly contaminated portion of the area indicated concentrations of 12 Bq/g. The samples collected by the consultant were dry samples. The agency believes that the consultant may have collected ground surface contamination with the faecal samples. Although the cattle may have ingested some contaminated grass, the literature reviewed indicated that deposition of americium in animals occurs primarily by inhalation. Absorption of americium through the gastrointestinal tract is only about 0.03% in adult animals[6]. Therefore, it is not believed that a health risk exists from consuming meat products from the cattle.

15.5. SOME PROBLEMS SOLVED

One of the major concerns was internal contamination of the drilling rig crew and other individuals who may have handled the source. A request was made through the U.S. Nuclear Regulatory Commission (NRC) for the U.S. Department of Energy (DOE) to perform bioanalyses on ten individuals directly involved in the incident. Through the cooperation between the state and federal agencies, ten individuals were scheduled to have whole body scans and urine analyses performed by Oak Ridge Institute for Science and Education at Oak Ridge, Tennessee at no cost to the individuals except travel and lodging. The good news was that the whole-body scans and urine analyses were negative for internal contamination.

Another major concern was the leaking source that was stored at the licensee's facility. Again, with the coordination between the state and federal agencies, a DOE Radiological Assistance Team was dispatched to the licensee's facility. The DOE Radiological Assistance Team recovered the source from the downhole storage location, packaged the source, and

[6] NCRP Report No. 65:, Management of Persons Accidentally Contaminated with Radionuclides, 70–74.

shipped the source to the DOE facility in Los Alamos, New Mexico (Figs 86–88). DOE performed an analysis of the source and determined that approximately 0.497 g of americium-241 was recovered with the source capsule. Rough estimates indicate that approximately half of the original activity remained in the capsule. The surface contamination at the well site is estimated to account for 11 to 18.5 GBq, indicating that an estimated 37 GBq of americium-241 remains downhole.

FIG. 86. Entering the contaminated site

FIG. 87. Retrieving (left), handling (centre) and packaging (right) of ruptured source

FIG. 88. Survey of logging truck, exterior (left) and interior (right)

15.6. REMAINING ISSUES

A pending issue is the contamination remaining downhole. Many States have rules concerning abandonment of sealed sources downhole, but not loose material associated with ruptured sources. Can the contamination downhole be cemented in place?

Also, if it is determined that the downhole contamination can be cemented in place, should the contaminated surface fluids and soil be placed downhole and cemented as well?

15.7. CONCLUSION

The immediate issue in any incident is to prevent health hazards from occurring. The immediate health issue can be addressed using surveys, whole body scans and removing the cause of immediate health concerns. The difficult issues are release limits, clean-up standards in accident situations, waste disposal issues, the high cost of cleaning low-level contamination and cost of disposal. Many licensees will be bankrupted due to clean-up and disposal costs and the State will then be responsible for the cost of decontamination. One answer may be for the regulatory bodies to begin a clean-up fund and charge a fee to licensees to support the fund.

16. DECOMMISSIONING PLANNING AND ACTIVITIES

When it has been determined that it is not economically beneficial to continue production at a specific well site, the physical structures may be removed and the well plugged and abandoned. Prior to abandonment of the site, the operator should assure that all radioactive sources used at the site have been removed and that residual contamination is not present or that the site has been decontaminated to the extent necessary to protect the public and the environment. This includes also the waste generated during the operations, the decommissioning and the decontamination. The operator should perform, or cause to be performed, surveys that assure that the well site is in compliance with the applicable standards for releasing sites for unrestricted use [111].

Decommissioning sites that have been restricted due to the use or generation of radioactive material can be expensive. Therefore, the decommissioning of sites must be considered at an early stage. A decommissioning plan should be developed during the initial stages of operation. The decommissioning plan should discuss the types and quantities of radiation sources that will be used at the site. The plan should discuss the possibilities of accidents that may happen and the impact of such accidents. Consideration should be given to the quantities of NORM that may be generated, the storage of NORM and the disposal options. The plan should include estimates of the expected cost of decommissioning the site.

16.1. DECOMMISSIONING PLANNING

It is important that the decommissioning aspects of a project be considered at an early stage in order to:

- Limit the quantities of radioactive waste generated;
- Limit the areas requiring decontamination;
- Ensure the selection of adequately safe, cost effective disposal options;
- Optimize the associated costs;
- Ensure compliance with the requirements of the regulatory body;
- Keep doses to workers and the public ALARA.

The development of a written decommissioning plan will assist the operator to determine where radioactive materials will be used and to establish procedures to assure that contamination of the site is maintained at a minimum. A written plan will further assist the operator to determine where NORM may accumulate and to plan for storage of NORM such that contamination is maintained at a minimum.

Planning for decommissioning will assist the operator to estimate the future cost associated with decommissioning the site. The operator will be able to budget for the decommissioning during the operational phase of business. This will result in the decommissioning of a site being less of an economic burden during a period when funding may be limited.

16.2. THE DECOMMISSIONING PROCESS

When an oil or gas reservoir has been depleted to the extent that further economic exploitation is no longer viable:

- The wells are abandoned and the production and transport systems are decommissioned and dismantled;
- Ancillary offshore and onshore structures (e.g. waste management, storage and treatment facilities) may become redundant and may need to be dismantled and/or returned to the public domain for unrestricted use;
- The owner or operator will request the regulatory body to terminate the licence for possession, use and processing of radioactive materials.

The licensee (i.e. the operator or owner) is responsible for ensuring that all buildings, land and equipment to be used for unrestricted purposes comply with applicable surface contamination and activity concentration criteria defined by the regulatory body. The licensee will need to:

- Perform an initial survey;
- Plot the survey points;
- Indicate any areas of elevated radiation levels;
- Submit all information to the regulatory body for review, approval and licence termination.

The decommissioning of oil and gas production facilities and their associated structures such as waste management and storage facilities gives rise to a variety of waste materials and items, some of which may be radioactive (e.g. sealed and unsealed sources, NORM scales, contaminated equipment, concrete and soil). Given the scale of the oil and gas industry worldwide, decontamination activities will become increasingly important and generate significant quantities of wastes over an extended period of time.

The preferred strategy for the decommissioning process will include the following steps:

- Decontamination of contaminated items to levels defined as suitable for unrestricted release by the regulatory body;
- Release of all decontaminated facilities and areas for unrestricted public use (clearance from regulatory control);
- Final disposal of radioactive wastes and remaining contaminated items to a facility authorized by the regulatory body.

16.3. SUMMARY

The decommissioning process involves numerous issues and activities including:

(i) Development of the decommissioning strategy and plan and associated quality assurance programmes;

(ii) Development of dismantling and decontamination strategies;

(iii) Assessment of risks to workers, the public and the environment during and after the decommissioning activities;

(iv) Submissions to the regulator, e.g. plans, strategies, records, reports and survey results;

(v) Approval by the regulatory body;

(vi) Identification of potentially contaminated structures and areas;

(vii) Identification, quantification and characterization of hazardous waste materials;

(viii) Identification and characterization of radioactive wastes (this would include surveys to locate and identify contaminated areas, items and materials);

(ix) Development of strategies to minimize the generation of radioactive wastes during decommissioning;

(x) Surveys to assess the levels of gamma dose rate and alpha and beta surface contamination;

(xi) Implementation of appropriate radiation protection programmes for workers, the public and the environment;

(xii) A wide range of decontamination activities, e.g. components, buildings and land areas;

(xiii) Disposal, at authorized facilities, of all radioactive wastes;

(xiv) Land remediation activities;

(xv) Transport of radioactive materials in accordance with applicable regulations;

(xvi) A final radiation survey after dismantling, removal and remediation have been completed.

General guidance on the principles, planning, approach and key issues involved in the decommissioning of industrial facilities and sources is given in the IAEA Safety Guide on Decommissioning of Medical, Industrial and Research Facilities [8].

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GROUP DISCUSSION NOTES

(These notes are for use in Group Discussions 1–6 and 8)

GROUP DISCUSSION 1

COURSE PARTICIPANTS' OWN INTRODUCTIONS

The objectives of this discussion are:

1. To enable individual participants to introduce themselves.

2. To enable all participants to become acquainted with the background and experience of other participants.

3. To provide course presenters with knowledge about the participants' background, experience and interests to assist them in focusing the practical content of their lectures.

The discussions are separated into three sessions to break up the early lectures.

Participants should be asked to each give a presentation of about 5 minutes. The presenter will display the following **slide** as a prompt:

- Personal details (your choice of what you include!)
- Your country's oil and gas industry and utilization of radiation techniques
- Your organization and its functions
- Your job description and brief content
- Your special professional interests
- What you hope to gain from this training course

GROUP DISCUSSION 2

AUDIT OF INDUSTRIAL RADIOGRAPHY

The objectives of this discussion are:

1. To prompt participants to discuss the radiological safety requirements for carrying out industrial radiography during site conditions.
2. To promote circumstances in which there is an exchange of information and cooperation between the relevant parties in the oil and gas industry.

Participants work in subgroups of about 5. The presenter displays the following **slide** as a prompt and to provide a structure for the discussion:

RADIOGRAPHY AUDIT
You are the RPO for an area in which a contracted radiography company is due to start work. As RPO you are responsible for the (radiation) safety of personnel in this area. You have decided to call a meeting with the Company to discuss how the work will be done safely. Draw up a list of questions you can use at the meeting to assess whether the Company is competent to start the work. Draw up a check sheet to assist you in auditing the work once it begins.

After each subgroup has reported back, the presenter hands out **answer sheets** to the participants before concluding the discussion.

GROUP DISCUSSION 3

PRACTICAL EXAMPLES OF APPLICATIONS

The objectives of this discussion are:

1. To prompt participants to relate their experiences and to identify practical examples of applications of sealed sources and radiation generators that differ from or expand upon those presented.

2. To enable the course to benefit from individual participants' own practical experiences of the oil and gas industry.

3. To further enhance an understanding of how widely sealed sources and radiation generators are used and radiation protection factors of particular relevance to the industry.

The presenter displays the following **slide** as a prompt and to provide a structure for the discussion:

> **Participants' own practical experiences of work with sealed sources and radiation generators**
>
> Expand upon or add to the following:
>
> - Radiography
> - Installed gauges
> - Mobile gauging equipment
> - Well logging

GROUP DISCUSSION 4

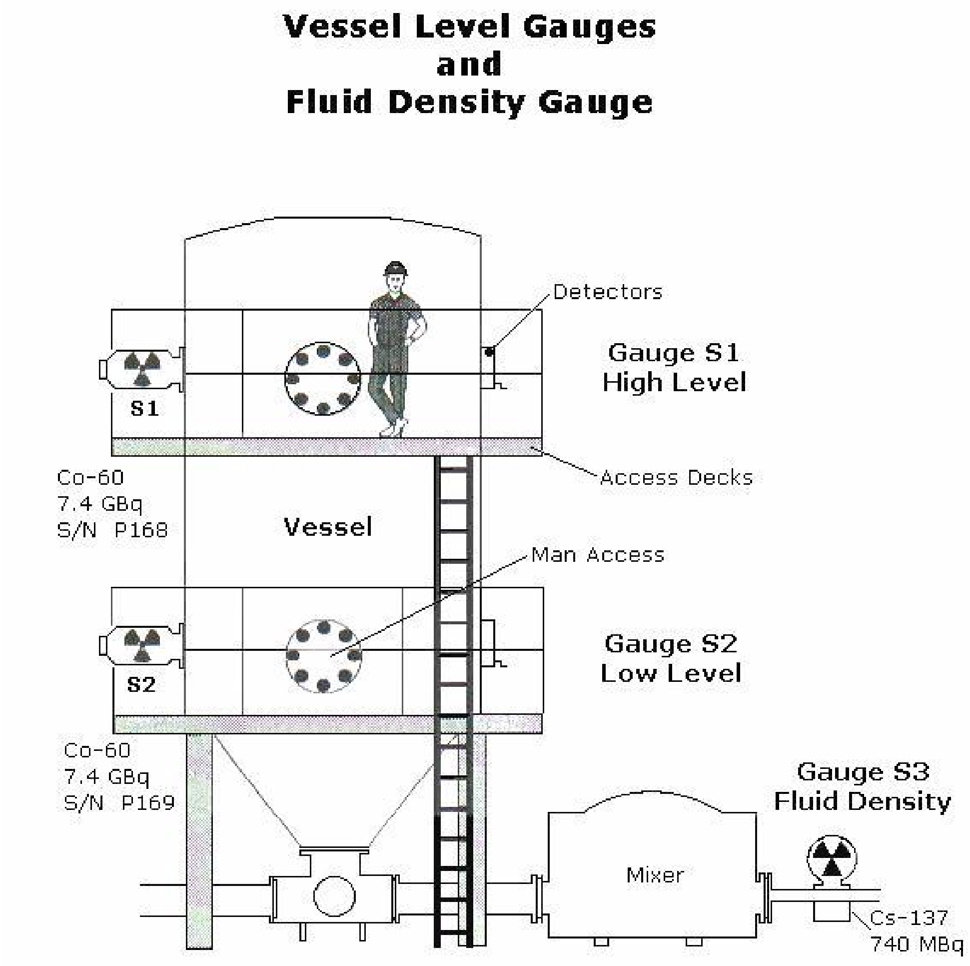
PRACTICAL EXAMPLE OF INSTALLED GAUGES

The objectives of this discussion are:

1. To prompt participants to consider the radiation safety arrangements of a vessel and associated pipeline on which gauges containing sealed sources are installed.
2. The participants will be asked to identify whether any Controlled or Supervised Areas will need to be designated.
3. The participants will need to consider the situation during normal production and during shutdown when vessel entry will be necessary.

CONTROLLED AREAS AND VESSEL ENTRY PROCEDURES

You are the Radiation Protection Officer for a company that uses gauges to monitor the high (S1) and low (S2) levels within a vessel. A third gauge (S3) monitors the densities of fluids flowing in a pipeline. The gauges are shown in the drawing. Every 2 years during shutdown you contract a specialist company to inspect and carry out repairs (usually minor) to the interior and exterior walls of the vessel. Two workers normally complete a vessel entry in 6 h.



Examine the drawing and tabulated information compiled by your company. Specify the following:

a) The precautions and procedures you would expect to have in place while the plant and equipment are in normal production.

b) The precautions and procedures you would consider necessary for the shutdown with particular reference to the vessel entry.

c) The contracted company has been informed of the gauges and been advised that they must remain in situ to minimize down time. Neither of your companies employs classified workers. What information will you supply to the sub-contracted company?

Prepare a report assessing the situation, especially noting the presence and extent of any designated areas, and detailing the work agreed with the contracted company. Provide sufficient information to support your conclusions and recommendations.

Gauge	Shutter condition	Position of measurement	Dose rate μSv/h
S1: 7.4 GBq ^{60}Co Serial nos: gauge: P168 source: HB1357	Open	Maximum at detector Maximum at source housing At 0.8 m from source housing on top staging	2 250 7.5
	Closed	Inside vessel close up to source housing At 1 m from inside surface of vessel	100 6.5
S2: 7.4 GBq ^{60}Co Serial nos: gauge: P169 source: HB1357	Open	Maximum at detector Maximum at source housing At 0.7 m from source housing Underneath S2 at 2.5 m above ground level	4 210 7.5 1.5
S3: 740 MBq ^{137}Cs Serial nos: gauge: 8066 source: MB2468	Open	Maximum at detector Maximum at source housing	4 3

GROUP DISCUSSION 5

PRACTICAL EXAMPLE OF A RISK ASSESSMENT

The objectives of this discussion are:

1. To prompt participants to consider an application of a sealed source that has not been described or discussed during the presentations.
2. The participants will be invited to carry out a prior risk assessment for the new practice in terms of who might be at risk, what are the hazards, what provisions are there for radiation protection, what other provisions might be called for.

Participants work in subgroups of about 5. The presenter hands out the **group discussion notes** and displays **slides** showing photographs of a test separator and a multiphase meter, and a risk assessment form. Participants should consider the descriptions presented to them and complete the risk analysis form. After each subgroup has reported back, the presenter hands out the **answer sheets** before concluding the discussion.

NOTES FOR PARTICIPANTS

Consider the radiological safety implications of operations involving a multiphase meter. This is used in place of a 'test separator' to determine the relative proportions of water, gas and oil in production. Production essentially stops to carry out assessments using the test separator whereas the multiphase meter provides continual assessment in real time during production.

A test separator

A multiphase meter

A multiphase meter is a transmission density gauge that contains a radioactive sealed source. A gadolinium-153 (^{153}Gd) source was used in some models but a barium-133 (^{133}Ba) source is used in more recent designs of the gauge. Both radionuclides emit several low energy gamma rays with maxima of 103 keV from ^{153}Gd and 356 keV from ^{133}Ba. The 3.7 GBq ^{153}Gd source with a 242 day half-life produces a dose rate of about 5.5 mSv/h at 10 cm whereas the 370 MBq ^{133}Ba source has a 10.7 year half-life and produces a dose rate of about 1.5 mSv/h. The sources are delivered in either Type A, Category I or 'excepted' packages to the service company's base where they are transferred from the transport packages to the gauges. When a source is secure within a gauge housing, shielding reduces accessible dose rates to less than 1 μSv/h.

- What are the relative merits and radiological risks of the two sources?
- What are the radiological risks in the service company that markets, maintains and services the gauges in which ^{133}Ba is used?

Consider only the occupational exposure to the workers employed by the service company and to other workers who work in the vicinity of the multiphase meters, for example on offshore installations. The risk assessments should include task specific work. For example, include movement of the source, the installation of a source in a gauge.

Use the form provided to list the tasks associated with exposure, the nature of the hazards, who is at risk, the controls and the likely level of risk. On completing the list, state the control measures that are or will need to be used to minimize the hazards and the risks to persons performing the work. State whether, following the introduction of appropriate control measures, the risks remain high, medium or low. Finally, consider what if any contingency plans would be needed.

Risk Assessment

Task	Hazards	Persons at Risk	Control Measures in Place	Risk		
				High	Medium	Low

GROUP DISCUSSION 6

AUDIT OF INDUSTRIAL RADIOTRACER LABORATORY

The objectives of this discussion are:

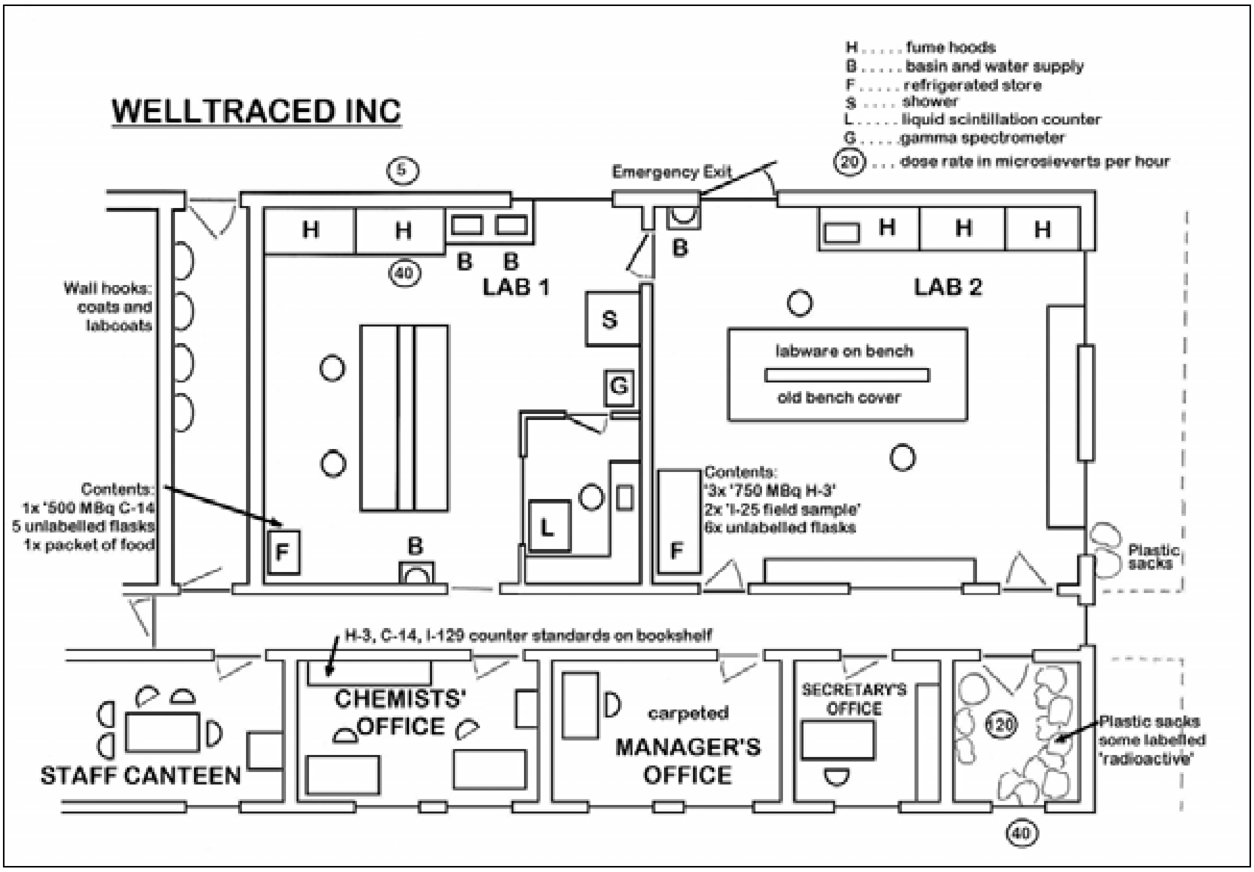
1. To prompt participants to discuss the radiological safety requirements for a laboratory preparing industrial radiotracers.
2. To promote circumstances in which there is an exchange of information and co-operation between the relevant parties in the oil and gas industry.

NOTES FOR THE PARTICIPANTS

You are the project manager for an injection company that requires a range of radiotracers for work that will start at a well site in 6 months. The radiotracers are to be purchased under subcontract from a laboratory recently formed in the country where the well site is located. Your contract gives you a ‘duty of care’ responsibility and you meet with the radiotracer supplier to discuss your quality assurance requirements and other matters to ensure the safety of the project. The facility layout and work in progress are shown in the drawing.

Discuss the facility and the work in progress. Prepare a report assessing the laboratory’s radiological safety standard explaining what improvements, if any are needed. Provide sufficient information to support your conclusions and recommendations.

What other matters need to be discussed and agreed between the radiotracer supplier and injection company to ensure co-operation between the companies/employers?



GROUP DISCUSSION 8

EXAMPLES OF DECOMMISSIONING PLANS

The objectives of this discussion are:

1. To prompt participants to consider the areas that need to be included in a decommissioning plan using their own experiences.
2. To prompt participants to consider areas where planning may result in cost savings during decommissioning.
3. To further enhance an understanding of the need and practical aspects of a good decommissioning plan.

The following facilities are to be decommissioned. Prepare a decommissioning plan for each facility.

- An industrial radiography service company. The facility has been used to store exposure containers but there is no shielded enclosure.
- A wireline well-logging base. Facilities exist for the storage of sources and the calibration of density and porosity tools at the base.
- A single offshore installation that has been licensed on the basis that level gauges have been installed there and NORM was known to occur.
- A laboratory at which tracers primarily for the oil industry have been prepared using imported radioactive material.

NOTES FOR PARTICIPANTS

Each decommissioning plan will need to include the following aspects:

1. A definition of the operations.
2. A list the types and quantities of radioactive material that are expected at the site.
3. A description of the expected use and disposition of sources and/or radioactive materials.
4. Any expected residual contamination from the use or generation of radioactive material, including NORM.
5. Descriptions of the types of radioactive waste that you would expect to be generated.
6. Descriptions of waste management with plans to minimize waste volumes.
7. Statements of the waste disposal options.
8. Descriptions of survey techniques that will be used to release areas for unrestricted use.
9. Descriptions of types of survey equipment that will be used to perform surveys.
10. Descriptions of sampling techniques (wipe samples, soil samples, etc).
11. A reasonable estimate of the cost for decommissioning and releasing the site for unrestricted use.
12. Describe the financial method that will be used to fund the decommissioning activities.

TRAINING COURSE PROGRAMME

Introduction to the course		55 min

MODULE 1: OCCUPATIONAL RADIATION PROTECTION: BASIC CONCEPTS

Lecture 1	Practical definition of occupational exposure Practices and interventions Natural sources of radiation	25 min
Discussion 1	Course participants' own introductions	25 min
Lecture 2	Principles of radiation protection and safety Dosimetric quantities Dose limits Application of annual limits Reference levels	60 min
Discussion 1	Course participants' own introductions (continued)	25 min
Lecture 3	Responsibilities of registrants, licensees and employers Responsibilities of workers Co-operation between registrants, licensees and employers	10 min
Discussion 1	Course participants' own introductions (continued)	25 min
Lecture 4	Oil and gas industry structure Industry technology and examples	55 min

MODULE 2: Sealed sources and radiation generators

Lecture 5	Industrial radiography • NDT locations • Underwater radiography	30 min
Lecture 6	PRSM-1 *'Gamma Radiography'* • Procedures and equipment • Maintenance • Preparation and co-operation • Monitoring	25 min

Discussion 2	Radiography audit	55 min
Lecture 7	Installed gauges • Locations of installed gauges • Uses of installed gauges	20 min
Lecture 8	Mobile gauges • Hand held gauges • Pipeline pigs • PIP tags and others	30 min
Discussion 3	Course participants' experience of work with sealed sources	40 min
Lecture 9	PRSM-2 *'Nuclear gauges'* • Storage and record keeping • Maintenance • Decommissioning	25 min
Discussion 4	Installed gauges on vessel	45 min
Lecture 10	Well logging • Wireline • Measurement While Drilling (MWD) and Logging while Drilling (LWD) • Logging techniques • Transport, storage of sources • Calibration and maintenance of tools	50 min
Lecture 11	Sealed source hazards • Control of hazards • Local constraints	15 min
Discussion 5	Risk assessment of a multi-phase meter	90 min

MODULE 3: Unsealed radioactive substances

Lecture 12	Radiotracer materials and examples of use Safe operating procedures Waste management	55 min
Lecture 13	Preparation of radiotracers Monitoring	40 min
Lecture 14	Waste minimization strategies Record keeping and storage facilities Waste treatment and disposal methods	35 min

Lecture 15	PRTM-1 *'Workplace Monitoring for Radiation and Contamination'* • Terminology and principal types of instrument • Instrument construction and application • Monitoring techniques and interpretation	65 min
Lecture 16	Images of monitoring equipment • Surface contamination monitors • Passive and active dosimeters • Biological monitoring • Whole body monitor	15 min
Lecture 17	PRTM, *'Personal Protective Equipment (PPE)'* • Respiratory protective equipment (RPE) • Types and terminology of PPE and RPE • Applications of PPE/RPE • Use and misuse of PPE/RPE	25 min
Discussion 6	Audit of a radiotracer laboratory	50 min

MODULE 4: NATURALLY OCCURRING RADIOACTIVE MATERIAL

Lecture 18	Naturally occurring radioactive material (NORM) • Origin of NORM and decay series • NORM concentrations • Occurrence of NORM in different industries	35 min
Lecture 19	NORM in the oil and gas industry • Mobilization and deposition of NORM • Forms and appearance • Radionuclide concentrations	30 min
Lecture 20	Radiological aspects of NORM • Occupational radiation protection • External and internal exposure	10 min
Lecture 21	Monitoring of NORM • Principles of dose rate meters • Surface contamination monitors • Monitoring strategies	15 min
Lecture 22	Analytical aspects of NORM • General considerations • Sludges and scales • Produced water	20 min
Lecture 23	Decontamination options • Manual and vacuuming • Mechanical dry and wet abrasive techniques • Chemical descaling • High-pressure water jetting • Melting	25 min

Lecture 24	Waste disposal • Wastes arising: produced water; sludges and scales • Waste disposal routes/methods • Issues in choosing a disposal method	45 min

MODULE 5: Emergencies and contingency planning

Lecture 25	Emergency planning Prior risk assessments Sealed source incidents Missing and lost sources Minimizing the risks	50min
Lecture 26	Case history Part I—Ruptured well logging source: details of an incident in which a well logging source was ruptured	25 min
Discussion 7	Course participants' views on how to respond to the ruptured well logging source incident	25 min
Lecture 27	Case history Part II—Ruptured well logging source: response and details of the clean-up	10 min
Lecture 28	Details of responses to sealed source incidents • Radiography incidents from PRSM-1 • Vehicle fire involving radiography source • Orphaned installed gauge • Stolen source in Goiania • Mobile gauge incident from PRSM-2	40 min

MODULE 6: decommissioning oil and gas facilities

Lecture 29	Decommissioning strategy Contents of the decommissioning plan Implementation of the decommissioning plan	55 min
Discussion 8	Decommissioning plans • Radiography base facility • Well logging base facility • Radiotracer laboratory • Offshore installation Report-back by course participants	80 min

CLOSING SESSION

Final discussion of training course

- Content
- Duration
- Practical content — 45 min

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