Safety Reports Series

No.34

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

IAEA
International Atomic Energy Agency

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# 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".



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

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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 to 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 the 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.

The Safety Fundamentals on Radiation Protection and the Safety of Radiation Sources (Safety Series No. 120), together with the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Safety Series No. 115), set out the principles and basic requirements for radiation protection and safety applicable to all activities involving radiation exposure. The Safety Guide on Occupational Radiation Protection (Safety Standards Series No. RS-G-1.1) provides guidance on meeting the occupational protection requirements of the International Basic Safety Standards. The Principles of Radioactive Waste Management (Safety Series No. 111-F) present the objectives and principles of radioactive waste management, while the Safety Requirements on Predisposal Management of Radioactive Waste, Including Decommissioning (Safety Standards Series No. WS-R-2) set out the requirements for the predisposal aspect of radioactive waste management: requirements with respect to disposal are under development. The Safety Guide on Management of Radioactive Waste from the Mining and Milling of Ores (Safety Standards Series No. WS-G-1.2) provides some relevant guidance for the management of NORM wastes similar to those produced in the oil and gas industry. Some of the guidance provided in two other Safety Guides: Decommissioning of Medical, Industrial and Research Facilities (Safety Standards Series No. WS-G-2.2) and Regulatory Control of Radioactive Discharges to the Environment (Safety Standards Series No. WS-G-2.3) is also relevant to the oil and gas industry.

The purpose of this Safety Report is to provide practical information, based on good working practices, on radiation protection and radioactive waste management in the oil and gas industry. It is intended to assist in meeting the relevant radiation safety requirements and promoting a common understanding between the industry and regulatory bodies. The Safety Report will be of interest to 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.

This Safety Report was drafted and finalized in six consultants meetings and one Technical Committee meeting, held during the period 1997–2002. The draft was also sent to a number of additional experts, yielding valuable comments from reviewers whose names are included in the list of contributors to drafting and review. In addition, the draft formed the basis for a regional workshop, held in the Syrian Arab Republic in 2000. Particular acknowledgement is paid to the contributions made to the preparation of this Safety Report by M.S. Al-Masri, T. Cardwell, A. van Weers and R. Wheelton.

The IAEA technical officer responsible for this report was D.G. Wymer of the Division of Radiation and Waste Safety.

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# 1. INTRODUCTION

## 1.1. BACKGROUND

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

(a) The construction sector responsible for manufacturing and fabricating facilities and equipment,
(b) The exploration sector responsible for finding and evaluating new resources,
(c) The production sector responsible for developing and exploiting commercially viable oil and gas fields,
(d) ‘Downstream’ sectors dealing with transport of the raw materials and their processing into saleable products,
(e) 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:

(a) Discrete sealed sources, e.g. spent and disused sealed sources;
(b) Unsealed sources, e.g. tracers;
(c) Contaminated items;
(d) Wastes arising from decontamination activities, e.g. scales and sludges.

These wastes are generated predominantly in solid and liquid forms and may contain artificial or naturally occurring radionuclides 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 control and waste management, and to have a common understanding of requirements and controls to establish efficient and safe operations.

The IAEA establishes principles, requirements and guidance with respect to radiation protection and safety in its Safety Standards Series publications, comprising Safety Fundamentals, Safety Requirements and Safety Guides. The Safety Guide on Occupational Radiation Protection [1] provides general guidance on the control of occupational exposures. This guidance is based on the requirements contained in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [2]. The objectives, concepts and principles of radioactive waste management are presented in the Safety Fundamentals publication on The Principles of Radioactive Waste Management [3].

The guidance material presented in Safety Guides is supplemented by a number of Safety Reports on specific issues.

## 1.2. OBJECTIVE

The objective of this Safety Report is to address the issues associated with radiation protection and radioactive waste management in the oil and gas industry and to promote a common understanding between the industry and regulatory bodies. It provides practical guidance based on good working practices in the industry and on the application of the BSS [2].

## 1.3. SCOPE

This Safety Report describes the technologies that involve the use of radioactive materials and radiation generators and situations where NORM is encountered within the various oil and gas industry sectors. It provides specific guidance on:

(a) Ensuring the radiological health, safety and welfare of workers, the public and the environment;
(b) The safe management of radioactive waste;
(c) Training in radiation safety.

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 Report 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 and situations which involve potential exposure to ionizing radiation and radioactive materials:

(a) Industrial radiography, including underwater radiography;
(b) Use of installed gauges, including those used to make level and density measurements;
(c) Use of portable gauging equipment;
(d) Well logging, including 'measurement while drilling' and wireline techniques;
(e) Work with radiotracers;
(f) Generation, accumulation and disposal of NORM and the decontamination of equipment contaminated by NORM;
(g) Radioactive waste management;
(h) Accidents involving radioactive sources and materials.

## 1.4. STRUCTURE

This Safety Report comprises seven sections, four appendices and a list of definitions. Section 2 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. Section 3 covers the applications of sealed sources and radiation generators, the types of source used, and their radiation protection and radioactive waste safety aspects. Section 4 deals with the use of unsealed radioactive substances, their radiation protection aspects and the management of radioactive waste arising from their regular use and from accidents. The origin and deposition of NORM in oil and gas production, NORM treatment and NORM transport facilities are described in Section 5. Section 5 also discusses radiation protection measures in dealing with NORM and the options for managing and disposing of the different types of waste arising at oil and gas facilities and at decontamination plants. Section 6 discusses the strategy, key issues and activities associated with the decommissioning of oil and gas facilities, including planning, licensee responsibilities and waste management issues. Section 7 summarizes the duties and responsibilities of all parties involved in order to:

(a) Protect the radiological health, safety and welfare of workers involved;
(b) Promote co-operation;

(c) Achieve an appropriate standard of radiation protection and radioactive waste management;
(d) Protect the public from exposure to radiation and the environment from radioactive contamination.

The Report recognizes the importance of information, training and supervision for those who have to carry out duties and meet their responsibilities. Detailed guidance on radiation monitoring, decontamination methods, training, and radioactive waste characterization is provided in the Appendices.

# 2. 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 human-made radiation sources and generators, and the existence of NORM, associated with this industry and to which reference is made in later sections.

The industry operates in all climates and environments, and under 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.

## 2.1. 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 personnel 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 and 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 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 source may be incorporated as an essential component of a larger piece of equipment that is shipped to a field or it may be a significant item that utilizes ionizing radiation and which is mentioned only in technical terms in shipping, technical, or similar documentation. In these circumstances, the regulatory bodies that have to exercise control over the import, transport and use of radioactive materials and machines must be informed accordingly.

## 2.2. RIGS AND DRILLING METHODS

### 2.2.1. 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 support services that employ self-contained, fully equipped road vehicles (Fig. 1) are provided by companies. 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 seabed to achieve 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 using other means such as thrusters linked to 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' which is usually cemented to the seabed. Modules are built on top of the jacket (Fig. 2) to accommodate crew and production equipment. The development of a field may involve numerous wells

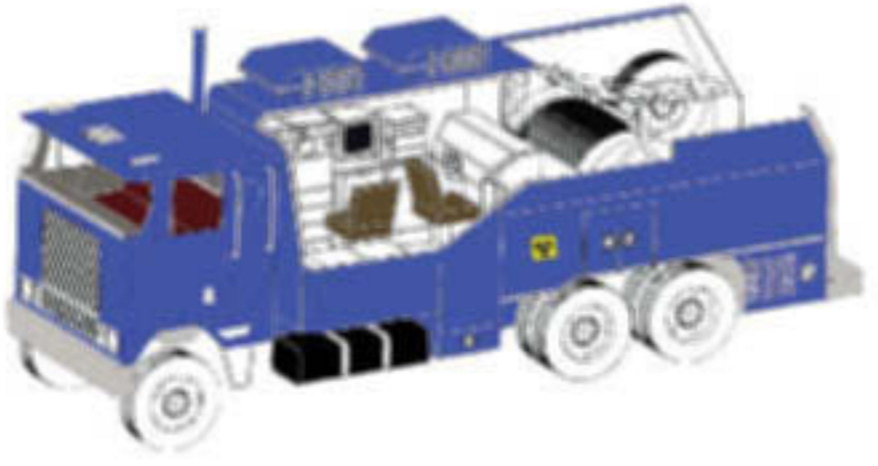

*FIG. 1. Heavy duty wireline truck.*

being drilled from a platform, and the use of 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; directional drilling allows them to be deviated in preferred directions through strata, even horizontally, over considerable distances and depths. The same topside plant and equipment may be used to serve separate fields or remote satellite fields.

### 2.2.2. Drilling and well construction methods

Most wells are formed by rotary drilling techniques. Referring to Fig. 3, 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 rock 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

FIG. 2. *Offshore production platform.*

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 occurring 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.

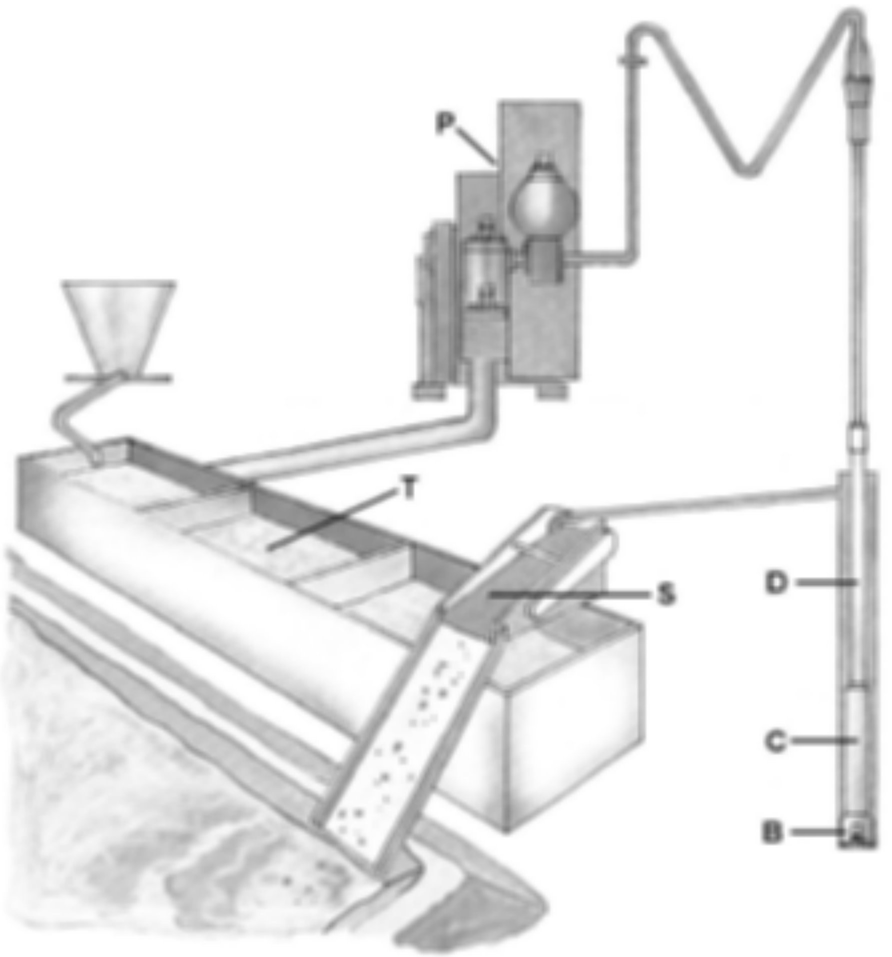


*FIG. 3. Oil well drilling and components of the circulation system.*

The open hole is next ‘cased’ by lowering (‘running’) into it a large diameter casing string. This is steel pipe normally fitted with external apparatus such as centralizers, scratchers and collars. One of their purposes is to maintain the casing coaxial with the hole; other functions may demand the installation of radiation sources. A 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 [4], will determine whether a well is viable and worth completing or is abandoned as a dry test well.

### 2.2.3. Well completions, development and workovers

Radioactive materials may also be used while completing a well, a procedure 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 from rising up the annulus. The production tubing is suspended from a collection of valves called the ‘Christmas tree’, installed at the well-head at the top of the casing, which enables the flow of fluids to be controlled. Other emergency valves, termed 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.

Periodically, workovers are carried out to replace production tubing or to allow necessary maintenance on the well. A number of techniques involving radioactive materials may be used to assess the success of techniques used 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 thereby 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 incorporate 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 drill bit, directional control equipment and a drill 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, taken while drilling is in progress, may require the use of radioactive sources. The new wellbore can be lined with tubing or left ‘barefoot’ to allow oil to flow into the old production system.

### 2.2.4. 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 risers that 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 termed separators which 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; 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. 4).

Oil refining and the processing of petrochemicals are complex subjects, a description of which is beyond the scope of this publication. 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 operated valves and controls used to transfer materials between the vessels. The vessels are usually identified by names that indicate their function such as distillation columns, exchangers, reactors, 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.

*FIG. 4. Pipeline pig trap (courtesy: Atomic Energy Commission of Syria).*

# 3. SEALED RADIATION SOURCES AND RADIATION GENERATORS IN THE OIL AND GAS INDUSTRY

## 3.1. 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 that all components and connections, particularly welds in the plant and equipment, 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 commonly used when pipelines are being laid and prior to the 'hook up' when the production and export systems are to be connected. The radiation sources, equipment and safe operating procedures associated with site radiography, which is commonly carried out, are described elsewhere [5, 6].

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 ready to carry out specific jobs on demand. Where the oil or gas field being developed or worked is in 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 pipelaying 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 co-operation from the separate service companies that specialize in diving and radiography.

### 3.2. INSTALLED GAUGES

'Nuclear (or nucleonic) gauges' are installed extensively on plant and equipment associated with the oil and gas industry [7]. 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 the 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; the radiation detectors are mounted diametrically opposite the source housing on the wall of the vessel or pipeline (Fig. 5). 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

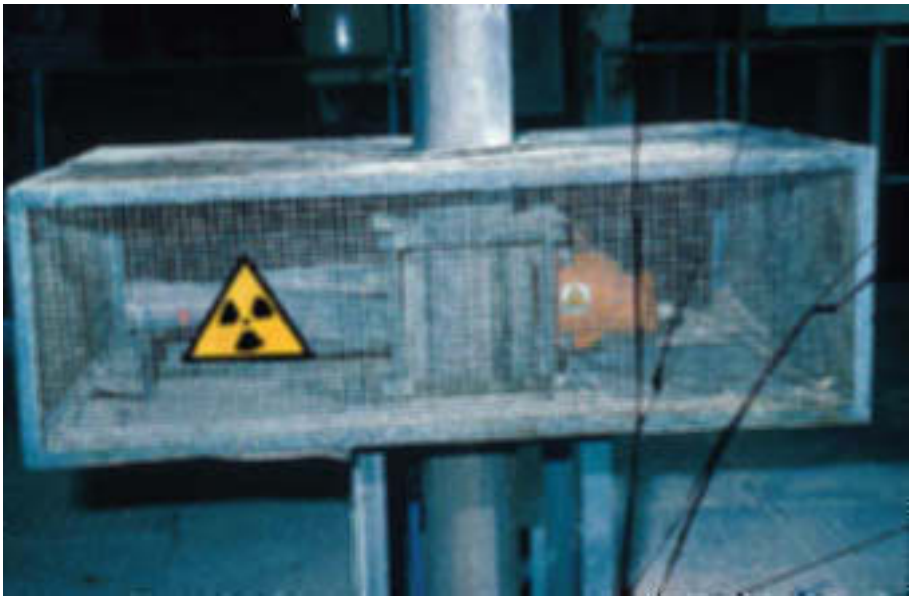

*FIG. 5. Installed density gauge (courtesy: National Radiological Protection Board, UK).*

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.

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

Gauges (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 also be installed 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 locations which render the gauges irretrievable, 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. Their use is 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 to make them 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 no space is left 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 vibration, 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 [8, 9].

## 3.3. MOBILE GAUGING EQUIPMENT AND ARTICLES

Numerous mobile gauging devices that utilize radiation, as well as other articles that contain radioactive substances, 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),

*FIG. 6. Mobile gauge for detecting the level of liquids in closed fire extinguisher cylinders (courtesy: National Radiological Protection Board, UK).*

hand-held testing instruments, and larger pieces of equipment intended primarily for use only at service companies' bases.

Fire protection equipment service companies commonly use hand-held level gauges to determine the fluid level in fire extinguisher bottles and 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. 6). 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 $^{241}Am$–Be source is used primarily by NDT service companies to detect water trapped between the 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 discovered using this procedure can then be released before it causes corrosion which would weaken the pipe.

The pipe wall profiler is an example of the larger sized 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 commonly used 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 the subsea sections of flooded members. The gauging system is either manipulated by divers or attached to the remotely operated vehicle of a miniature submarine. Other examples of usage include: detection of liquid levels in storage containers, still bases, reactors and transport tankers; checking for blockages caused by solid deposits and accumulations on internal pipe walls; and determination of the location of a vessel's 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 that shows that the catalyst has been spent and that the packed beds have expanded, thereby narrowing the vertical separation 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 [10]. The vapour spaces are clearly differentiated on the basis of the relatively high levels of 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 and 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. By 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 [11]. Neutron sources are used to monitor flare stack lines for ice deposits that start to form when condensates freeze in very cold weather and thereby create a potential flare stack hazard.

Radioactive sealed sources may be incorporated in a pipeline pig (Fig. 7) 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.

## 3.4. WELL LOGGING

### 3.4.1. Logging tools and techniques

Well logging companies place rugged, technologically sophisticated 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. 8). Among the many types of tool are means to

*FIG. 7. Radioactive sealed sources incorporated in a pipeline pig (courtesy: Scotoil Group plc).*

measure fluid temperature, pressure, density and flow rates; detect casing corrosion, wear and other damage; and measure rock density, porosity and isotope content. Some of the tools contain one or more radiation detectors and radioactive sources or a machine that generates ionizing radiation [12]. These are referred to as nuclear logging tools.

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) that 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

*FIG. 8. Well logging tool string suspended by a derrick above an oil well (courtesy: Baker Hughes INTEQ).*

measured against the 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 in coiled tubing. Signals are sent back to the surface by means of a positive 'mudpulse' telemetry system [13]. Equipment at the wellhead interprets the mud pulses and logs the data.

There are four common nuclear logging techniques:

(1) 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 distinguish the shale content of sedimentary rocks and aid lithological identification. The log records the uranium, thorium and potassium content of the rocks.

(2) 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 by 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.

(3) The third technique uses a tool, the gamma–gamma or density tool, which 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.

(4) The fourth technique, termed neutron–gamma logging, employs 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 [14]. The chlorine or salt water content of the rocks is of particular interest. A brand name may refer to this technique.

*FIG. 9. Radioactive source being transported by road (courtesy: National Radiological Protection Board, UK).*

The gamma and neutron sources used in these tools are normally transported in separate heavy containers termed shipping shields or carrying shields. They are Type A transport packages (or sometimes Type B for the neutron source) that meet the specifications for Category III labelling as defined by the IAEA Regulations for the Safe Transport of Radioactive Material [15]. They may be transported by road in the vehicles of the logging companies (Fig. 9) to the land well. When they are to be used offshore, the shields are usually contained in an overpack [15]. 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. 10). The shields do not provide adequate shielding to allow storage of 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 approximately 1.5 m long (Fig. 11). The dose rates of the $^{137}Cs$ source are significant [16, 17] but not normally isotropic owing 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 of up to about 4 m. In

*FIG. 10. Transport container used as a temporary store for well logging sources (courtesy: National Radiological Protection Board, UK).*

*FIG. 11. Wireline engineers transferring radioactive sources to logging tools on the drill deck (courtesy: National Radiological Protection Board, UK).*

*FIG. 12. Wireline engineer using a handling tool to transfer a radioactive source during a calibration procedure (courtesy: National Radiological Protection Board, UK).*

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 into a section of the tool (Fig. 12) 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. 13).

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 (Fig. 14).

The logging tools and the sources they contain are subjected to very high downhole temperatures and pressures. The sources normally fall within the definition of 'special form radioactive material' as sealed sources satisfying the test criteria specified by the IAEA [15] and ISO standards [18]. Nevertheless, the sources are normally given the further protection of a special container (a pressure vessel) whenever they are in the shield or logging tool. The sources

*FIG. 13. Facilities to enable high dose rate radiation sources to be safely exposed during logging tool calibrations (courtesy: National Radiological Protection Board, UK).*

*FIG. 14. Controlled area in which low dose rate radiation test sources are used during tests in the workshop (courtesy: National Radiological Protection Board, UK).*

also need frequent checks for leakage of radioactive substances in accordance with test criteria specified by ISO standards [19].

#### 3.4.2. Additional uses of sources

While running the casing it is normal practice to insert small radioactive sources to act as depth correlation markers — these provide, on the logs, clear indications of 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 perforation 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 whether the perforation 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. 15). A source of $^{241}$Am of several gigabecquerels and a detector are located opposite each other across the 'eye' of the needle to provide a measure of the attenuation of gamma radiation that occurs when fluids enter between them. The sleeve shown in Fig. 15 is positioned over the gauge to prevent access to the source during storage and transport.

### 3.5. SAFETY OF SEALED SOURCES

#### 3.5.1. Sealed sources

Sealed radioactive sources used in the oil and gas industry are normally manufactured to specifications defined by the ISO [18]. Under normal circumstances, the radioactive material will remain encapsulated throughout its working life and be returned intact to the supplier, manufacturer or other recipient authorized by the regulatory body. Sealed sources are routinely subjected 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 concerned 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. Appropriate measures to control such hazards and guidance on occupational radiation protection are given in a number of publications, including specific guidance on various practices [1, 2, 5, 6, 9, 15].

### 3.5.2. Radiation safety in normal working conditions

Radiation sources are in common use throughout the oil and gas industry, and therefore represent sources of potential exposure to a wide range of workers in that industry. The transport and movement of packages and freight containing sources potentially expose workers employed by the various transport service companies supplying the industry's material needs by land, sea and air (Fig. 9). There is a need for good logistical organization on the part

*FIG. 15. Gauge for measuring the density of well fluids (courtesy: National Radiological Protection Board, UK).*

*FIG. 16. Store for radioactive sources (courtesy: National Radiological Protection Board, UK).*

of the operator to ensure that the sources and the workers trained to use or install them are mobilized to arrive in a co-ordinated 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 made available for the sources on their arrival must meet standards that satisfy the responsible regulatory body (Fig. 16). 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 workplaces.

Work that includes the removal of radiation sources from shielded containers, particularly those manipulated during radiography and well logging, normally demands the use of barriers (Fig. 17) to designate the extent of the controlled areas [1]. 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

*FIG. 17. Chain barriers designating a controlled area on the drill floor while logging sources are in use (courtesy: National Radiological Protection Board, UK).*

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 worksite 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 furthest from normally occupied areas, for example, 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 the carrying out of the work in the vicinity of topside plant, such as storage tanks and vessels, that provides 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 methods 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 restrict access to controlled areas.

### 3.5.3. 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 [20]. Improper handling of well logging sources and emergency situations such as extended exposure arising 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 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 that is locked in the closed position. This is particularly important where dip tube or suspended source configurations are used within the vessel. Radiation monitoring must be carried out to confirm that the shutters have actually closed and that 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.

### 3.5.4. Lost or misplaced sources

Radiation sources used in the oil and gas industry are frequently transported between service company bases and points of use (Fig. 9); 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 simply to being misplaced. Service companies and operators must keep detailed and accurate records to account for the whereabouts of sources at all times (see example documentation, Fig. 18) so as to prevent accidental occupational exposure 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. 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 where 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.

### 3.5.5. 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 [21, 22]. 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 source. Specialist service companies using special 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,

## INSTALLATION SOURCE REGISTER

Details of all radioactive consignments, that is, sealed sources and unsealed substances arriving at and departing from the installation should be recorded. Use one line per consignment.

| Service company | Source arrival date | Nuclide e.g. $^{192}Ir$ | Activity e.g. GBq, Ci | Physical form e.g. sealed, gas, liquid, powder | Source serial number | Storage location | Source disposal date | Disposal route e.g. beach, well number, rig transfer | Audit date |
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*FIG. 18. Example of a record to account for radioactive sources.*

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 in the returned fluids would call for the operator to stop recovery operations immediately, pending an assessment to determine the source's 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.

### 3.5.6. Physical damage to sources, containers and other equipment

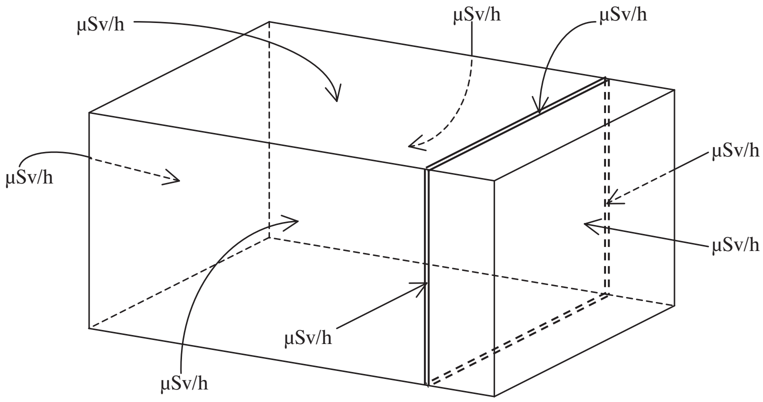
The containers in which radiation sources are transported, moved and stored are generally designed to provide adequate shielding and radiation safety under most climatic conditions. They demand a degree of maintenance that may need to be increased in more arduous working environments, for example, in salty or sandy environments where corrosion and increased wear may be of concern. 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.

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:

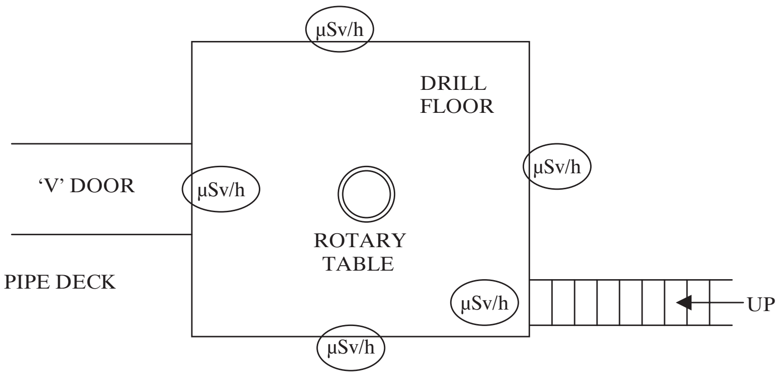
(a) Taking regular measurements of the shielding properties of radiation source containers.
(b) Monitoring measured surface dose rates using control charts (see example documentation, Fig. 19); the charts are likely to indicate even subtle deterioration in the standard of radiation safety.

Date of measurements . . . . . . . . . . . . . . . . . . . . .
Instrument used: Gamma meter . . . . . . . . . . . . Neutron meter . . . . . . . . . . . .

**Radioactive sources storage container results**




**Controlled area results**




**RPO Signature** . . . . . . . . . . . . . . . . . . . . .

*FIG. 19. Example of a radiation survey form.*

(c) Performing source leakage tests (smear tests) at intervals advised by the source or equipment manufacturer or as 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 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 the requirements of the regulatory body.

A ruptured industrial radiography source could create a severe, immediate health threat to individuals [20]. 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 the consequent potential for extremely large internal and external doses being received by those exposed to the contamination.

To deal with an 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), written emergency procedures that the licensee can implement in conjunction with the operator [23] need to be immediately available, including procedures for the:

(a) Immediate notification of the regulatory body by the licensee in conjunction with the operator.
(b) Securing of the affected area in order to limit the spread of contamination and to prevent anyone from incurring either an internal or external dose as a result of being exposed to the ruptured source.
(c) Restriction of 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 to any equipment used in the recovery operations.

(d) Retrieval of all contaminated items and their storage in such a way as to prevent further exposures and the spread of contamination, pending their decontamination to authorized clearance levels [24] or their disposal as radioactive waste in accordance with the requirements of the regulatory body.
(e) Monitoring for internal contamination of those persons involved in the operations that gave 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 [25, 26].
(f) Retention in the company records of the results of these assessments and the copying of them to the companies that employ the workers involved.

General guidance is available on occupational radiation protection in intervention situations and emergencies [1].

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:

(a) Managing individuals who may be contaminated so that the contamination is contained within a controlled area;
(b) Decontaminating any person found to be contaminated, in accordance with established procedures [27];
(c) 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;
(d) Setting up cordons to prevent access to the area concerned in the event of there being any doubt whether contamination exists but where there are elevated radiation readings;
(e) 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 [23];
(f) Performing leak tests on the radiography sources as soon as possible after any incident or other occurrence that could cause stress to the source encapsulation.

### 3.5.7. 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.

Site emergency plans will need to include contingencies to deal with the potential radiation exposure of firefighters 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 either to make safe a source or to implement suitable countermeasures in the event that a radiation worker is incapacitated during the emergency.

It is important that equipment and radiation sources be secured against damage or loss in situations where natural disaster or strife is imminent.

## 3.6. WASTE MANAGEMENT OF SEALED SOURCES

### 3.6.1. Introduction

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 to the environment. In many ways, the waste management of sealed sources is more easily facilitated than the management of unsealed sources and NORM wastes owing 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 [28, 29]. The most important aspects of the waste management programme are described in Sections 3.6.2. to 3.6.8.

### 3.6.2. Waste minimization strategies

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

(a) The use of relatively short lived radionuclides where possible;
(b) The use of the minimum quantity of radioactive material consistent with achieving the objective of the work application;
(c) Ensuring that sources are not physically damaged;
(d) Routine monitoring for source leakage (to minimize contamination of other items);
(e) Reuse of sealed sources and ancillary equipment, e.g. shielding containers;
(f) 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. $^{192}Ir$.

### 3.6.3. Waste inventories and characterization

A detailed waste inventory is maintained which includes details of:

(a) Source type, radionuclide and activity;
(b) All sources removed from regulatory control;
(c) All sources transferred to other facilities, e.g. manufacturer, storage, disposal.

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

### 3.6.4. 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:

(a) Physical security,
(b) Access controls,
(c) Handling systems and other operational aspects,
(d) Gamma dose rates on the exterior of the facility.

### 3.6.5. Predisposal management of radioactive waste

The predisposal management of radioactive waste may include a number of processing steps covering pretreatment, 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.

### 3.6.6. Disposal methods

The preferred disposal option is that contractual arrangements be made when purchasing sealed sources which allow for their return 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 should make 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 must:

(a) Ensure isolation;
(b) Ensure protection of workers, the public and the environment;
(c) Enable 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.

### 3.6.7. Transport of radioactive waste

All waste must be packaged and transported in accordance with the IAEA Regulations for the Safe Transport of Radioactive Materials [15]. Waste consignments should be accompanied by the necessary waste inventory and waste characterization information.

#### 3.6.8. Record keeping and reporting

A suitable and comprehensive record keeping system is usually required for radioactive waste management activities. The record system allows the tracing 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.

# 4. UNSEALED RADIOACTIVE SUBSTANCES IN THE OIL AND GAS INDUSTRY

## 4.1. RADIOTRACER AND MARKER STUDIES

#### 4.1.1. Unsealed radioactive materials used as tracers and markers

The oil and gas industry uses unsealed radioactive solids (powder and granular forms), liquids and gases to investigate or trace the movement of other materials, even within closed and sometimes inaccessible pipework and vessels [4, 7]. Most of these radiotracers can be detected and/or measured easily by their emissions. To achieve the objectives of a study, the physical form of the radiotracer is selected or manufactured so as to be consistent with the materials to be studied and its decay characteristics need to be appropriate [30]. 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 unsuitable as radiotracers. 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 $^{46}Sc$, $^{140}La$, $^{56}Mn$, $^{24}Na$, $^{124}Sb$, $^{192}Ir$, $^{99}Tc^{m}$, $^{131}I$, $^{110}Ag^{m}$, $^{41}Ar$ and $^{133}Xe$ are used extensively because of the ease with which they can be identified and measured. They are readily traced or followed by detectors placed outside the system. They allow the use of non-invasive procedures that involve minimal or no disruption to production.

### 4.1.2. Examples of the upstream use of radiotracers and markers

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 of $^{46}Sc$ 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 $^{110}Ag^{m}$ are added to a proppant during the 'frac job'. When the fracturing work is complete and when surplus fluids have been removed from the well so as 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.

To indicate the flow rate of the well fluids, radiotracer 'spikes', comprising $^{99}Tc^{m}$ and $^{131}I$ solutions, are released from logging tools into production wells and the time taken for them to traverse the known distance

*FIG. 20. Tritiated water for injection as a radioactive tracer (courtesy: Scotoil Group plc).*

between two radiation detectors is determined. 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 of the nuclides injected are significant (Fig. 20) — 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.

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.

### 4.1.3. Examples of the downstream use of radiotracers and markers

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 [31] 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 ($T$) 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 does not need the flow to be full bore or be confined within a closed circuit [32]; 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 ($S$) 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.

## 4.2. SAFETY OF UNSEALED RADIOACTIVE MATERIALS

### 4.2.1. Preparation of 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 onto 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 help minimize the handling and complexity of manipulations at the site where the radiotracer is introduced into the system being 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 be able to deal with potential contamination arising through routine handling or more serious spills. Engineered controls, such as a hood or an extract ventilation system, will prevent the dispersal, ingestion or inhalation of radioactive material. A monitoring programme needs to include provision for conducting surface contamination measurements and dose rate surveys, airborne contamination measurements and personnel monitoring for external and internal doses [25, 26].

The laboratory will package the radiotracer for transport 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).

### 4.2.2. 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:

(a) Adequate containment for actual and potential contamination;
(b) Suitable equipment, including personal protective equipment (including respiratory protection as appropriate) and monitoring instruments;
(c) 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 will also reduce the risk of external and internal exposure to radiation workers and to other persons in the vicinity. These procedures include carrying out 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 entering the area and 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 so as to contain any such spillage. All relevant exposure pathways must be considered, including the inhalation of volatile substances such as $^{131}$I. The risk of inhalation can be minimized or eliminated by using alternative non-volatile radionuclides such as $^{99}$Tc$^{m}$ instead of $^{131}$I.

When the radiotracer is to be injected into a high pressure system (Fig. 21), it is particularly important that the service company use suitable valve systems and operating procedures to 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

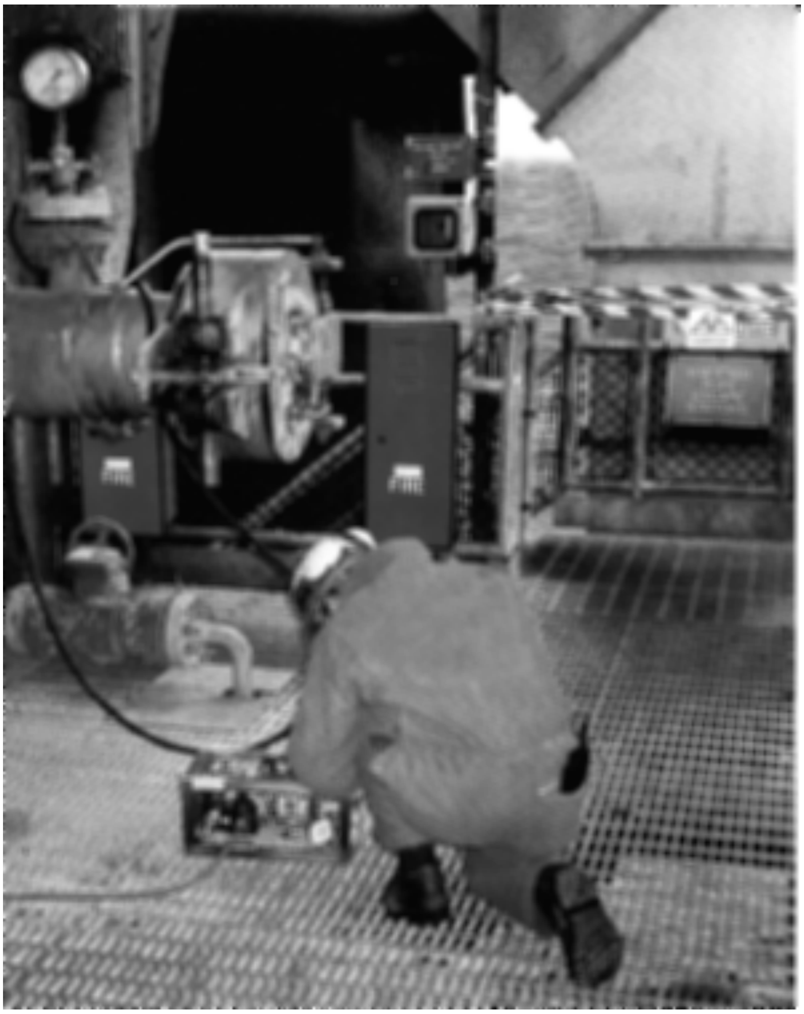


*FIG. 21. Radioactive gas being injected at high pressure for use as a tracer (courtesy: Scotoil Group plc).*

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 which 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.

### 4.2.3. Accidents involving radiotracer material

Accidents involving unsealed radioactive material can result from a number of situations, for example:

(a) Spillage and releases of radioactive material from pressurized systems;
(b) Unintended or unauthorized disposal of waste;
(c) Site emergencies such as fires and explosions;
(d) Natural disasters, strife and transport accidents.

The licensee's emergency response plan lists appropriate actions and suitable countermeasures for these situations and for other reasonably foreseeable accidents.

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 the presence of uncontrolled, open radioactive material in restricted or unrestricted areas. The licensee's emergency procedures address all reasonably foreseeable incidents and occurrences so as 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 is available [23, 27]. The licensee is responsible for ensuring adequate decontamination of any areas and/or items that have been contaminated as a result of the incident. The licensee must either be authorized to perform the decontamination or employ an authorized entity to perform it. Materials will be generated during decontamination that must be handled as radioactive waste. After any decontamination efforts, a survey of the area and any items to be released for unrestricted use must be undertaken to verify compliance with appropriate authorized clearance levels [24].

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.

## 4.3. WASTE MANAGEMENT OF UNSEALED SOURCES AND MATERIALS

### 4.3.1. Introduction

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 accumulated 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 (see example documentation, Fig. 18).

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. [28], and the important aspects are discussed in Sections 4.3.2. to 4.3.8.

#### 4.3.2. Waste minimization strategies

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

(a) Using relatively short lived radionuclides wherever possible;
(b) Using the minimum quantity of radioactive material consistent with achieving the objective of the work application;
(c) Applying strict controls during the use of unsealed sources in order to minimize the contamination of other materials and objects;
(d) Minimizing the presence of unnecessary materials and items in controlled areas where open sources are handled;
(e) Recycling of unused source material by the manufacturer;
(f) 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 <100–200 d), e.g. $^{192}$Ir.

Waste volumes can be reduced by various methods; for example, 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 possible, either at on-site or off-site facilities.

Equipment and materials that cannot be decontaminated to authorized clearance levels [24] must be disposed of as radioactive waste in accordance with the requirements of the regulatory body.

### 4.3.3. Waste inventories and characterization

A detailed waste inventory has to be maintained which includes:

(a) Details of source type, radionuclide and activity;
(b) Lists of all sources removed from regulatory control;
(c) 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.

### 4.3.4. 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:

(a) Physical security,
(b) Access controls,
(c) Waste handling systems,
(d) Controls over contamination,
(e) Gamma dose rates on the exterior of the facility.

### 4.3.5. Predisposal management of radioactive waste

The predisposal management of radioactive waste may include several processing steps that cover pretreatment (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:

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

(b) Segregation of wastes at the point of generation, for instance:
    (i) Segregation of radioactive and non-radioactive wastes;
    (ii) Segregation based on half-life (e.g. for the purpose of decay storage);
    (iii) Segregation based on activity levels;
    (iv) Segregation based on the physical and chemical forms of the waste (e.g. solid, liquid).
(c) Treatment aspects, such as:
    (i) Compaction or decontamination of solids,
    (ii) Absorption of liquids into a solid matrix.
(d) Conditioning (e.g. to meet packaging, handling and transport requirements).

#### 4.3.6. Disposal methods

The preferred disposal option for unsealed radioactive waste is transfer to a waste management or disposal facility that is authorized by the regulatory body. Some degree of predisposal management such as compaction may be required to reduce waste volumes. In addition, the waste would need 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:

(a) Ensures isolation;
(b) Ensures protection of workers, the public and the environment;
(c) Enables subsequent handling, movement, transport or disposal of the waste.

#### 4.3.7. Transport of radioactive waste

All waste must be packaged and transported in accordance with the IAEA Regulations for the Safe Transport of Radioactive Materials [15]. Waste consignments should be accompanied by the necessary waste inventory and waste characterization information.

#### 4.3.8. Record keeping and reporting

A suitable and comprehensive record keeping system is usually required for radioactive waste management activities. The record system allows the waste to be traced 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.

# 5. NORM IN THE OIL AND GAS INDUSTRY

## 5.1. INTRODUCTION

The first reports of NORM associated with mineral oil and natural gases appeared in 1904 [33]. Later reports describe the occurrence of $^{226}$Ra in reservoir water from oil and gas fields [34, 35] and in the 1970s and 1980s several observations prompted renewed interest [36–44]. The radiological aspects of these phenomena, the results of monitoring and analyses and the development of guidelines for radiation safety are now reported extensively [45–49].

## 5.2. ORIGIN AND RADIOLOGICAL CHARACTERISTICS OF NORM

The radionuclides identified in oil and gas streams belong to the decay chains of the naturally occurring primordial radionuclides $^{238}$U and $^{232}$Th. These parent radionuclides have very long half-lives and are ubiquitous in the earth's crust with activity concentrations that depend on the type of rock. Radioactive decay of $^{238}$U and $^{232}$Th produces several series of daughter radioisotopes of different elements and of different physical characteristics with respect to their half-lives, modes of decay, and types and energies of emitted radiation (Figs 22 and 23, and Table I) [50].

Analyses of NORM from many different oil and gas fields show that the solids found in the downhole and surface structures of oil and gas production facilities do not include $^{238}$U and $^{232}$Th [49]. These elements are not mobilized from the reservoir rock that contains the oil, gas and formation water (Figs 22 and 23). The formation water contains Group II (Periodic Table) 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 (Fig. 22) and $^{228}$Ra and $^{224}$Ra from the $^{232}$Th series (Fig. 23). 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. The $^{228}$Th radionuclide sometimes detected in aged sludge and scale is likely to be present as a product of the decay of the mobilized $^{228}$Ra. 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. Referring to Fig. 24, this causes their precipitation as sulphate and carbonate scales on the inner walls of production tubulars (T), 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

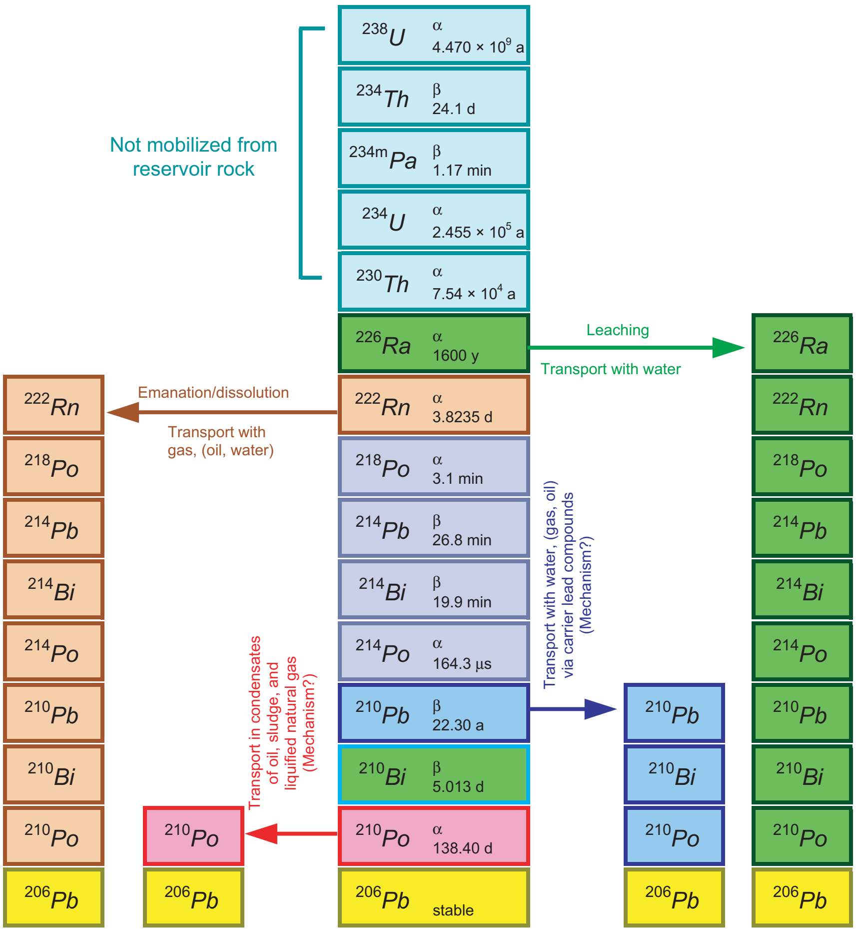



FIG. 22. *Uranium-238 decay series.*

TABLE I. RADIOACTIVE DECAY CHARACTERISTICS OF NATURALLY OCCURRING RADIONUCLIDES ASSOCIATED WITH OIL AND GAS PRODUCTION (FROM REF. [50])

| Radionuclide | Half-life | Mode of decay | Main decay product(s) |
|---|---|---|---|
| Ra-226 | 1600 a | Alpha | Rn-222 (noble gas) |
| Rn-222 | 3.8235 d | Alpha | Short lived progeny |
| Pb-210 | 22.30 a | Beta | Po-210 (alpha emitter) |
| Po-210 | 138.40 d | Alpha | Pb-206 (stable) |
| Ra-228 | 5.75 a | Beta | Th-228 |
| Th-228 | 1.9116 a | Alpha | Ra-224 |
| Ra-224 | 3.66 d | Alpha | Short lived progeny |

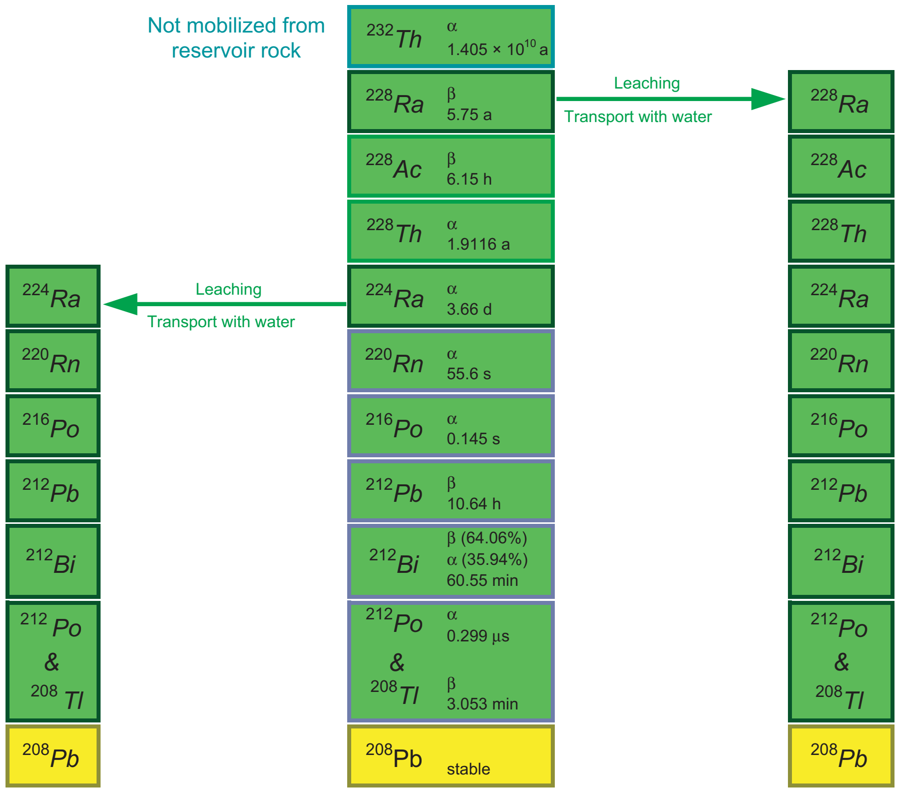



*FIG. 23. Thorium-232 decay series.*

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 (Fig. 22). 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

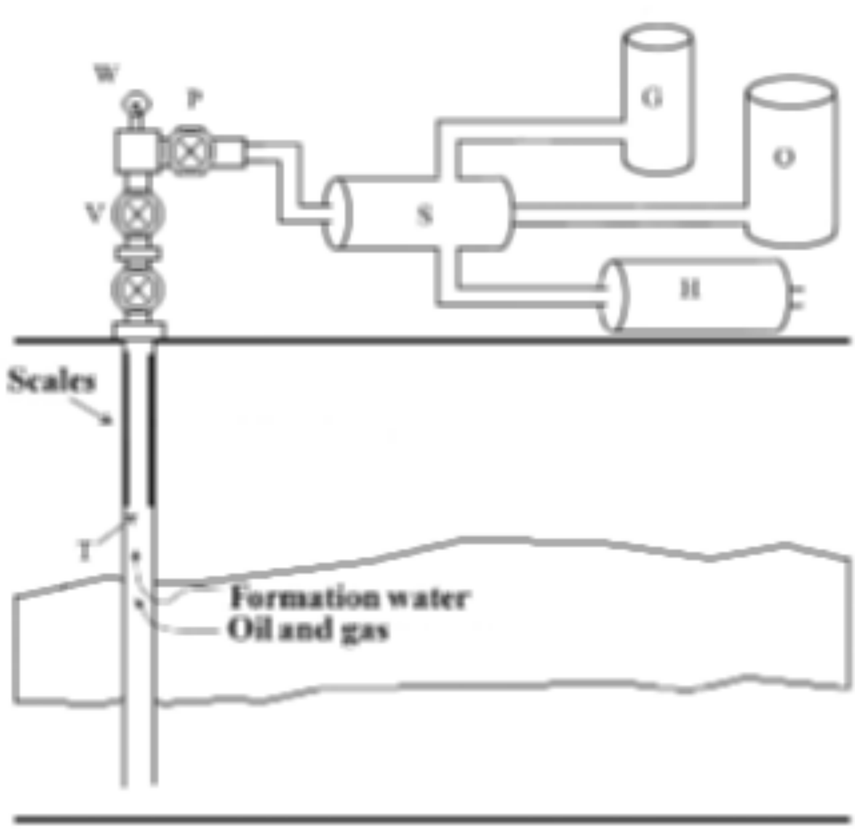



*FIG. 24. Precipitation of scales in production plant and equipment.*

surfaces of gas lines. These $^{210}Pb$ deposits are also encountered in liquefied natural gas processing plants [33–37].

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 [49], 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. 22).

### 5.3. MAIN FORMS OF APPEARANCE OF NORM

The main forms of appearance of NORM in oil and gas production are summarized in Table II.

An additional type of NORM associated with oil production has been reported recently [51]. 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 [52]. 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 [53, 54].

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. Over the production lifetime, the produced water may become increasingly more saline, indicating the co-production of brine. This

TABLE II. NORM IN OIL AND GAS PRODUCTION

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

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.

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 [36].

## 5.4. RADIONUCLIDE CONCENTRATIONS IN NORM

A large amount of data has been collected over the years on the radionuclide concentrations in NORM, although relatively few reports have been published. It would appear that 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 [49] (Table III). 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 which may reach a concentration of more than 1000 Bq/g in lead deposits and sludge. 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 about 150% of the concentration of $^{228}$Ra still present.

## 5.5. 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 owing to

TABLE III. CONCENTRATIONS OF NORM IN OIL, GAS AND BY-PRODUCTS (FROM REF. [49])

| Radio-nuclide | Crude oil Bq/g | Natural gas Bq/m$^3$ | Produced water Bq/L | Hard scale Bq/g | Sludge Bq/g |
|---|---|---|---|---|---|
| U-238 | 0.000 000 1–0.01 | | 0.0003–0.1 | 0.001–0.5 | 0.005–0.01 |
| Ra-226 | 0.0001–0.04 | | 0.002–1200 | 0.1–15 000 | 0.05–800 |
| Po-210 | 0–0.01 | 0.002–0.08 | | 0.02–1.5 | 0.004–160 |
| Pb-210 | | 0.005–0.02 | 0.05–190 | 0.02–75 | 0.1–1300 |
| Rn-222 | | 5–200 000 | | | |
| Th-232 | 0.000 03–0.002 | | 0.0003–0.001 | 0.001–0.002 | 0.002–0.01 |
| Ra-228 | | | 0.3–180 | 0.05–2800 | 0.5–50 |
| Ra-224 | | | 0.5–40 | | |

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 also arise during the decommissioning of oil and gas production facilities and their associated waste management facilities.

### 5.5.1. External exposure

The deposition of contaminated scales and sludge in pipes and vessels may produce significant dose rates inside and outside these components (Table IV). 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 a period of several months. The dose rates depend on the amount and activity concentrations of the radionuclides present inside and the shielding provided by pipe or vessel walls. Maximum dose rates are usually in the range of 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 [49, 55], which is about 1000 times greater than normal background values due to cosmic radiation and

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

| Location | 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 |

terrestrial radiation. The buildup of radium scales can be monitored without opening plant or equipment (Fig. 25). Where scales are present, opening the system for maintenance or for other purposes will increase dose rates. External exposure can be restricted only by maximizing the distance from, and minimizing duration of 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.

Deposits consisting almost exclusively of $^{210}$Pb cannot be assessed by measurements outside closed plant and equipment. Neither the low energy gamma emissions 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.

### 5.5.2. 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

*FIG. 25. Monitoring the outside of plant and equipment using a dose rate meter (courtesy: National Radiological Protection Board, UK).*

precautions are not taken prior to eating, drinking, smoking, etc. More detail on this issue is provided in Section 5.5.4.2.

Effective precautions are needed during the aforementioned operations to contain the radioactive contamination and prevent its transfer to areas where other persons might also 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 [2] quotes the following lung absorption types for the elements of interest for dose calculations:

| | | | |
|---|---|---|---|
| (a) | Radium | (all compounds): | medium (M) |
| (b) | Lead | (all compounds): | fast (F) |
| (c) | Polonium | (all unspecified compounds): | fast (F) |
| | | (oxides, hydroxides, nitrates): | medium (M) |
| (d) | Bismuth | (nitrate): | fast (F) |
| | | (all unspecified compounds): | medium (M) |
| (e) | Thorium | (all unspecified compounds): | medium (M) |
| | | (oxides, hydroxides): | slow (S). |

Table V 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 [56] are quoted, based on a more conservative assumption that all radionuclides are of lung absorption type S.

Table V 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

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

| Radionuclide | Committed effective dose per unit intake (Sv/Bq) | | |
|---|---|---|---|
| | 5 µm AMAD | | 1 µm AMAD |
| | Slowest lung absorption type listed in BSS [2] | Slow (S) absorption type [56] | Slowest lung absorption type listed in BSS [2] |
| Ra-226 | $2.2 \times 10^{-6}$ | $3.8 \times 10^{-5}$ | $3.2 \times 10^{-6}$ |
| Pb-210 | $1.1 \times 10^{-6}$ | $4.5 \times 10^{-6}$ | $8.9 \times 10^{-7}$ |
| Po-210 | $2.2 \times 10^{-6}$ | $2.8 \times 10^{-6}$ | $3.0 \times 10^{-6}$ |
| Ra-228 | $1.7 \times 10^{-6}$ | $1.2 \times 10^{-5}$ | $2.6 \times 10^{-6}$ |
| Th-228 | $3.2 \times 10^{-5}$ | $3.2 \times 10^{-5}$ | $3.9 \times 10^{-5}$ |
| Ra-224 | $2.4 \times 10^{-6}$ | $2.8 \times 10^{-6}$ | $2.9 \times 10^{-6}$ |

(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 0.1–1 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).

### 5.5.3. Decontamination of plant and equipment

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:

(a) On-site decontamination cannot be performed effectively and/or in a radiologically safe manner;
(b) The plant or equipment has to be refurbished by specialists prior to reinstallation;
(c) 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. 26) or a designated area dedicated to the task (Fig. 27). Personal protective measures will comprise protective

*FIG. 26. Workers wearing personal protective equipment decontaminating a valve inside an on-site facility (courtesy: National Radiological Protection Board, UK).*

*FIG. 27. Barrier designating a controlled area to restrict access to NORM-contaminated equipment stored outside a decontamination facility (courtesy: National Radiological Protection Board, UK).*

clothing and, in the case of handling dry scale, respiratory protection as well. The regulatory body needs to set down conditions for the:

(a) Protection of workers, the public and the environment;
(b) Safe disposal of solid wastes;
(c) Discharge of contaminated water;
(d) Conditional or unconditional release of the decontaminated components.

Decontamination methods used by the oil and gas industry are described in Appendix II.

### 5.5.4. Practical radiation protection measures

The requirements for radiation protection and safety established in the BSS [2] 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 the regulatory dose limits for workers [1]. The practical measures that need to be taken in order to reach these goals differ principally for the two types of radiation exposure: through external radiation and internal contamination.

*5.5.4.1. 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:

(a) Minimizing the duration of any necessary external exposure;
(b) Ensuring that optimum distances be maintained between any accumulation of NORM (installation part) and potentially exposed people;
(c) Maintaining shielding material 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 it 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 on the exterior of the waste storage facility to acceptably low levels.

*5.5.4.2. 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:

(a) Use protective clothing in the correct manner to reduce the risk of transferring contamination [57];

(b) Refrain from smoking, drinking, eating, chewing (e.g. gum), applying cosmetics (including medical or barrier creams, etc.), licking labels, or any other actions that increase the risk of transferring radioactive materials to the face during work;
(c) Use suitable respiratory protective equipment as appropriate to prevent inhalation of any likely airborne radioactive contamination [57];
(d) Apply, where practicable, only those work methods that keep NORM contamination wet or that confine it to prevent airborne contamination;
(e) Implement good housekeeping practices to prevent the spread of NORM contamination;
(f) Observe industrial hygiene rules such as careful washing of protective clothing and hands after finishing the work.

## 5.6. WASTE MANAGEMENT CONSIDERATIONS WITH RESPECT TO NORM

### 5.6.1. Introduction

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 waste are generated during oil and gas industry operations, including:

(a) Produced water,
(b) Sludges and scales,
(c) Contaminated items,
(d) Wastes arising from waste treatment activities,
(e) Wastes arising from decommissioning activities.

The radionuclide activity concentrations in produced water are low, but the volumes are large. The radionuclide activity concentrations in solid wastes vary from low to high, but the volumes are always relatively small. The long half-lives of the radionuclides have important implications for the management of solid wastes because of the long time periods for which control may be necessary. The fact that most of the wastes are depleted in the parent uranium and/or thorium radionuclides also needs to be taken into consideration.

### 5.6.2. Wastes from the decontamination of plant and equipment

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:

(a) Sludges removed from pipes, vessels and tanks;
(b) Solid scale suspended in water;
(c) Liquids containing dissolved scale and chemicals used for chemical decontamination;
(d) Solid scale recovered from wet or dry abrasive decontamination processes;
(e) 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 (HPWJ);
(f) Filters used to remove airborne particulates generated by dry abrasive decontamination methods;
(g) Slag from melting facilities;
(h) Flue dust and off-gas (containing the more volatile naturally occurring radionuclides) from melting facilities.

In practice, these waste streams contain not only naturally occuring 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. In practice, 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.

### 5.6.3. Waste management strategy and programmes

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 radioactive 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 [3] 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 [28]. Good operating practice will focus on ways in which the amount of radioactive waste can be minimized.

#### *5.6.3.1. Risk assessment*

A waste management risk assessment 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 [1–3]. 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.

*5.6.3.2. Regulatory approach*

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 [3] and the BSS [2]. 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 Member States. For example, the management of NORM residues from industrial processes (including the oil and gas industry) by Member States of the European Union is now subject to the requirements of Article 40 of the Council Directive 96/29/Euratom of 13 May 1996 [58]. Implementation of this is in various states of progress and involves the identification of work activities that may give rise to significant exposure of workers or of 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.

### 5.6.4. Characteristics of NORM wastes in the oil and gas industry

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 Appendix IV.

#### *5.6.4.1. 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 [59]. 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 [60] 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. Cation concentrations can be very high when brine is co-produced. 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.

*5.6.4.2. Solid wastes*

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 [34]. For comparison, the average concentration of radionuclides in the $^{238}$U decay series (including $^{226}$Ra) in soils is about 0.03 Bq/g [61]. 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 [62, 63]. Decontamination of equipment will produce solid and/or liquid waste, the latter also being contaminated with non-radioactive substances if chemical methods have been used (Section 5.6.2).

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 substances. 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:

(a) Non-volatile hydrocarbons, including waxes;
(b) Polycyclic aromatic hydrocarbons, xylene, toluene and benzene;
(c) 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.

### 5.6.5. Disposal methods

Various disposal methods for liquid and solid NORM wastes are described in this section. 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:

(1) Dilution and dispersal of the waste into the environment, e.g. liquid or gaseous discharges;
(2) Concentration and containment of the waste at authorized waste disposal facilities;
(3) Processing of the waste with other chemical waste by incineration or other methods;
(4) 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 [24] specified by the regulatory body may be disposed of as normal (non-radioactive) waste.

#### *5.6.5.1. Regulatory review and approval*

The disposal of NORM radioactive wastes originating from the oil and gas industry will require the approval of the regulatory body with regard to:

(a) The acceptability and long term safety of the proposed disposal method;

(b) The risk assessments submitted by the owner/operator to demonstrate that the disposal method meets all relevant national and international legal and regulatory requirements.

*5.6.5.2. Safety implications of waste disposal methods*

Disposal methods are discussed in Sections 5.6.5.5 and 5.6.5.6. 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 5.6.5.5(c)) and the shallow land burial of scales and sludges (Section 5.6.5.6(d)). 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.

*5.6.5.3. Significant non-radiological aspects*

The selected disposal method, in addition to meeting the fundamental principles of radioactive waste management [3], 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 lies outside the scope of this Safety Report, but they may constitute a dominant aspect in the selection of a disposal method.

*5.6.5.4. 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:

(a) Have clear markings to identify its purpose,
(b) Contain the waste material adequately,
(c) Provide suitable warnings,
(d) 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.

#### *5.6.5.5. Examples of 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. Methods that have been used to dispose of produced water include (a) reinjection into the reservoir, (b) discharge into marine waters and (c) discharge into seepage ponds.

(a) Reinjection into the reservoir

Reinjection into the reservoir from which the water originated is a common practice at many onshore and offshore production facilities, although there are 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 [64–69]. Risk assessments of discharges from platforms on the Dutch continental shelf are based on modelling of dispersion and exposure pathways [70]. 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. 28). 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 [71–73] (Fig. 29). It has been estimated that 30 000 contaminated waste pits and bottom sediment sites exist in coastal Louisiana, United States of America [74].

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:

(a) The radionuclide activity levels in the produced water,
(b) The proportion of the activity contained in the deposited salts,

*FIG. 28. Lagoons of produced water (courtesy: Atomic Energy Commission of Syria).*

(c) The degree of dilution into local surface water and groundwater,
(d) The volumes produced.

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 5.6.5.6), 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.

*FIG. 29. Remediation of contaminated land after drying the lagoon (courtesy: Atomic Energy Commission of Syria).*

In considering this disposal method, the following aspects need to be addressed:

(a) Selection of a suitable site;
(b) Controls to prevent public access to the area;
(c) Risk assessments to determine the human and environmental impacts, including long term implications, arising from contamination of soil, groundwater and surface water;
(d) 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;
(e) Quality assurance (QA) and record keeping programmes such as those for waste inventories;
(f) Transport costs and compliance with transport regulations [15];
(g) Cleanup and remediation costs;
(h) Disposal of the solid residues as radioactive wastes.

#### 5.6.5.6. *Examples of disposal methods for scales and sludges*

NORM scales and sludges have a wide range of radionuclide activity levels and half-lives. These are produced in varying quantities during the life of an oil or gas facility. Various disposal methods are practised by Member States on a routine basis. Other methods have been evaluated by practical application and yet others have been assessed on a theoretical basis only. Some disposal methods are subject to international maritime conventions such as the London Convention and the OSPAR Convention. A brief summary with a few selected references is presented below.

(1) Discharge 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 [55, 75]. 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:

(a) Need for risk assessments to determine the human and environmental impacts;
(b) 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;
(c) Need for QA and record keeping programmes such as waste inventories.

(2) Injection by hydraulic fracturing

Methods of disposal that employ hydraulic fracturing have been developed and used for offshore generated solid NORM wastes in the Gulf of Mexico [76, 77]. Hydraulic fracturing is also considered in the generic radiological dose assessments carried out for various NORM disposal options [78] and for a Class II well[1] [79]. In considering this disposal method, the following aspects need to be addressed:

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[1] 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.

(a) Site selection in relation to the long term stability of the surrounding geological structures and the required depth of emplacement;
(b) Possible need for encapsulation/stabilization (e.g. in concrete) of the solid wastes;
(c) Need for risk assessments to determine the human and environmental impacts;
(d) 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;
(e) Need for QA and record keeping programmes such as those for waste inventories.

(3) 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 [78] and has been described as a preferred option for onshore disposal of scales and mercury-containing sludges [80]. In considering this disposal method, the following aspects need to be addressed:

(a) 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 only). 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.
(b) Possible need for encapsulation and the associated costs.
(c) Need for risk assessments to determine the human and environmental impacts, including long term implications, arising from groundwater contamination.
(d) 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.
(e) Need for QA and record keeping programmes such as those for waste inventories.

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.

(4) Surface disposal

Shallow land burial is discussed as one of the NORM waste disposal options in a study made by the American Petroleum Institute [81] and is described as being practised on a limited scale in Texas [82] and in three other states in the USA [63, 83]. Remediation problems caused by earthen pit disposal of scale and sludge appear to be considerable [84]. 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. Smith et al. [85] discuss the radiological assessment of NORM waste disposal in non-hazardous waste landfills. Operational guidance on possible shallow ground disposal methods is available in Ref. [86]. The following aspects need to be addressed:

(a) 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:
    (i) Anticipated duration of the facility, i.e. temporary or final;
    (ii) Climate and meteorology;
    (iii) Hydrology and flooding;
    (iv) Geography;
    (v) Geology, geochemistry and geomorphology;
    (vi) Seismicity;
    (vii) Mineralogy;
    (viii) Demography and land use;
    (ix) Biota;
    (x) Amenability to decommissioning and the permanent disposal of wastes.
(b) Institutional control issues.
(c) Long term stability of the facility.
(d) Need for risk assessments to determine the human and environmental impacts, including long term implications, arising from groundwater contamination.

(e) 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.
(f) Need for QA and record keeping programmes such as those for waste inventories.
(g) Transport costs and compliance with transport regulations [15].

(5) Land dispersal

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" [87], 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:

(a) Need for risk assessments to determine the human and environmental impacts, including long term implications, arising from groundwater contamination;
(b) 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;
(c) Need for QA and record keeping programmes such as those for waste inventories;
(d) Transport costs and compliance with transport regulations [15].

(6) 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 [88]. 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:

(a) Costs of setting up, operating and maintaining such a repository in comparison with the costs associated with other disposal methods;
(b) Repository location in relation to the oil and gas producing areas;
(c) Selection of a suitable site requiring minimum depth of emplacement;
(d) Waste treatment, handling and packaging;
(e) Institutional control issues;
(f) Long term stability of the facility;
(g) Transport costs and compliance with transport regulations [15];
(h) Need for risk assessments to determine the impacts on the public and on the environment;
(i) 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;
(j) Need for QA and record keeping programmes such as waste inventories.

(7) Recycling by melting

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 [55], 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 [89] 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 [90]. 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. [91]. The radiological aspects are presented in more detail in Refs [78, 90]. Issues that need to be addressed include:

(a) 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.
(b) 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.
(c) The safe disposal of the contaminated slag and other wastes such as flue dust.
(d) 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.
(e) 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 [92, 93]. 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.

# 6. DECOMMISSIONING OF OIL AND GAS PRODUCTION FACILITIES

## 6.1. INTRODUCTION

When an oil or gas reservoir has been depleted to the extent that further economic exploitation is no longer viable then:

(a) The wells will be abandoned and the production and transport systems decommissioned and dismantled;
(b) The 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;
(c) The owner or operator will request that the regulatory body terminate the licence for possession, use and processing of radioactive materials.

It is important that the decommissioning aspects of a project be considered at an early stage in order to:

(a) Limit the quantities of radioactive waste generated;
(b) Limit the areas requiring decontamination;
(c) Ensure the selection of adequately safe, cost effective disposal options;
(d) Optimize the associated costs;
(e) Ensure compliance with the requirements of the regulatory body;
(f) Minimize doses to workers and to the public in accordance with the ALARA principle.

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:

(a) Perform an initial survey;
(b) Plot the survey points;
(c) Indicate any areas of elevated radiation levels;
(d) 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, and concrete and soil). Given the scale of the oil and gas industry worldwide, decontamination activities (Appendix II) will become increasingly important and generate significant quantities of wastes over an extended period of time.

## 6.2. STRATEGY

The preferred strategy for the decommissioning process will include the following steps:

(a) Decontamination of contaminated items to levels defined by the regulatory body as suitable for unrestricted release;
(b) Release of all decontaminated facilities and areas for unrestricted public use (clearance from regulatory control);
(c) Final disposal of radioactive wastes and remaining contaminated items in a facility authorized by the regulatory body.

## 6.3. KEY ISSUES AND ACTIVITIES

The decommissioning process involves numerous issues and activities including:

(a) Development of the decommissioning strategy and plan and associated QA programmes;
(b) Development of dismantling and decontamination strategies;
(c) Assessment of risks to workers, the public and the environment during and after the decommissioning activities;
(d) Submissions to the regulator, e.g. plans, strategies, records, reports and survey results;
(e) Approval by the regulatory body;
(f) Identification of potentially contaminated structures and areas;
(g) Identification, quantification and characterization of hazardous waste materials;
(h) Identification and characterization of radioactive wastes (this would include surveys to locate and identify contaminated areas, items and materials);
(i) Development of strategies to minimize the generation of radioactive wastes during decommissioning;
(j) Surveys to assess the levels of gamma dose rate, and alpha and beta surface contamination;
(k) Implementation of appropriate radiological protection programmes for workers, the public and the environment;
(l) A wide range of decontamination activities, e.g. components, buildings and land areas (Appendix II);
(m) Disposal of all radioactive wastes at authorized facilities;

(n) Land remediation activities;
(o) Transport of radioactive materials in accordance with applicable regulations [15];
(p) A final radiation survey after dismantling, removal and remediation activities 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 Safety Guide on Decommissioning of Medical, Industrial and Research Facilities [94].

# 7. ORGANIZATIONAL RESPONSIBILITIES AND TRAINING IN THE OIL AND GAS INDUSTRY

## 7.1. INTRODUCTION

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

(a) The various regulatory bodies;
(b) The operating organizations (operators) responsible for the oil and gas fields and the distribution of the products;
(c) The service companies (or organizations) that work under contract for the operator, including but not limited to companies that carry out radiography, work involving gauges, well logging, tracer and workover services, fishing operations and NORM decontamination operations.

It is also 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. Information must be provided to those who are not involved but who may indirectly be affected by the work and who need information or specific instructions to minimize their potential exposure. The level of instruction needs to be appropriate for the different levels of competence and recipients will include qualified experts, radiation protection officers (RPOs), qualified workers occupationally exposed to radiation, general workers and other persons. Suggestions for training are given in Appendix III and discussed in detail in Refs [95, 96]. It is important that suitably qualified professionals — those 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.

## 7.2. 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:

(a) Development and production of oil and gas;
(b) Transport of radioactive and other hazardous material;
(c) Possession, use and disposal of radioactive material.

These various regulatory bodies must co-ordinate any overlapping responsibilities. In these circumstances it is important to identify a lead regulatory body which will assume responsibility for radioactive material and which will promulgate appropriate rules and regulations and ensure their enforcement. Additionally, it will have 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 will be made to confirm that adequate training is provided and that it is in accordance with programmes approved by the regulatory body as required. It is important that any findings resulting from an inspection be communicated to the persons or organizations involved and that follow-up inspections be performed to verify that corrective actions have been implemented [97, 98].

The regulatory body needs to establish criteria to ensure that it receives notification from the licensee of any accidents or incidents involving radioactive material. The types of incident 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, i.e. nuclide, activity and serial number, where applicable. The regulatory body arranges that the licensee's reports include a description of the incident, investigations of exposures of 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 a 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.

## 7.3. 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 licensed to own, possess, or use radioactive material including NORM. The operator establishes sufficient methods, for example employing a qualified expert in the use of risk assessment techniques, for determining whether the operations involve work with ionizing radiation and therefore 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 an 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) Monitoring radiation and contamination;
(b) Identifying and maintaining an 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) Providing hazard assessments and identifying controlled and supervised areas;
(f) Using a QA 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) Checking to ensure compliance with authorized conditions and other regulatory requirements;
(k) Supervising work in areas that are controlled as a result of radiation levels or storage of radioactive material;
(l) Advising and requiring the use of appropriate personal protective equipment in controlled areas;
(m) Providing 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 maintaining the inventory and for tracking 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. Suitable training programmes are outlined in Appendix III.

## 7.4. SERVICE COMPANIES

Service companies perform radiography, drilling, tracer work, workovers, well logging, fishing operations, perforations, NORM decontamination, maintenance and repair, etc. Some of these companies are licensed to possess and use radioactive material and have appointed RPOs (Section 7.3). 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 to the regulatory body any incidents or accidents involving the radioactive material. The licensed company co-operates with the service company to ensure that the necessary assessments of the doses received by workers are made and recorded according to national regulations.

## 7.5. WORKERS

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.

Radiation protection training is tailored to a 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 on the 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 are 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.

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.

# Appendix I

# RADIATION MONITORING IN THE WORKPLACE

## I.1. MEASUREMENT PRINCIPLES AND INSTRUMENTS

### I.1.1. Principles

A wide range of instruments is available for carrying out workplace monitoring for ionizing radiation and radioactive contamination [99]. 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 radiations used in the industry. It is important to select and make available instruments that are appropriate and efficient for the different applications. Intrinsic safety to permit use in flammable atmospheres may be an important requirement for the instruments used.

Radiation measuring instruments are usually designed to quantify only one of the two types of potential exposure:

(1) External exposure to penetrating radiation emitted by sources outside the human body. Such exposures are associated with sealed sources, unsealed sources such as radiotracers (whether contained or not), bulk quantities of NORM, and radiation generators or machines.
(2) Internal exposure associated with radioactive materials that are in a form capable of being inhaled or ingested or which otherwise enter and interact with the human body. Unesaled 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.

Dose rate meters are used to measure the potential external exposure, whereas dosimeters are used to indicate the cumulative external exposure. Surface contamination meters indicate the potential internal exposure when the radioactive substance is distributed over a surface; airborne contamination meters and gas monitors indicate the potential internal exposure when a radioactive substance is distributed within the atmosphere.

### I.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, near installed level gauges or near accumulated NORM. For other purposes, such as taking measurements on 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. In some situations, such as when implementing an emergency plan to recover an unshielded radiography source, a high dose rate range instrument capable of a continued response where there are dose rates of 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 multirange instruments covering dose rates of 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.

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. 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 also be used 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 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 a gamma spectrometry capability. Gamma spectrometry enables the radiations that are responsible for the dose rate to be analysed in terms of the radiation energies present. This characterizes, unequivocally, the nature of the radioactive substance (identifying it as $^{137}$Cs or $^{226}$Ra, etc.) emitting the gamma radiation.

The response of any dose rate meter is dependent on the characteristics of the detector it employs, in particular on its detection efficiency at the energy (or energies) of the radiation to which it is exposed. An instrument may have 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 the actual dose rate attributable to those radiations. 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 only be able to detect radiation of a certain type or having an energy greater than some threshold value. The neutron sources used in well logging, typically $^{241}$Am–Be, emit both gamma and neutron radiations 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. 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 and 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 one minute or longer, depending on whether the prevailing dose rate is apparently constant or transient.

### I.1.3. Dosimeters

There are many situations in which workers are exposed and where the transient dose rates 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 dosimeter [100] 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 radiations so that the total cumulative exposure to these radiations can be assessed. Occupationally exposed workers must wear a suitable dosimeter and where high dose rates are possible, such as in radiography, a direct reading dosimeter in addition. 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 [5].

#### I.1.4. Surface contamination monitors

Surface contamination monitors are usually 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 to beta and gamma radiations. 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 radiations but not those of 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 instruments need to be calibrated for the particular radiation being detected to enable the indicated reading to be converted into meaningful units such as $Bq/cm^2$. Some instruments are designed either to allow the calibration response factor to be programmed into the instrument, or to allow 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 displayed directly in $Bq/cm^2$.

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 substances 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 radiations that differ widely in their capability to penetrate matter. NORM usually emits alpha particles but these may be stopped from reaching the detector as a result of 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 energies are likely to be detected by use of an appropriate instrument. Gamma radiations have a much greater range in matter but any instrument used to measure them 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 by which to monitor thin layers of NORM on surfaces. 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 to be made that are necessary to allow calibration of 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.

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 (e.g. 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 gained to internal surfaces (Fig. 30). This is because the beta 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 terms of $Bq/cm^2$) 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. 31).

Gamma radiation detectors (either sensitive dose rate meters or contamination meters) may be used to detect accumulations of NORM within plant

*FIG. 30. NORM contamination within a vessel being measured using a surface contamination measuring instrument (courtesy: National Radiological Protection Board, UK).*

*FIG. 31. Checking tubulars for NORM contamination (courtesy: National Radiological Protection Board, UK).*

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 substances will need to be submitted to a laboratory for gamma spectrometric analysis to identify and determine the NORM activity concentrations (in terms of Bq/g).

### I.1.5. Contamination monitors for measuring airborne radioactive material

Instruments for measuring airborne contamination are used where there is a need to assess the risk of radioactive substances either being 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 substance 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 as with 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.

## I.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. Generally, three levels of expertise may be recognized: task, routine and special monitoring [1]. Further guidance on monitoring can be found in Refs [25, 26].

### I.2.1. Task monitoring

The worker who has day-to-day use of the radiation source or who 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 to 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) A radiographer to check that a radioactive source has safely returned to its shielded container after an exposure;
(b) The user of a mobile gauge to check that a shutter has closed after the gauge has been used;
(c) A well logging engineer to check the safe return of the sources after a logging tool returns from the well;
(d) A radiotracer technician to check for contamination around high pressure joints and mixer vessels after injection of the radiotracer;
(e) A NORM worker to check for contamination on clothing before leaving an area where decontamination work is being carried out;
(f) A technician to monitor the radon level at the exit points of liquids and gases.

### I.2.2. Routine monitoring

In order to oversee, supervise, maintain and keep under review a programme for monitoring in the workplace, the 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 carried out by RPOs 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 and show no signs of physical damage, and to confirm that the shutter of the 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 to facilitate this (Fig. 32).
(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.

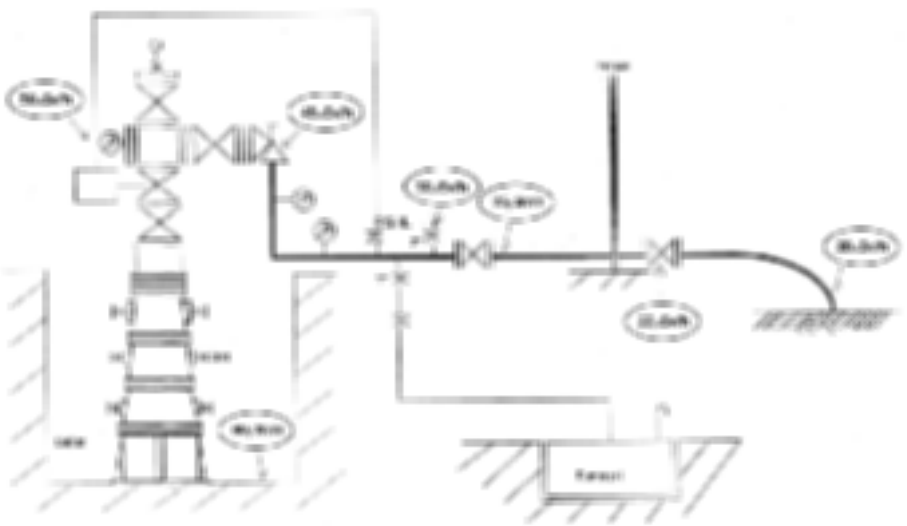

*FIG. 32. Example of a completed area monitoring diagram.*

### I.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. Special monitoring might be used in:

(a) Situations involving 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 QA 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 is shown in Fig 33.
(f) Baseline surveys to establish the conditions at a location prior to its development as a radioactive waste disposal facility.
(g) Situations where NORM is present in operational plant, sampling and analysis of produced waters, scales, sludge, natural gas, gas condensates, etc., being carried out, as appropriate, to determine radionuclide and activity concentrations.
(h) Decommissioning surveys of redundant facilities.

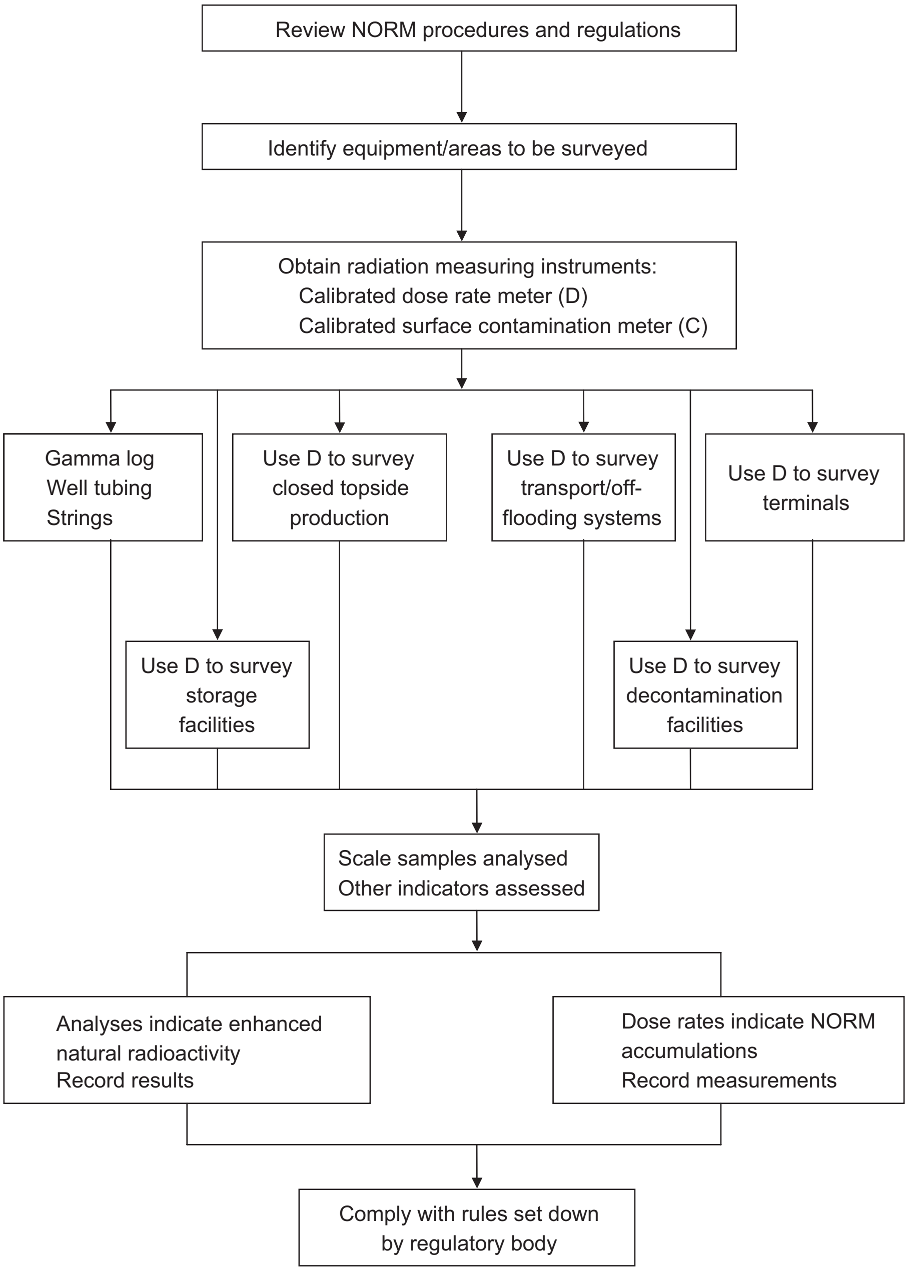


*FIG. 33. Flow diagram for NORM assessments.*

(i) Location and recovery of lost sources, damaged sources, etc., following an incident.
(j) Investigation of accident conditions and provision of specialized dosimetric methods to determine effective doses and acute partial body doses.
(k) Obtaining samples and measurements and in the analysis of samples for presentation as evidence in a legal action.

### I.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 measurement and dosimetry, especially for use with gamma emitting radionuclides and radon. Superficial repairs are effected easily in the field provided the necessary spare parts, such as cables and foils to cover 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 the 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) A test source of low activity available or at 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.
(b) 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 being available. It is normally the responsibility of the service company owning the radiation source to provide the instrument(s). However, the field operator may want to 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.

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).

## Appendix II

## METHODS FOR THE DECONTAMINATION OF PLANT AND EQUIPMENT

### II.1. INTRODUCTION

Various decontamination methods are being applied on and off the site, the choice of method depending on the type and size of the components and the characteristics of the contaminating substance. Methods range from removal of bulk sludge from vessels (Fig. 34) followed by rinsing with water to the application of chemical or mechanical abrasive techniques. The methods of specific operational importance are described briefly below and summarized in Table VI.

*FIG. 34. Removal of bulk sludge from a vessel (courtesy: Atomic Energy Commission of Syria).*

TABLE VI. NORM DECONTAMINATION METHODS

| Method | Comment |
|---|---|
| Manual removal or cleaning | Does not involve any machinery and may be as simple as hand washing or shovelling. Commonly used for removing sand and sludge from topside equipment. |
| Mechanical removal by drilling or reaming | Commonly used to remove scale (hard deposits) from tubulars and other types of surface contaminated equipment. Wet drilling processes should be used to reduce/prevent the generation of radioactive dust. Should be enclosed to contain the contaminants and wash water should be filtered to remove scale. |
| HPWJ | Commonly used to remove scale (hard deposits) from tubulars and other types of surface contaminated equipment. Provides effective scale removal and reduces dust generation by keeping the material wet. Should be enclosed and wash water contained, recirculated or filtered to remove scale. |
| Vacuuming | Can be wet or dry processes to remove loose particle contamination. |
| Chemical cleaning | Using commercially available scale dissolvers. Chemicals are also used to remove thin films of NORM from gas plant equipment. |
| Melting | Equipment melting as scrap metal. Most of the NORM ends up in the slag, but volatile radionuclides end up in the off-gas dust and fume. |

## II.2. IN SITU CHEMICAL DESCALING

Chemical methods are applied and are being developed further for downhole scale removal and scale prevention [53, 54, 101–103]. 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 removal of scale also removes the radionuclides contained in the deposits, resulting in a liquid stream containing the radionuclides from the dissolved scale.

## II.3. 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 are normally to be avoided because of the risk of spreading radioactive contamination in the air. With wet abrasive methods, this risk is reduced considerably. Consequently, the application of dry abrasive methods needs protective measures for workers and the environment, which can in practice only be provided by specialized companies or organizations.

HPWJ has been shown to be effective for the decontamination of components from oil and gas production (Figs 35 and 36). Water pressures of 10–250 MPa are used, which necessitate the use of special pumps and safety measures. In principle it can be applied on the site and offshore as well as onshore, but its effective and radiologically safe application needs special expertise and provisions to obtain the correct 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 [55]. Decontamination of tubulars is carried out with the aid of long HPWJ lances fitted 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. 37). It is relatively easy to contain the recoiling water from tubulars. The application of HPWJ to the outer surfaces of components is strongly complicated by the mist produced by the impact of the jet. In the open air this will cause the spread of the radioactive contamination removed from the object and in enclosed spaces it greatly reduces visibility.

## II.4. CHEMICAL DECONTAMINATION

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.

*FIG. 35. Workers with personal protective equipment and HPWJ lance (courtesy: Atomic Energy Commission of Syria).*

### II.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, but only on a small scale. The typical processes involved in the melting of scrap steel are as follows:

*FIG. 36. Workers using HPWJ lance (overhead extractor removes airborne contamination) (courtesy: Atomic Energy Commission of Syria).*

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

*FIG. 37. Facility for tubular decontamination by HPWJ (courtesy: Atomic Energy Commission of Syria).*

## Appendix III

## TRAINING COURSES FOR PERSONS WORKING WITH IONIZING RADIATION IN THE OIL AND GAS INDUSTRY

### III.1. INTRODUCTION

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. This Appendix recommends minimum safety training requirements for the following persons:

(a) RPOs in the oil and gas industry,
(b) Qualified operators,
(c) Workers occupationally exposed to radiation.

The aims and objectives of each training course need to be specified clearly in advance.

### III.2. RPOs

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.

As a minimum, the training course needed for an RPO would include the following topics, to be covered by lectures and practical exercises in a period of not less than four days:

(a) Basic concepts:
  (i) Types of radiation,
  (ii) Interaction of radiation with matter,
  (iii) Radioactive decay,
  (iv) Sealed and unsealed sources,
  (v) Machines (radiation generators).
(b) Radiological units:
  (i) Activity,
  (ii) Absorbed dose,
  (iii) Equivalent dose,
  (iv) Dose rate,
  (v) Commonly used prefixes,
  (vi) SI and non-SI units.
(c) Dose limitation:
  (i) Principles of protection,
  (ii) BSS and national dose limits,
  (iii) Optimization of protection (ALARA).
(d) Biological effects of radiation exposure:
  (i) Biological systems,
  (ii) Radiation detriment,
  (iii) Stochastic and deterministic effects,
  (iv) Acute and chronic exposures.
(e) Protection from external exposure:
  (i) Time, distance and shielding.
  (ii) Dose rates associated with sources/machines (output).
  (iii) Half and tenth value thicknesses.
  (iv) Practical aspects of the RPO's work, e.g.:
    — radiography equipment,
    — well logging equipment,
    — nucleonic gauges,
    — radiotracer applications,
    — NORM accumulations.
  (v) Safety signs and signals.
(f) Protection from internal exposure:
  (i) Inhalation, ingestion, absorption of radioactive material;
  (ii) Values of dose per unit intake;
  (iii) Containment of radioactive materials;
  (iv) Personal protective equipment (clothing and respiratory);
  (v) Engineered control measures;
  (vi) Working procedures and industrial hygiene.

(g) Individual (personal) monitoring:
  (i) Individual dose monitoring.
  (ii) Dose record keeping.
  (iii) Types and characteristics of dosimeters, i.e.:
    — film badges,
    — thermoluminescent dosimeters,
    — neutron dosimeters,
    — radon dosimeters,
    — electronic personal dosimeters (alarms).
  (iv) Wearing and care of dosimeters.

(h) Radiation measuring instruments and their use:
  (i) Types of radiation monitoring survey instrument:
    — surface contamination monitors,
    — airborne contamination monitors,
    — dose rate monitors.
  (ii) Laboratory instruments (e.g. spectrometers) and installed monitors.
  (iii) Correct use and care of monitors.
  (iv) Testing, calibration and QA.
  (v) Frequency of monitoring.
  (vi) Record keeping.

(i) BSS and requirements of the relevant regulatory body:
  (i) Hazard evaluations and risk assessments,
  (ii) Radioactive source accounting and records,
  (iii) Storage requirements,
  (iv) Controlled and supervised areas,
  (v) Role of the RPO,
  (vi) Standard operating procedures,
  (vii) QA programmes,
  (viii) Control of public exposure,
  (ix) Health surveillance of workers.

(j) Transport and movement of sources:
  (i) Containment of sources.
  (ii) Labelling of packages.
  (iii) Documentation.
  (iv) Accountability.
  (v) Vehicle placards, etc.
  (vi) Loading vehicles, vessels, aircraft.
  (vii) Storage in transit requirements.

(k) Radiation accidents and emergency procedures:
   (i) Examples of accidents and lessons learned,
   (ii) Actions to take in the event of an emergency,
   (iii) Use of emergency equipment,
   (iv) Contingency plans,
   (v) Notification(s),
   (vi) Written reports of incidents and accidents.

## III.3. 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, decontamination of NORM. 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.

## III.4. 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 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.

## III.5. MANAGERS AND SAFETY OFFICERS

Managers and safety officers who are not directly involved in work with ionizing radiation frequently have a responsibility to co-ordinate 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.

## III.6. 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.

## Appendix IV

## METHODS OF RADIOACTIVE WASTE CHARACTERIZATION

### IV.1. SCALES AND SLUDGES

The radiological characterization of NORM waste will usually demand nuclide specific analysis by high resolution gamma spectrometry. 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. Samples of sludges and scales need only drying and homogenizing for the preparation of counting samples. The method allows the determination of NORM nuclides as summarized in Table VII.

Because the emanation rate of the $^{226}$Ra progeny $^{222}$Rn from sludges and scales is usually very low, $^{226}$Ra can be measured directly by its 186 keV gamma photon in all samples with low uranium concentrations. If interference of the 186 keV photon from $^{235}$U cannot be excluded, $^{226}$Ra has to be measured by its progeny $^{214}$Pb (or $^{214}$Bi) and secular equilibrium ascertained either by the low emanation rate from the sample material or by confinement of the $^{222}$Rn in a gas-tight geometry.

The assessment of the concentration of $^{210}$Pb will need correction for self-absorption of the low energy gamma photon in the sample matrix. Correction for self-absorption can be based on transmission measurements with a $^{210}$Pb source. The use of flat cylindrical sample geometries allows such transmission measurements.

Efficiency calibration of the counting system can best be based on counting, in the same geometry, of reference materials such as IAEA-RGU-1 and IAEA-RGTh-1, which can be obtained from the IAEA [104].

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.

TABLE VII. SUMMARY OF GAMMA SPECTROMETRY ON NORM-CONTAINING SOLIDS FROM THE OIL AND GAS INDUSTRY

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

## IV.2. 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.

At activity concentrations greater than 10 Bq/L, liquid samples containing $^{226}$Ra and $^{228}$Ra can be counted without preconcentration provided the counting system is adequately calibrated, and taking the following into account:

(a) 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.

(b) 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.

(c) 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.

(d) The method is inherently insensitive when used for determining $^{210}Pb$ because of the high self-absorption of its low energy photon (46 keV).

(e) 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.

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, preconcentration 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.

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# DEFINITIONS

## RADIATION PROTECTION

**absorbed dose, *D*.** The fundamental dosimetric quantity $D$, defined as:

$$D = \frac{d\bar{\varepsilon}}{dm}$$

where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter in a volume element and $dm$ is the mass of matter in the volume element.

**contamination.** Radioactive substances on surfaces, or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable, or the process giving rise to their presence in such places.

**controlled area.** A defined area in which specific protection measures and safety provisions are or could be required for controlling normal exposures or for preventing the spread of contamination during normal working conditions, and preventing or limiting the extent of potential exposures.

**effective dose, *E*.** The quantity $E$, defined as a summation of the tissue equivalent doses, each multiplied by the appropriate tissue weighting factor:

$$E = \sum_{T} w_T \cdot H_T$$

where $H_T$ is the equivalent dose in tissue T and $w_T$ is the tissue weighting factor for tissue T. From the definition of equivalent dose, it follows that:

$$E = \sum_{T} w_T \cdot \sum_{R} w_R \cdot D_{T,R}$$

where $w_R$ is the radiation weighting factor for radiation R and $D_{T,R}$ is the average absorbed dose in the organ or tissue T.

**equivalent dose, $H_T$.** The quantity $H_{T,R}$, defined as:

$$H_{T,R} = w_R \cdot D_{T,R}$$

where $D_{T,R}$ is the absorbed dose delivered by radiation type R averaged over a tissue or organ T and $w_R$ is the radiation weighting factor for radiation type R. When the radiation field is composed of different radiation types with different values of $w_R$ the equivalent dose is:

$$H_T = \sum_{R} w_R \cdot D_{T,R}$$

**exposure.** The act or condition of being subject to irradiation.

**half-life.** For a radionuclide, the time required for the activity to decrease, by a radioactive decay process, by half.

**ionizing radiation.** For the purposes of radiation protection, radiation capable of producing ion pairs in biological material(s).

**NORM (naturally occurring radioactive material).** Material containing no significant amounts of radionuclides other than naturally occurring radionuclides.

**radioactive material.** Material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity.

**radioactive substance.** See radioactive material.

**source.** Anything that may cause radiation exposure — such as by emitting ionizing radiation or by releasing radioactive substances or materials — and which can be treated as a single entity for protection and safety purposes.

**supervised area.** A defined area not designated a controlled area but for which occupational exposure conditions are kept under review, even though specific protection measures and safety provisions are not normally needed.

## OIL AND GAS PRODUCTION

**jacket.** Steel substructure which supports the above sea level topsides.

**Christmas tree.** Arrangement of pipes and valves at the wellhead, which controls the flow of oil and gas and prevents blow-outs.

**condensate.** The heaviest fraction of natural gas liquid (hydrocarbons which can be extracted as liquids from natural gas in gas processing plants or from gas field facilities). It may exist in the producing formation either as a liquid or as a condensable vapour.

**platform.** Fixed or floating structure from which wells are drilled or oil or gas produced.

**produced water.** Water produced in the form of vapour or liquid with crude oil and natural gas. The liquid water may be free or emulsified.

**reservoir rock.** Porous rock containing interconnected pores or fissures in which oil or gas are found.

**scale.** Solid deposit of low solubility sulphates or carbonates on the inside of components of gas and oil production installations.

**separator.** A pressure vessel used for separating well fluids produced from oil and gas wells into gaseous and liquid components.

**skimmer tank.** Tank or vessel used to separate, by gravity, hydrocarbons from water and solids.

**sludge.** Mixture of organic and mineral solids in water and liquid hydrocarbons separated from oil or gas at production facilities.

**topside.** The entire superstructure of a platform, normally consisting of production equipment and facilities, accommodation, 'helideck', etc.

**well.** A hole drilled in rock from the surface to the reservoir in order to explore for, or extract, oil or gas.

**wellhead.** Control equipment fitted on top of the well and consisting of outlets, valves, blow-out preventers, etc.

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| Al-Taifi, I.M.A. | Permanent Mission, Embassy of Saudi Arabia, Austria |
| Bennet, P. | North Sea Instruments Ltd, United Kingdom |
| Cardwell, T. | Texas Department of Health, United States of America |
| Conlon, P.J. | International Atomic Energy Agency |
| Fawaris, B.H. | TNRC, Libyan Arab Jamahiriya |
| Gustafsson, M. | International Atomic Energy Agency |
| Guy, M.S.C. | ALARA Consultants, South Africa |
| Heaton, B. | Aberdeen University, United Kingdom |
| Holland, B. | Australian Nuclear Science and Technology Organization, Australia |
| Kustiono, A.S. | Nuclear Energy Control Board, Indonesia |
| Lancee, P.F.J. | NAM Assen, Netherlands |
| Massera, G. | International Atomic Energy Agency |
| McGregor, R.G. | Health Canada, Canada |
| McKenna, T. | International Atomic Energy Agency |
| Mohd Ali, H. | Atomic Energy Licensing Board, Malaysia |
| Omar, M. | Malaysian Institute for Nuclear Technology Research, Malaysia |
| Oresegun, M. | International Atomic Energy Agency |
| Orr, D. | Scottish Environment Protection Agency, United Kingdom |
| Othman, I. | Atomic Energy Commission of Syria, Syrian Arab Republic |
| Pope, R. | International Atomic Energy Agency |

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| Seitz, R. | International Atomic Energy Agency |
| Strand, T. | Norwegian Radiation Protection Authority, Norway |
| van Weers, A. | Nuclear Research and Consultancy Group, Netherlands |
| Vaziri, M. | Atomic Energy Organization of Iran, Islamic Republic of Iran |
| Westmeier, W. | Gesellschaft für Kernspektrometrie mbH, Germany |
| Wheatley, J. | International Atomic Energy Agency |
| Wheelton, R. | National Radiological Protection Board, United Kingdom |
| Wrixon, A. | International Atomic Energy Agency |
| Wymer, D.G. | International Atomic Energy Agency |
| Yusko, J. | International Atomic Energy Agency |

**Consultants Meetings**

Vienna, Austria: 15–19 September 1997, 30 November–4 December 1998,
6–10 December 1999, 11–13 December 2000,
28–29 November 2001, 10–12 June 2002

**Technical Committee Meeting**

Vienna, Austria: 31 May–4 June 1999