Safety Reports Series

No. 100

Occupational Radiation Protection in the Uranium Mining and Processing Industry

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OCCUPATIONAL RADIATION PROTECTION IN THE URANIUM MINING AND PROCESSING INDUSTRY

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FOREWORD

The Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, and Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, establish the principles and basic requirements for radiation protection and safety applicable to all activities involving radiation exposure, including exposure to natural sources of radiation. International radiation safety regulations have been applied at uranium mines for over forty years. Even though radiation safety regulations in many uranium producing countries are among the most comprehensive and stringent, there is still scope to enhance protection of occupationally exposed workers in terms of improving mechanisms to reduce occupational exposure, achieve informed personal behaviours and apply best engineered controls and other aspects.

Uranium mining companies take active steps to reduce radiation doses and to control exposures wherever they can. They often voluntarily adopt the most recent international requirements and recommendations on dose limits and occupational radiation protection before they become part of national regulations. Enhancing radiation protection of workers on an industry wide and global basis supports the implementation of internationally consistent standards and approaches with regard to the protection of workers.

In 2011, the IAEA initiated the Information System on Uranium Mining Exposure (UMEX) to enhance radiation protection of workers in uranium mining and processing. As a first step, the IAEA conducted a global survey to evaluate worldwide occupational radiation protection. Following an analysis of the results, the IAEA has been able to identify both good practices and opportunities for improvements. This publication presents the results of the questionnaire and identifies actions to assist industry, workers and regulatory bodies in implementing the principle of optimization of protection. This publication also presents information on uranium mining and processing methods, radiation protection considerations, monitoring, dose assessment and radiation protection programmes for the range of commonly used mining and processing techniques.

The IAEA is grateful to all who contributed to the drafting and review of this publication, in particular I. Ženatá (Czech Republic). The IAEA officers responsible for this publication were P.P. Haridasan and H.B. Okyar of the Division of Radiation, Transport and Waste Safety.

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1. INTRODUCTION

1.1. BACKGROUND

Natural uranium is the dominant fuel for global nuclear power programmes, and an increase in the momentum of the prospecting, mining and processing of uranium is inevitable in the future as more countries adopt national nuclear power programmes. The World Nuclear Association[1] reports:

"• **In the last 60 years uranium has become one of the world's most important energy minerals.**
• **It is mined and concentrated similarly to many other metals.**

…….

"Uranium is a naturally occurring element with an average concentration of 2.8 parts per million in the Earth's crust. Traces of it occur almost everywhere. It is more abundant than gold, silver or mercury, about the same as tin and slightly less abundant than cobalt, lead or molybdenum."

The three main methods of producing uranium are underground mining, open pit mining and in situ leaching (ISL) (sometimes referred to as in situ recovery, ISR). Conventional mines, either underground or open pit, are usually associated with a mill, where the ore is crushed, ground and then leached[2] to dissolve the uranium and separate it from the host ore. At the mill of a conventional mine or at the treatment plant of an ISL operation, the uranium which is now in solution is then separated by ion exchange before being precipitated, dried and packed. The product, uranium oxide concentrate, is also referred to as yellow cake and mixed uranium oxide (U_3O_8, UO_4).

Uranium can also be recovered as a by-product from phosphate fertilizer production and from the mining of other minerals, such as copper and gold, when the ores contain economically exploitable quantities of uranium. In such situations, the treatment process to recover uranium can be more complex.

During uranium mining and processing, workers may be exposed externally to gamma rays emitted from the ores, process materials, products and tailings.

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[1] See www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.aspx

[2] Depending on the mineralogy of the ore, various processes, including either sulphuric acid or alkaline (carbonate) leaching, are employed to liberate the uranium from the host ore.

Internal exposure can arise from the inhalation of long lived radionuclide dust (LLRD) and radon and radon decay products (RDP), and through absorption, ingestion and wound contamination.

1.2. OBJECTIVE

The objective of this publication is to provide detailed information to assist regulatory bodies and industry operators in implementing a graded approach to the protection of workers against exposures associated with uranium mining and processing. This information will also serve as the basis for creating a common understanding among various stakeholders (e.g. regulators, operators, workers and their representatives, health, safety and environmental professionals) about the radiological aspects of the various processes involved and the ways in which these aspects can be addressed appropriately and effectively.

1.3. SCOPE

This publication describes the methods of production in the uranium industry and provides practical information on the radiological risks to workers in exploring, mining and processing. This publication also describes the methods of assessing and controlling the radiological risks based on the application of the appropriate IAEA safety standards and good working practices. This information has been compiled from published literature, from unpublished data provided by the contributors to this publication and from numerous experts with extensive experience in the various sectors of the uranium mining and processing industry. Guidance provided here, describing good practice, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

Section 2 provides an overview of the uranium industry and the general radiation protection aspects of various uranium mining and processing methods. Section 3 summarizes the radiation protection principles and considerations that apply to the industry and the application of the international standards, the graded approach to regulation and specific aspects of radionuclides in the uranium decay series. Section 4 addresses the general methodology for control with the introduction of occupational health and safety considerations, the hierarchy of control, dose reduction and exposure pathways. Section 5 explores the arrangements for monitoring and dose assessment of various exposure pathways, and Section 6 presents the occupational radiation protection programmes during the life cycle of different uranium mining and processing methods and stages. The six appendices begin with a description of the Information System on Uranium Mining Exposure (UMEX) survey, which is followed by the methods and analysis of the survey results, and concludes with technical details on the assessment and control of the major exposure pathways.

2. OVERVIEW OF THE URANIUM INDUSTRY AND GENERAL RADIATION PROTECTION

2.1. GLOBAL URANIUM PRODUCTION

With the current interest in nuclear power, there has been an increase in uranium exploration and in the development of new uranium mining and processing facilities in many countries. World uranium production was 55 975 tU as of 1 January 2015 [1, 2]. This uranium production occurred in 16 different countries at approximately 50 different mining and processing facilities. Uranium production has increased by 50% since 2007; and because of this increased demand, the numbers of workers in the uranium mining and processing industry is set to increase substantially within a few years.

In 2012, as part of UMEX, the IAEA developed a questionnaire that was distributed to 36 operators in uranium producing countries. The responses to this first questionnaire were received in 2013. The information in Appendix I is based on the analysis of the questionnaire results from the operating facilities, which comprises 18 operators and accounts for nearly 85% of the global uranium production, and it includes summaries of current practices for monitoring exposures and reporting doses.

Many ISL facilities (also known as uranium solution mining) have operated since the late 1960s (e.g. in Central Asia and the United States of America). In recent years, they have been producing almost half of worldwide uranium supplies, accounting for 48.7% of uranium mined in 2015 [2]. Most uranium mining in Kazakhstan, the United States of America and Uzbekistan is now conducted using ISL methods. ISL mining is also undertaken in Australia, China and the Russian Federation, and ISL operations are being considered in Mongolia and the United Republic of Tanzania [2]. Underground mining (27%), open pit mining (14%), co-product and by-product recovery from copper and gold operations (7%), heap leaching (<1%) and other methods (<1%) accounted for the remaining uranium production [2].

2.2. OVERALL OCCUPATIONAL EXPOSURE

Occupational exposure is the exposure of workers in the course of their work, whether full time or part time, as either a company employee or contract worker. Occupational exposure arises mainly from external gamma radiation and the inhalation of LLRD and RDP.

The monitoring practices and dose calculation procedures and assumptions used to estimate worker doses vary according to operations and regulations. Doses can be assessed, for example, from area monitoring and estimates of occupancy times, or be based directly on individual dose measurements. The procedures and assumptions for dose assessment affect not only the estimation of dose by pathway but also the total dose. Thus, it is important to document any assumptions made in estimating and reporting the dose and the values of other key parameters used in calculating the dose. Figure 1 presents the average dose components from the UMEX survey of each pathway of exposure in different types of mining and processing.

The UMEX data for the various operations were combined into four mining methodologies: underground, open cut, ISL and other. Both the underground

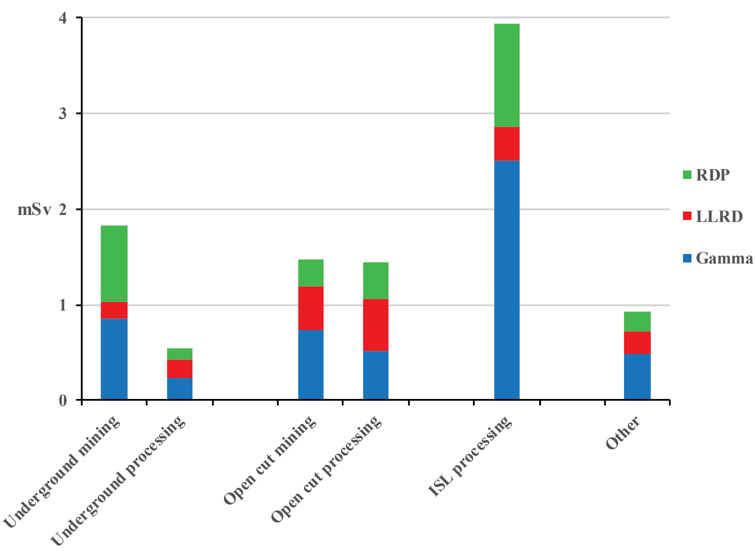

FIG. 1. Average dose for different operations.

and open cut mining data were further separated into mining and processing personnel. The other category included exposures from uranium recovery from rehabilitation, wastewater treatment and toll milling. The results of the survey can be summarized as follows:

(a) General observations:
  - The dominant uranium mining method was ISL, followed by underground and open cut methods.
  - The main process for uranium extraction from ores was acid leaching, followed by alkali leaching.

(b) Assessment of external exposure:
  - Most operators used thermoluminescent dosimeter (TLD) methods for the assessment of individual gamma doses.
  - Most operators monitored each worker's dose; the remainder monitored selected group averaging and selected individual monitoring to assess doses.
  - Approximately half of operations did not use background subtraction, which can lead to a small overestimation of the occupational dose.

(c) Assessment of LLRD and dust sampling:
  - Approximately half the operators used area dust sampling values to estimate doses; the remainder used personal dust sampling methods on individual workers.
  - Most operators used gross alpha counting methods for assessing alpha activity.
  - Most operators used periodic monitoring for the assessment of inhaled dust.
  - Most operators did not use routine bioassay; however, some operators used urine analysis.

(d) Monitoring of inhalation of RDP:
  - For monitoring RDP, most operators used area RDP monitoring with worker occupancy factors to estimate doses.
  - The monitoring methodology used by most operators was workgroup averaging, followed by individual monitoring.
  - Most operators did not use background subtraction, which can lead to a small overestimation of the measured dose.

(e) Dose assessment:
  - For the dose calculations, most operators followed the time sheet method, while most of the remainder used electronic devices for time measurement.
  - Different types of dose conversion factor (DCF) were used by operators for RDP and LLRD exposure pathways; with regard to RDP exposure,

however, most operators followed the values recommended by the International Commission on Radiological Protection (ICRP) [3].
- The approach to DCFs needs to be harmonized, especially in the case of doses arising from RDP.
- To have an accurate LLRD dose estimate, factors such as the particle size distribution of the inhaled dust, solubility factors and radionuclide mixture need to be considered.

2.3. URANIUM MINING AND PROCESSING STAGES AND TECHNIQUES

The life cycle of a uranium mining and processing operation is a complex process which can extend over decades. The life cycle stages include exploration, planning, construction and operation, decommissioning, handover and surveillance (see Fig. 2). The mining method and design parameters have a significant bearing on the occupational exposures, control measures and monitoring that will be necessary.

The design stage of the life cycle is a critical stage of the process in which the mining and processing method and the plant design is optimized. In addition,

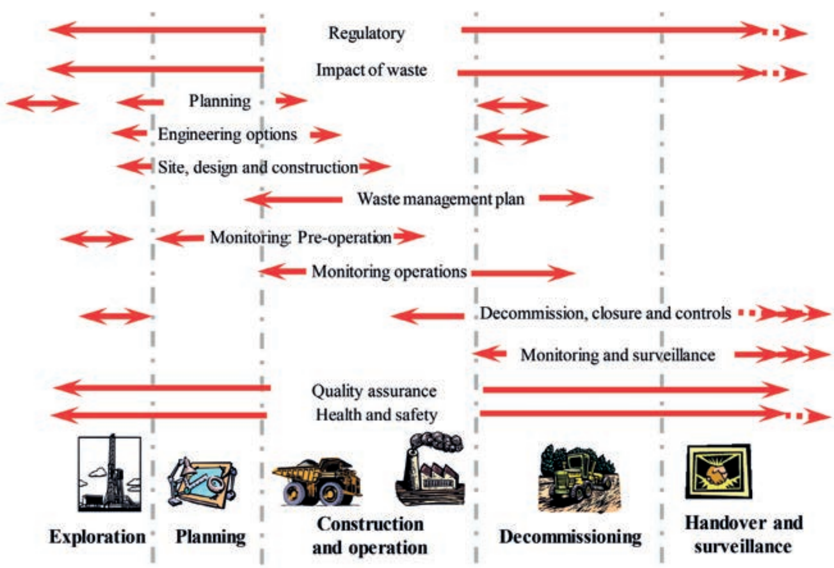

FIG. 2. Life cycle of a uranium mining operation.

the design stage needs to take account of conventional and radiation safety requirements, the methods of waste management and the decommissioning approach. There are a range of mining options available, including underground, surface and in situ mining. Processing also has a large range of options and some are integrally linked to the mining method, such as ISL. The mining and processing are generally closely linked and collectively can be called the operational phase.

Occupational exposure is associated with all of the above stages except for the design stage. Poor decisions in the design phase can have major negative impacts on occupational exposure, and these can be difficult to correct during the operational phase. The choice of mining and processing technique is heavily dependent on the ore grade and the characteristics of the ore body. Other important factors include topography, hydrogeology, geotechnical aspects, logistics and the perspectives of interested parties (e.g. the public, indigenous people, regulatory bodies). Therefore, awareness of the impact of the design approach on the control of occupational exposures is a critical aspect.

2.3.1. Exploration

Exploration is characterized by operations in the field to discover and assess the uranium resource. In most cases, the occupational exposures during exploration are expected to be low, due to the limited amount of radioactive material being handled (a few tonnes) and the usually low ore grades involved in most operations. However, there are exceptions where significantly higher grade ores and quantities are involved and, in some cases, where exploration involves trial mining including underground operations. In the past, the radiation protection aspects of exploration have often been ignored. The modern approach is to assess potential radiation hazards and doses through a prospective assessment and then implement an appropriate radiation protection programme.

2.3.2. Underground mines

Underground mines are designed to facilitate the safe and economic extraction of a mineral resource, and the mining approach will in large part be dictated by the geological constraints of the deposit. Uranium mines face the same safety challenges as mines for other minerals, with the additional constraint of dealing with the radiation associated with the ore. However, except in the case of high grade uranium deposits, it is usually typical mining constraints, such as ground conditions and the size and orientation of the ore zone, and not radiation issues, that determine the optimal mining method. Nevertheless, factors associated with controlling radiation need to be incorporated into the design of the mine to extract the uranium ore safely. The exception is mine ventilation, where far more control of ventilation conditions is likely to be necessary than in conventional underground mines to prevent the buildup of radon concentrations.

The basic radiation protection approach of time–distance–shielding serves as a useful way to highlight some of the key issues that need to be considered in the design and operation of underground uranium mines. With regard to 'time', the goal is, to the extent possible, to minimize the amount of time workers are in direct contact with the ore. For low grade ore deposits, this design constraint is not as serious as it is for high grade deposits, where it can eliminate or at least severely restrict the use of some mining methods. Other strategies such as the use of remote controlled equipment and shielding (e.g. clean waste rock on floors and shotcrete on walls) can also be incorporated into the design and operation of an underground mine to reduce gamma doses. The choice of mining method and the layout of the mine will also have an impact on the ventilation system, which is a critical component in controlling radiation and dust exposures. Finally, careful consideration needs to be given to the handling and movement of ore out of the mine to the processing plant to minimize the spread of surface contamination and the creation of airborne LLRD. The typical mining methods that have been successfully used include:

— Room and pillar open stope mining;
— Sublevel stoping;
— Cut and fill stoping;
— Undercut and fill mining;
— Block caving;
— Non-entry mining.

It is also important to note that there are variations within each of these broad mining methods (see Section 6).

2.3.3. Surface mines

Open cut mining involves extracting the ore directly via a surface cutting [4]:

> "This is most commonly used for ore bodies which are either on surface or relatively near surface. As depth to the deposit increases, the size and cost of the operation will increase as will the amount of waste rock generated. [Open cut] operations are characterised by a high ratio between waste rock and ore and hence have the largest surface impact."

This waste rock can then be a secondary source of radiological concern. Waste rock can be a direct source of dust and radon and may also be an indirect source of radionuclides in the form of releases to surface water and groundwater and subsequent distribution. However, waste rock can be useful during the decommissioning stage by providing a cost effective source of cover material, enabling the effective isolation of the higher grade tailings material from the general environment.

During operation, open cut mines are generally a cost effective method for extracting large volumes of lower grade ore [5]. This means that there is potential for bulk extraction techniques (e.g. milling, leaching and extraction, or alternative techniques such as heap leaching), which would be uneconomical for underground operations [5]. For deeper deposits, there may be a need for bulk excavation of barren or low grade covering rock, and this can increase costs and reduce the speed at which the operation can be started.

Upon closure, open cut operations can be the most expensive to remediate due to the large number of disturbed areas and greater waste rock and tailings volume. Remediation options are likely to be heavily dependent on site specific factors, such as climate and topography.

2.3.4. In situ leaching mines and processing

The ISL process for uranium mining and milling involves dissolving the uranium within the ore body itself by circulating groundwater fortified with oxygen and a chemical additive (slightly alkaline in the United States of America, acidic in Australia and Kazakhstan) into the formation through injection wells, dissolving the uranium in situ and extracting the pregnant uranium solution through recovery wells. The final steps in processing (separation via ion exchange or solvent extraction, precipitation, drying, packaging) may be partially or totally carried out at the in situ facility near to the well fields, or an intermediate product (loaded resin or slurry precipitates) may be shipped to another ISL facility or a conventional uranium mill for final processing. Some ISL operations in the United States of America are referred to as satellite plants in that they load uranium onto ion exchange resin at the well fields and/or produce intermediate products that are then shipped to another uranium recovery facility some distance away for further processing [6].

The absence of production scale acidic ISL in the United States of America is on account of the practical limitations of geochemistry and concern about a greater environmental impact relative to the alkaline leach method [6]. However, studies indicate that the environmental impact from alkaline leach processes (in the United States of America [6]) and acid leach processes (in Australia [7]) is low.

Section 6 details the typical ISL processes and the radiation protection and radiological monitoring programmes appropriate to adequately monitor and control doses to workers. Although many radiological characteristics are similar to those of conventional mills, conventional type tailings as such are not generated. However, liquid and solid by-product materials can be generated and impounded, which can result in a source of occupational exposure; and some specific monitoring considerations are necessary due to the manner in which radon gas is released in the process [8].

2.3.5. Heap leaching

Heap leaching is an alternative method of extracting uranium rich liquor from extracted ore. The mining of the ore is conventional (either underground or surface) and the ore is placed on surface pads where extractive liquors (acid or alkaline) are pumped over and through the material. This process can be repeated until liquor of sufficient uranium content is transferred for further processing to extract the uranium.

The highest occupational exposures will occur in individuals who spend a high proportion of their time near to the heap leaching pads. Gamma exposure will be the dominant exposure pathway; LLRD and RDP exposures are usually much lower.

2.3.6. Processing

The processing facility is designed to extract the uranium from the incoming stream (either ore or liquor), purify and concentrate it, and produce a solid final product for sale and transport. The general approach is to prepare the ore (by crushing, grinding, milling), extract the uranium (by acid or alkali leaching), separate out the uranium bearing liquid, and then concentrate, purify, precipitate, dry and pack the product. The final products include U_3O_8, UO_4, UO_2 and ammonium diuranate.

Occupational exposure during processing is best controlled by the design of the plant. The material is wet for most of the process, so gamma exposure usually dominates. However, during final product drying and packaging, the material is dry and inhalation of LLRD is likely to dominate the dose. The final product area generally has the highest occupational doses.

2.3.7. Non-conventional uranium extraction

Most of the world’s uranium production comes from facilities dedicated to uranium extraction. However, a small percentage is a by-product of mining for copper, gold, nickel, phosphate, silver, vanadium and rare earth elements and also from water treatment facilities. Occupational exposures from these facilities are heavily influenced by the specifics of the extraction processes and the quantity of the uranium being produced.

2.3.8. Tailings facilities

After the processing of uranium ore, the residual material or tailings still contain about 85% of the original radioactivity. This material has to be stored and isolated from the environment. The options available include the use of purpose built impoundments or natural features, or disposal back into the mine pit or underground workings.

Occupational exposures at tailings facilities are usually low due to the low grade of many uranium ores. The dominant exposure pathway is generally gamma exposure, although both RDP and LLRD exposures can become significant in specific circumstances involving high grade ore tailings.

2.3.9. Transport

The transport of material containing uranium by road can result in occupational radiation exposures. The material can include both low and high grade ores, the high grade final product and some types of waste and contaminated plant items. Transport can be on-site or involve the transfer of material between sites on public roads. Transport also occurs once the final uranium product is shipped to the customer. On-site transport of uranium material is generally covered in the site radiation protection programme. The transport of radioactive material on public roads is subject to specific national and international transport regulations. During transport the dominant exposure pathway is usually gamma exposure. The other pathways are normally only of concern during accident or emergency situations.

2.3.10. Decommissioning

The final stage of the uranium mine life cycle is decommissioning, which involves the demolition or removal of plant structures, the rehabilitation of tailings and waste rock structures, and other longer term activities to process wastes arising from the decommissioned facility (mainly contaminated surface water and groundwater). Occupational exposures from the three main exposure pathways will occur and a radiation protection programme is needed. The highest exposures will occur around the contaminated plant and land, during dusty operations, during entry into plant vessels, and during the decontamination, cutting and grinding of contaminated objects.

3. GENERAL RADIATION PROTECTION CONSIDERATIONS IN URANIUM MINING AND PROCESSING

3.1. INTERNATIONAL SAFETY STANDARDS

IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [9], published in 2006, sets out the fundamental safety objective and the principles of protecting people and the environment from harmful effects of ionizing radiation. IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [10], published in 2014, sets out the requirements to meet the Fundamental Safety Principles [9].

The three general principles of radiation protection, which concern justification, optimization of protection and application of dose limits, are expressed in Safety Principles 4–6 and 10 of the Fundamental Safety Principles [9]. Occupational exposure to ionizing radiation can arise from exposure to raw materials containing elevated concentrations of radionuclides of natural origin, such as uranium ores. Section 2 provided an overview of uranium mining and processing practices which can result in occupational exposures. This section reviews the framework for occupational radiation protection that is established to oversee uranium mining and processing activities. In addition, this section covers the responsibilities of governments, regulatory bodies, operators and workers, the basic radiation protection principles, and the graded approach to regulation that fulfils the requirements of GSR Part 3 [10].

3.2. SCOPE OF REGULATION

GSR Part 3 [10] distinguishes between three different types of exposure situation: planned, emergency and existing exposure situations. Exposure due to natural sources and naturally occurring radioactive material (NORM) (which includes uranium) is considered to be an existing exposure situation and is subject to the requirements in section 5 of GSR Part 3 [10]. However, para. 3.1(f) of GSR Part 3 [10] states that the requirements for planned exposure apply to the practice of “The mining and processing of raw materials that involve exposure due to radioactive material”. Ores containing uranium are raw materials with radionuclides of the uranium decay chain, and the mining and processing of them to produce uranium products result in occupational exposure to ionizing radiation [10].

Paragraph 3.4(a) of GSR Part 3 [10] states (footnote omitted):

> “...the relevant requirements in Section 3 for planned exposure situations apply to:
>
> (a) Exposure due to material in any practice specified in para. 3.1 where the activity concentration in the material of any radionuclide in the uranium decay chain or the thorium decay chain is greater than 1 Bq/g or the activity concentration of ^{40}K is greater than 10 Bq/g”.

The mining and processing of uranium ores involves materials with radionuclide specific activity concentrations of up to several thousand Bq/g. Producing uranium concentrate is therefore a planned exposure situation and is to be conducted in accordance with the relevant requirements of GSR Part 3 [10]. In some scenarios, for example operations where uranium is a contaminant or a secondary mineral, the radiological hazards may be significantly reduced and the arrangements for control might not be clear. The concept of a graded approach is therefore important in defining the scope of regulatory control. Paragraph 3.159(b) of IAEA Safety Standards Series No. GSG-7, Occupational Radiation Protection [11] states:

> “If, in every process material, the activity concentrations of all radionuclides in the ^{238}U decay series and the ^{232}Th decay series are 1 Bq/g or less and the activity concentration of ^{40}K is 10 Bq/g or less, the material is not regarded as naturally occurring radioactive material, the industrial activity is not regarded as a practice and the requirements for existing exposure situations apply.”

3.3. RESPONSIBILITIES

Requirement 1 of GSR Part 3 [10] states:

> **“Parties with responsibilities for protection and safety shall ensure that the principles of radiation protection are applied for all exposure situations.”**

In meeting Requirement 1 of GSR Part 3 [10], four groups are designated responsibilities for protection and safety and ensuring that the principles of radiation protection are applied.

3.3.1. The government

The responsibilities of the government with regard to protection and safety are set out in paras 2.13–2.28 of GSR Part 3 [10] and include:

(a) Establishing an effective legal and regulatory framework for protection and safety in all exposure situations;
(b) Establishing legislation that meets specified requirements;
(c) Establishing an independent regulatory body with the necessary legal authority, competence and resources;
(d) Establishing requirements for education and training in protection and safety;
(e) Ensuring that arrangements are in place for the provision of technical services, education and training services.

3.3.2. The regulatory body

The broad responsibilities of the regulatory body with regard to protection and safety are set out in paras 2.29–2.38 of GSR Part 3 [10] and include:

(a) Establishing requirements for the application of the principles of radiation protection;
(b) Establishing a regulatory system that meets specified requirements;
(c) Ensuring the application of the requirements for education and training in protection and safety;
(d) Ensuring that mechanisms are put in place for the dissemination of lessons from incidents and accidents;
(e) Setting acceptance and performance criteria for sources and equipment with implications for protection and safety;
(f) Making provision for the establishment and maintenance of records.

The responsibilities of the regulatory body specific to occupational exposure in planned exposure situations are laid out in paras 3.69–3.73 of GSR Part 3 [10]. The regulatory body is responsible for establishing and enforcing requirements for ensuring that protection and safety is optimized, that the applicable dose limits are complied with, and that the operator monitors and records occupational exposures.

3.3.3. Employers, registrants and licensees (management)

Requirement 4 of GSR Part 3 [10] states:

> **"The person or organization responsible for facilities and activities that give rise to radiation risks shall have the prime responsibility for protection and safety Other parties shall have specified responsibilities for protection and safety."**

In planned exposure situations, employers, registrants and licensees (also referred to as management) are responsible for ensuring that protection and safety is optimized, that applicable dose limits are complied with, and that appropriate radiation protection programmes are established and implemented.

3.3.4. Workers

Requirement 22 of GSR Part 3 [10] states:

> **"Workers shall fulfil their obligations and carry out their duties for protection and safety."**

This requirement reflects that workers can by their own actions contribute to the protection and safety of themselves and others at work. The obligations of workers in this regard are listed in para. 3.83 of GSR Part 3 [10] and relate to rules and procedures, the proper use of monitoring equipment and personal protective equipment (PPE), cooperation in health surveillance and dose assessment programmes, and acceptance of instruction and training. Workers are also required to provide relevant information to management and to act in a responsible manner with regard to protection and safety.

3.4. GRADED APPROACH TO REGULATION

Requirement 6 of GSR Part 3 [10] states:

> **"The application of the requirements of these Standards in planned exposure situations shall be commensurate with the characteristics of the practice or the source within a practice, and with the likelihood and magnitude of exposures."**

The graded approach to regulation and the implementation of radiation protection programmes optimizes the use of available resources. The graded approach takes account of the scale and complexity of installations and factors such as the radioactivity of the materials handled in the operation to develop and implement a radiation protection programme commensurate with the nature and extent of the radiation hazards and the resulting annual occupational exposure [11]. Occupational radiation hazards need to be assessed throughout the life cycle of a facility and as appropriate radiation protection programmes are implemented [11]. Site and activity specific hazard assessments are used to determine the necessary scope and depth of occupational radiation protection programmes in uranium mining and processing facilities. Uranium mining and processing facilities are usually regulated in terms of a site specific licence issued by the appropriate regulatory body.

An overview of the graded approach to the regulation of NORM is provided in Fig. 3 (note that the indicated dose criteria are annual occupational doses). This flow chart can also be used for those situations where the requirement for regulatory control is not clear, to assist in determining the appropriate regulatory approach.

An additional planned exposure situation relevant to uranium operations would be the remediation of a legacy uranium mining and processing site. Paragraph 5.26 of GSR Part 3 [10] states:

> "Employers shall ensure that the exposure of workers undertaking remedial actions is controlled in accordance with the relevant requirements on occupational exposure in planned exposure situations as established in Section 3."

Additional guidance on the graded approach to the regulation of minerals and raw materials is provided in GSG-7 [11] and Ref. [12].

3.5. SPECIFIC ASPECTS OF RADIONUCLIDES IN THE URANIUM SERIES

One of the most common mistakes made in the design and implementation of radiation protection programmes is an inadequate understanding of the importance and behaviour of all the radionuclides in the material at all stages of the uranium mining and processing life cycle. Uranium (^{238}U) is the dominant parent radionuclide in uranium bearing material, and other radionuclides of the ^{238}U decay series can therefore become very significant in terms of occupational radiation protection. In addition, some of the actinide (^{235}U) decay series can

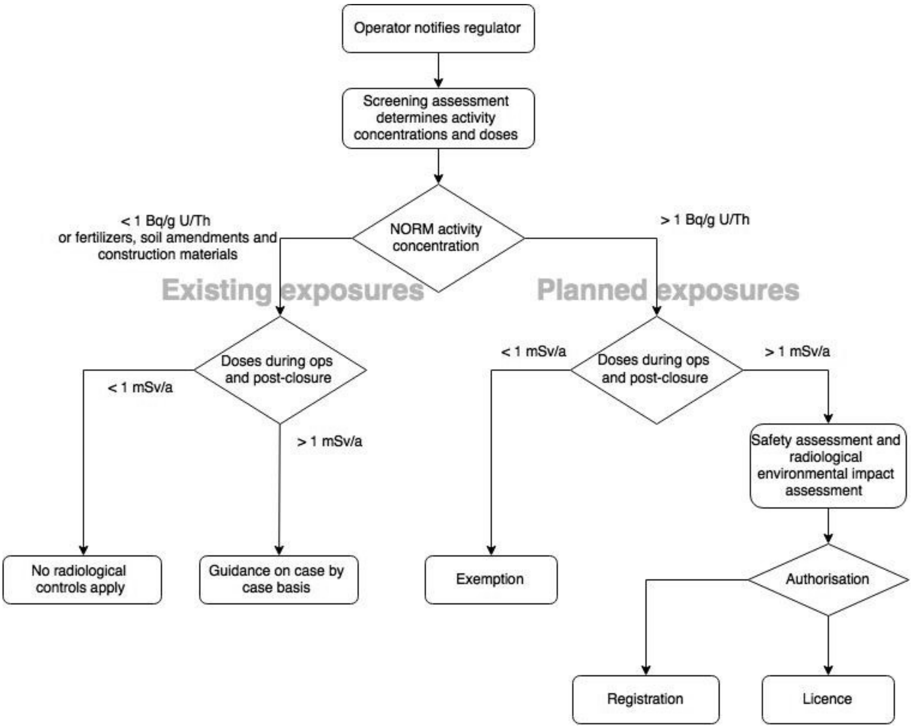

FIG. 3. Graded approach to regulation of NORM (including uranium), as laid out in GSR Part 3 [10].

become significant; and if the ore body also contains thorium, then the thorium (^{232}Th) decay series might need to be considered. In these situations, different radionuclides in any of these decay series have different chemical and physical properties and hence can be present at different phases of mining and processing. Understanding the behaviour of all the radionuclides present is therefore critical in determining the potential radiation exposure pathways during mining and processing.

When considering the importance of a radionuclide, there are many factors to be taken into account. The half-life of the individual radionuclide is critical. If the half-life is less than about a month, it can generally be considered to be in equilibrium with its parent radionuclides and is not considered separately. The DCFs for these short lived radionuclides are also low and hence are not as significant in dose calculations. There are, however, special cases, such as RDP and other short lived radionuclides that may have unique chemical or physical characteristics (e.g. ^{210}Bi, ^{231}Pa) that result in their accumulation in greater concentrations than other radionuclides at specific stages during uranium processing.

3.5.1. Uranium series

The critical radionuclides for radiation protection in the uranium series are ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb and ^{210}Po, which represent the longer lived radionuclides. Radon (^{222}Rn) and its progeny (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) are also of high importance due to their gaseous nature and ability to enter the working atmosphere and contribute directly to occupational exposure. From the specific perspective of gamma exposure, the critical radionuclide is ^{214}Bi (due to the strong 609 keV peak). For the final uranium product, however, the contribution of the ^{234}Th gamma peak is of importance.

In most ore bodies, the decay series radionuclides can be considered to be in equilibrium. There may be some disequilibrium between ^{238}U and ^{234}U due to changes in solubility caused by alpha recoil, and there is potential for disequilibrium after ^{226}Ra due to radium's solubility in neutral pH groundwater. This is particularly important for exploration, as the gamma dose rate is often used as a surrogate for uranium concentration and any radium disequilibrium will cause errors in this assay approach. During processing, disequilibrium will start to occur once chemical separation is initiated. Typically, the material is in approximate equilibrium until uranium separation occurs. After this point, there are two primary streams: the tailings and the uranium rich liquor. The tailings here can generally be assumed to be in equilibrium from ^{230}Th down and with the uranium isotopes significantly reduced owing to the extraction efficiency of the process. Conversely, the uranium rich liquor is effectively made up solely of uranium radionuclides (^{238}U, ^{234}U, ^{235}U). Another important consideration is changes in the uranium final product over time due to the ingrowth of the short lived progeny and, in particular, ^{234}Th. Fresh uranium product has very little ^{234}Th and hence has a small gamma signature. However, the gamma dose rate increases with time owing to gamma emissions from ^{234}Th, which can impact the exposure of workers near the uranium product storage areas and during transport.

It is also important to understand where the various radionuclides are present or concentrated, particularly during the processing stage. The behaviour of uranium is generally well known because it is comparatively easy to measure and is the primary focus of mine and processing plant operations. The behaviour of the other radionuclides is often either unknown or poorly understood and may have radiological impacts. The most common impact is due to the gaseous nature of radon and its ability to escape the primary material and potentially concentrate in work areas (particularly within mine workings and confined spaces). Another important radionuclide is radium because of the combination of its solubility in neutral pH and its strong gamma signature (from the ^{214}Bi decay product). Often the strongest gamma sources arising from uranium mining and processing are associated with process or mine water lines where radium has preferentially deposited as a scale.

In special cases, ^{210}Pb and ^{210}Po can become important for occupational exposure. Both of these radionuclides can be preferentially volatilized during the high temperature processing stages. Although this is not generally significant in conventional uranium processing plants, it can become a dominant exposure pathway in non-conventional processing plants.

The longest lived radionuclide associated with the tailings material arising from uranium processing is ^{230}Th. It has the potential to concentrate preferentially in crusts forming on tailings structures or to be the primary radionuclide in evaporation residues for wastewater systems. During tailings operation and decommissioning, ^{230}Th can be an unrecognized contributor to worker dose and might need appropriate monitoring and control mechanisms.

3.5.2. Actinium series

Actinium (^{235}U) generally exists in a fixed ratio to ^{238}U (0.7% by weight and 4% by activity). Because of its lower relative activity, its contribution to occupational exposure in mining and processing is generally far smaller than that from the ^{238}U series. The small exposure component from the actinium series is usually insignificant and therefore does not form part of the monitoring and dose assessment programmes.

The radionuclide from the actinium series which might be significant is ^{227}Ac because of its high solubility in near neutral liquors. This high solubility means it can become concentrated in some process streams and items (e.g. resins), and this might need to be considered in operations with specific liquors with near neutral pH.

3.5.3. Thorium series

When mining and processing ore bodies contain both uranium and thorium decay chains, the thorium series needs to be considered for radiation protection purposes. The most important radionuclides in the thorium decay series are ^{232}Th, ^{228}Ra and ^{228}Th, as well as ^{220}Rn (thoron) and its progeny (^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po (60%), ^{208}Tl (40%)). One particularly important aspect of the thorium decay series is the extremely high energy gamma emission (2.6 MeV) which arises from ^{208}Tl. This high energy requires that shielding from thorium ores be thicker for the same degree of dose reduction compared to uranium ores of the same grades.

4. GENERAL METHODOLOGY FOR CONTROL

4.1. OCCUPATIONAL HEALTH AND SAFETY CONSIDERATIONS

Radiation protection is one part of the overall management system for occupational health and safety in uranium mining. There are other occupational hazards in mining and processing operations that can present a much greater and more immediate threat than exposure to low levels of radiation. These include physical injury from accidents involving heavy vehicles, working at heights, explosives, and powered plant machinery and tools. Both acute and chronic health effects from exposure to hazardous materials, including fugitive emissions of chemical reagents, diesel particulates and process dusts, also need to be considered. Good management of the health and safety of workers, including measures to prevent or reduce the risk of accidents and exposures, is a fundamental obligation for employers and is enforced through legal requirements.

The International Labour Organization promotes national legal requirements for occupational health and safety in mining through the Safety and Health in Mines Convention [13], which has been ratified by many States and supported by the Safety and Health in Mines Recommendations [14]. Together, they offer a framework and guidance for international consistency in the development of national legislation and codes of practice for occupational health and safety in mining.

Requirements for radiation protection apply concurrently with the general requirements for occupational health and safety to ensure that safety is treated holistically. The radiation protection principle of optimization needs to be observed, considering all relevant factors. Non-radiation occupational health and safety issues can also affect the outcome of an optimization analysis.

4.1.1. Approach to health and safety: Implementation of a management system

The health and safety of workers needs to be a primary goal for employers in the mining industry. Safety generally refers to hazards that have the potential for immediate impact, such as vehicle accidents, rock falls, chemical burns, and injury from powered plant machinery and tools. Health refers to the hazards that can have long term impacts, such as noise, vibration, ergonomics and exposure to various dusts. These health components are sometimes referred to as occupational/industrial hygiene. Health also includes general well being relating to fitness for work and physiological considerations, such as fatigue and hydration when working in hot environments. The measures implemented to ensure safety might therefore be different from those directed at preserving health, but synergies can be exploited wherever possible.

Employers need to ensure that a management system for the occupational health and safety of workers is developed and implemented, and that it adheres to applicable legislation and regulations. Compliance with IAEA safety standards requires that the system for health and safety be an integral part of the management system, and it needs to include provision for training of the workforce in the implementation of the management system and for a periodical refresher programme [15, 16]. It also needs to provide for performance evaluation and review as part of a process of continual improvement.

The system needs to include documentation that sets out the following:

(a) Principles, policies and objectives to be adopted for health and safety;
(b) Identification of responsibilities and accountabilities;
(c) Criteria for competence and training in health and safety;
(d) Processes to be adopted for risk management, hazard identification and implementation of health and safety controls;
(e) Provisions for dealing with emergencies and accidents;
(f) Processes for performance monitoring and review.

A crucial part of the review and development process is the incorporation into the system of measures that address experience in the workplace, including any corrective actions from incidents and data from health or hygiene monitoring programmes. For quality management purposes and to ensure the effectiveness of the system, independent audits are needed on a regular basis.

In some jurisdictions, or by agreement with the employer, health and safety representatives from the workforce may be involved in the planning and development of the management system and the review of its performance. An important aspect for the success of the system is to provide for input from workers who are directly engaged in the work activities that are subject to occupational health and safety requirements, including, as appropriate, protection for whistle blowers and favourable consideration of the prompt reporting and admission of errors.

4.1.2. Risk management, hazard analysis and control

An essential component of risk management is risk identification. Hazards and risks to the health and safety of workers need to be identified and assessed prior to a work practice being undertaken; and they need to be continually reviewed thereafter, especially when changes are introduced to work procedures. All potential risk scenarios and fault conditions need to be evaluated and ranked by likelihood and severity to design appropriate preventative and protection measures, which in turn need to be applied in priority using the hierarchy of control.

4.1.3. Optimizing protection from radiation and other hazards

The principle of optimization of protection is more generally applicable than its conventional definition might imply when multiple hazards present. It is important that no single hazard receives undue attention to the detriment of the management of others. Preventative and protection measures need to be developed based on the assessment of the likelihood and severity of all potentially hazardous events and exposures.

4.1.4. Safety culture

Culture refers to factors that influence overall attitudes and behaviours in organizations. Leadership and management styles, institutional mission and goals, and the organization of work processes are aspects of culture. Culture provides the background against which day to day tasks are performed and has been shown to be strongly associated with worker perceptions of job characteristics and organizational functioning. A safety culture should be promoted and maintained at all levels within the organization. Such factors include:

(a) Openly supporting safety culture through the supply of resources;
(b) Engaging worker participation in safety planning;
(c) Having written safety guidelines and policies;
(d) Making appropriate safety devices and PPE available;
(e) Influencing workgroup norms on acceptable safety practices;
(f) Introducing workers to a safety culture when they first start.

These factors serve to communicate the organization's commitment to worker safety. A safety culture permeates all aspects of the work environment and is reflected in a level of awareness and accountability for safety on the part of every individual in an organization. The need for an effective safety culture is not new to mining, and specifically the uranium mining and processing industry has a long history of lessons from past events, and new knowledge and experience being added, both at the national and international level. Under modern health and safety legislation, there is a high expectation that operators develop and maintain a positive safety culture through all stages of the facility's life. Achieving this goal is underpinned by strong regulatory controls and the enforcement of health and safety in the workplace. As stated in para. 2.51 of GSR Part 3 [7]:

“The principal parties shall promote and maintain safety culture by:

(a) Promoting individual and collective commitment to protection and safety at all levels of the organization;
(b) Ensuring a common understanding of the key aspects of safety culture within the organization;
(c) Providing the means by which the organization supports individuals and teams in carrying out their tasks safely and successfully, with account taken of the interactions between individuals, technology and the organization;
(d) Encouraging the participation of workers and their representatives and other relevant persons in the development and implementation of policies, rules and procedures dealing with protection and safety;
(e) Ensuring accountability of the organization and of individuals at all levels for protection and safety;
(f) Encouraging open communication with regard to protection and safety within the organization and with relevant parties, as appropriate;
(g) Encouraging a questioning and learning attitude, and discouraging complacency, with regard to protection and safety;
(h) Providing means by which the organization continually seeks to develop and strengthen its safety culture.”

4.1.5. Emergency and non-conformance management

The occupational health and safety management system needs to include the provision for responding to emergencies and for dealing with less urgent incidents and non-conformances that involve a risk to health and safety. During the development of emergency response plans, all foreseeable accidents and incidents need to be assessed and countermeasures put in place that are commensurate with the estimated degree of risk.

The presence of radioactive materials in uranium mines and mills introduces some additional considerations to be considered in emergency response planning. Most foreseeable incidents will be like those that may arise in the mining or milling of non-radioactive minerals. In metalliferous and other non-coal mines, fatal accidents are often a result of fires, explosions and rock falls. Non-fatal injuries are more frequent and are comparable to those from other heavy industries (e.g. interaction with machinery and vehicles, falls, burns, exposure to corrosive chemicals). Emergency response planning needs to provide for prompt first aid and timely medical attention for work injuries (see Ref. [17] for guidance on good practice for emergency management in mining).

4.2. HIERARCHY OF CONTROL

The decreasing trend in occupational radiation exposures in the mining and processing of uranium is attributable to improvements in control practices. Good control practices are essential for optimizing doses, and the focus on control is essential in any modern uranium operation. Controls have to be suitable to the risk and will vary according to mining methodology, ore grade, plant age and other site specific factors. Consideration of the range of control mechanisms needs to be aligned with the respective exposure pathways. It is vital to consider other elements, such as worker health and safety, economics, societal factors, environmental effects and design constraints, when selecting appropriate controls.

The hierarchy of control forms the phased approach to instituting controls, with an emphasis on controls that reduce risk without active human participation. By instituting controls in this order, the effectiveness is maximized and the risk of control failure is minimized:

- Elimination;
- Substitution;
- Engineering;
- Administration;
- Behaviour;
- Use of PPE.

The hierarchy of control can be applied to all mining and industrial practices for protecting the health and safety of workers. Not all the hierarchy can be practically applied in all cases, but the general approach of relying on hazard elimination and engineered controls rather than human intervention provides a stronger basis for protection.

4.2.1. Elimination

The most effective way to control any risk is through the elimination of the source. In uranium mining and milling operations, the total elimination of radiation is not possible. However, exposure pathways can be eliminated by using techniques such as isolating material from personnel (i.e. blocking off mined out underground stopes so they have no radiological impact on operations). Removing as many of the exposure pathways as possible is the primary radiological concern during the design stage of an operation. Simple considerations such as placing buildings away from ore stockpiles or process operations and using barren rock areas for workshops and offices can minimize exposure.

4.2.2. Substitution

As radiation is a physical characteristic of uranium and its progeny, it is not possible to substitute the source material to control the risk of exposure. Substitution can still be used to minimize radiation exposure in an operation through control of the exposure pathways. For example, dry process methods can be substituted with wet ones, and processes that can result in the accumulation of radioactive material, specifically gamma emitters, can be substituted with ones that do not.

4.2.3. Engineering

Engineered controls are generally the highest level that can be applied for the control of radiation in uranium mines and mills. The implementation of engineered controls needs to be incorporated into the initial design of an operation, as retrofitting this level of control is often difficult and time consuming. A range of engineering solutions can be applied that meet the radiation protection principles, specifically distance and shielding. These include the use of shotcrete in underground mining operations and local or area ventilation for the control of RDP and LLRD concentrations. Engineered controls are critical to minimize exposure in an operational situation and appropriate review and maintenance need to be put in place to ensure their effectiveness.

4.2.4. Administration

Administrative controls rely on a comprehensive health and safety management system being in place. This level of control can be bypassed by personnel through choice and it works best when the safety culture of an organization is sufficiently strong and the controls are enforced with adequate supervision. Minimizing exposure can be achieved with effective administrative controls such as safe work procedures, implementation of exposure limits, restriction of access to high exposure areas, task rotation, warning signage, training and personal hygiene arrangements.

4.2.5. Behaviour

The behaviour of individuals as well as the overall safety culture of the organization can have a significant impact on occupational exposure in uranium operations. Organizations with employees and leaders who demonstrate and reinforce good behaviours coupled with a strong safety culture are more likely to adhere to their administrative controls and use PPE when necessary. Organizations with good behaviours are more likely to have individuals that recognize potential exposure situations and implement controls to reduce exposure.

4.2.6. Personal protective equipment

PPE can be very effective in minimizing exposure where the application of higher level controls cannot be achieved in reasonable time frames. Its selection and use needs to adhere to the relevant regulatory requirements. For radiation protection in uranium mining and milling, PPE in the form of respiratory protection is generally used as a protective measure against RDP and LLRD. PPE is the lowest control on the hierarchy of control and can cause discomfort and interference with other safety equipment and work efficiency.

4.3. DOSE MINIMIZATION

Time, distance and shielding can be applied through the hierarchy of control. Ensuring that the controls are fit for purpose is critical for optimizing radiation protection in uranium operations. There is no standardized approach to radiation protection and this is important in uranium operations due to the bulk nature of the material being handled. Working with the unique aspects of an ore body together with handling large quantities of material means that controls which work well in one operation might not be appropriate for another.

Controls often target specific pathways, although the overall protection approach of time, distance and shielding still applies. In uranium mining the source is generally dispersed and can cover entire work areas (such as in an underground or open cut mine), so these principles have different applications than in other fields of radiation protection.

4.3.1. Time

The time spent in areas with higher dose rates from any pathway generally needs to be minimized, which can be achieved through a variety of administrative controls. The high dose rate areas in mining can change over time, and the nature of the work tasks can cause difficulties in minimizing exposure times whilst allowing mining to continue. Implementing systems that identify and restrict work areas with high dose rates while controls can be put in place is critical to controlling these exposures. A strong knowledge of the dose rates from the various pathways can assist with planning and operations to reduce worker occupancy time in the higher dose rate areas. When individuals have intimate knowledge of the dose rates in their area (i.e. by using direct reading instrumentation), they can consciously reduce their individual dose and leave areas with high dose rates.

It is good practice for meal and rest breaks and safety meetings to take place in areas of barren rock with clean air feeds. Non-working areas with high gamma dose rates or high RDP or LLRD concentrations can be designated as restricted areas.

4.3.2. Distance

In mining and processing environments, the use of distance for dose minimization can be constrained owing to the nature of the facilities and the ore body. Simple practices such as maximizing the working distance from the ore face and positioning high occupancy areas (e.g. offices) far away from work areas and stockpiles can help to minimize exposures. Processing plants need to be designed to maximize the separation of personnel and processing materials, with fixed working positions located in low dose areas.

4.3.3. Shielding

Shielding can easily be incorporated into the engineering design and is normally integrated with equipment and other systems of work. Heavy mining equipment made of steel can often provide a significant shield against gamma radiation. The use of enclosed cabins with a filtered air supply can significantly reduce the ingress of RDP and LLRD. In underground operations, shotcrete is commonly used for ground support, but it also can be used to provide shielding against gamma radiation. The ventilation systems of underground operations are also a form of shielding to control RDP by isolating personnel from areas with high radon progeny concentrations. During processing, shielding is present as a part of the pipes, tanks and vessels used for the handling of the process materials. For plants processing higher grade ores or where space is constrained, additional shielding might be necessary.

4.4. EXPOSURE PATHWAYS

4.4.1. External exposure to gamma radiation

Gamma radiation is an electromagnetic form of radiation capable of penetrating steel and concrete. The exposure of the workforce to direct external gamma radiation is often the most significant pathway in uranium mining. Shielding against gamma sources and using remote handling equipment is the main mitigation strategy in the very high grade uranium mines such as Cigar Lake and McArthur River, in Canada. A key aspect of minimizing the gamma exposure in the workplace is a good knowledge of the gamma dose rates in all work areas and management of these accordingly. Simple changes in work practices can be very effective in reducing gamma doses.

Further details on gamma radiation and its control are provided in Appendix II.

4.4.2. Inhalation of radon and radon progeny

Radon is emitted from uranium or thorium bearing ores into the working environment of operational mines and mills. In uranium mining and milling, radon and radon progeny can be controlled through methods following the hierarchy of control, including:

(a) Adequate and effective ventilation systems;
(b) Management of the source of the radiation;
(c) Management of water sources and process liquors containing dissolved radium and radon;
(d) Working in an enclosed and filtered operating environment (e.g. ventilated driver's cab or static plant control room);
(e) Administrative controls establishing action levels for airborne contaminants.

Further details on radon and radon progeny and their control are provided in Appendix III.

4.4.3. Inhalation of long lived radionuclide dust

Paragraph 9.21 of GSG-7 [11] states:

> "To ensure that adequate methods for the control of dust are in place in underground mines and in buildings where the dry processing of radioactive minerals is carried out, programmes for the air sampling and control of airborne dust should be formalized. The following measures should be taken:
>
> (a) The generation of dust in operations should be reduced to the extent practicable by the use of appropriate techniques for mining and mineral processing, such as the use of proper blasting patterns and timing, the use of water and other means of suppressing dust, and the use of appropriate equipment.

(b) Where dust is generated, it should be suppressed at source. Where necessary and practicable, the source should be enclosed under negative air pressure. Air might have to be filtered before being discharged to the environment.
(c) Dust that has not been suppressed at source may be diluted to acceptable levels by means of frequent changes of air in the working area. Again, the exhaust air might have to be filtered before being discharged to the environment.
(d) Care should be taken to avoid the resuspension of dust as a result of high air velocities.
(e) Where methods of dust control do not achieve acceptable air quality in working areas, enclosed operating booths with filtered air supplies should be provided for the workers."

Further information is supplied in Appendix IV.

4.4.4. Contamination control

The primary method of control is engineered controls to prevent significant quantities of material escaping during the process. This is supported by good housekeeping and working practices and a contamination monitoring programme. GSG-7 [11] states:

> "9.42. To prevent inadvertent intakes by workers, the employer should provide washing facilities for all workers that are convenient to the place of work, and should allow sufficient time to each worker for the use of the washing facilities before rest breaks and meal breaks, and at the end of the shift. ...
>
> "9.43. No person should be permitted to eat, drink, chew gum or tobacco, smoke, take snuff or apply cosmetics in working areas in which radioactive substances could be ingested."

Appendix V presents methods for assessing contamination, conducting surface contamination surveys and establishing control limits for contamination.

4.4.5. Ingestion, wound contamination and absorption

Appendix VI describes methods for performing uranium bioassays to verify the appropriateness of the air sampling programme and to assess potential intakes by workers, and presents methods for the calculation of doses from air sampling and bioassay results.

5. MONITORING AND DOSE ASSESSMENT

As with all occupational exposure situations, the only reliable way to assess the effective dose received by a worker exposed to ionizing radiation is through a properly developed radiation monitoring programme in the workplace. This section provides a summary of the principal reasons for conducting monitoring and a description of the techniques to monitor and subsequently assess doses to workers for each exposure pathway.

5.1. OBJECTIVES OF A MONITORING PROGRAMME

Although taking measurements is a major part of any monitoring programme, it also involves interpretation and assessment. Paragraph 3.98 of GSG-7 [11] states:

> "A programme of monitoring may serve various purposes, depending on the nature and extent of the practice. These purposes can include the following:
>
> (a) Assessing the exposure of workers and demonstrating compliance with regulatory requirements.
> (b) Confirming the effectiveness of working practices (e.g. the adequacy of supervision and training) and engineering standards.
> (c) Determining the radiological conditions in the workplace, whether these are under adequate control and whether operational changes have improved or worsened the situation.
> (d) Evaluating and improving operating procedures from a review of the collected monitoring data for individuals and groups. Such data may be used to identify both good and bad features of operating procedures and design characteristics, and thereby contribute to the development of safer working practices in relation to radiation.
> (e) Providing information that can be used to enable workers to understand how, when and where they are exposed, and to motivate them to take steps to reduce their exposure.

(f) Providing information for the evaluation of doses in the event of accidental exposures.

“Furthermore, monitoring data may be used for the purpose of risk–benefit analysis and to supplement medical records.”

IAEA Safety Standards Series No. RS-G-1.8, Environmental and Source Monitoring for Purposes of Radiation Protection [18], states:

“4.1. The general objectives of any monitoring programme for the protection of the public and the environment...are...:

(a) To verify compliance with authorized discharge limits and any other regulatory requirements concerning the impact on the public and the environment due to the normal operation of a practice or a source within a practice;
(b) To provide information and data for dose assessment purposes and to assess the exposure or potential exposure of critical groups and populations due to the presence of radioactive materials or radiation fields in the environment from the normal operation of a practice or a source within a practice and from accidents or past activities;
(c) To check the conditions of operation and the adequacy of controls on discharges from the source and to provide a warning of unusual or unforeseen conditions and, where appropriate, to trigger a special environmental monitoring programme.

“4.2. Some subsidiary objectives, which should usually be fulfilled by a monitoring programme, are...:

(a) To provide information for the public;
(b) To maintain a continuing record of the impacts of an installation or a practice on environmental radionuclide levels;
(c) To check the predictions of environmental models so as to modify them as appropriate in order to reduce uncertainties in the dose assessment.”

5.2. RESPONSIBILITY FOR THE MONITORING PROGRAMME

The management is responsible for ensuring that protection and safety is optimized, that applicable dose limits are complied with, and that appropriate radiation protection programmes are established and implemented. All personnel managing or working in any capacity at the mine are responsible in some form for radiation protection. All employees and contractors (workers) are expected to comply with all arrangements for radiation protection relevant to their role.

The employer's responsibility is to ensure the safety, health and welfare of workers in all circumstances of the employment. The employer is expected, as far as practicable, to provide and maintain a working environment in which workers are not exposed to hazards. This duty of care includes the provision of:

(a) A safe place of work;
(b) Safe systems of work;
(c) Information, instruction and training;
(d) Safe plant and equipment;
(e) Adequate PPE;
(f) Competent staff to manage and supervise the business.

The workers' responsibility is to ensure their own health and safety and to ensure that their actions do not adversely affect the safety and health of others.

5.3. TYPES OF MONITORING PROGRAMME

A monitoring programme is one component of the radiation protection programme, and para. 3.101 of GSG-7 [11] divides it into four primary types:

— Routine monitoring;
— Special monitoring;
— Confirmatory monitoring;
— Task related monitoring for a specific operation.

In addition to exposure pathways relevant to those locations, GSG-7 [11] states:

> "3.102. Each of these types of monitoring programme can be subdivided on the basis of the location of the monitoring....
>
> "3.103. Individual monitoring can be further subdivided into monitoring for external exposure, for internal exposure and for skin contamination. Workplace monitoring can be further subdivided into monitoring for external radiation, for air contamination and for surface contamination. The details of the programmes will be influenced by factors such as the type and energy of the radiation and the radionuclides involved....

“3.104. The programme design should reflect the objectives of the monitoring programme, and these should be clearly specified and recorded. ...A distinction should be made in the programme between monitoring for the purpose of controlling operations and monitoring for the formal assessment of exposure to meet regulatory requirements.

“3.105. The equipment to be used in the monitoring programme should be suitable for the types of radiation and the forms of radioactive material encountered in the workplace. The equipment should be calibrated to meet appropriate standards. ...

“3.106. The design and implementation of a monitoring programme should conform to the quality assurance requirements embodied in the management system to ensure that procedures are established and followed correctly and to ensure that records are promptly compiled and correctly maintained. The design of the monitoring programme should indicate the records that should be kept, and the associated procedures for keeping and discarding records. All of these aspects should be reviewed regularly, at predetermined intervals or following any major change in operations of the installation or in regulatory requirements. The purpose of such reviews should be to ensure that the monitoring effort (type, frequency and extent) is appropriately employed. The information should also be used to identify both good and bad features of operating procedures, and both good and bad design characteristics.”

5.3.1. Demonstration of compliance with regulatory and corporate requirements

There will be regulatory requirements for worker doses, discharges and other matters for protection and safety. Requirement 14 of GSR Part 3 [10] states:

“**Registrants and licensees and employers shall conduct monitoring to verify compliance with the requirements for protection and safety.**

“3.37. The regulatory body shall establish requirements that monitoring and measurements be performed to verify compliance with the requirements for protection and safety. The regulatory body shall be responsible for review and approval of the monitoring and measurement programmes of registrants and licensees.”

The operator is likely to have corporate requirements with respect to the protection of human health and the environment from its operations. Paragraph 3.38 of GSR Part 3 [7] states the key criteria for monitoring that need to be considered:

"Registrants and licensees and employers shall ensure that:

(a) Monitoring and measurements of parameters are performed as necessary for verification of compliance with the requirements of these Standards;
(b) Suitable equipment is provided and procedures for verification are implemented;
(c) Equipment is properly maintained, tested and calibrated at appropriate intervals with reference to standards traceable to national or international standards;
(d) Records are maintained of the results of monitoring and verification of compliance, as required by the regulatory body, including records of the tests and calibrations carried out in accordance with these standards;
(e) The results of monitoring and verification of compliance are shared with the regulatory body as required."

Furthermore, techniques need to be sufficiently sensitivity to demonstrate that outcomes are within regulatory and corporate limits and that monitoring results are correct and accurate. Verification includes auditability and chain of custody of samples and dosimeters. Dosimeters, procedures, analytical methods and computer algorithms used also need to meet international standards and techniques.

5.3.2. Operational control

Requirement 24 of GSR Part 3 [10] states:

"**Employers, registrants and licensees shall establish and maintain organizational, procedural and technical arrangements for the designation of controlled areas and supervised areas, for local rules and for monitoring of the workplace, in a radiation protection programme for occupational exposure.**

....

“*Monitoring of the workplace*

“3.96. Registrants and licensees, in cooperation with employers where appropriate, shall establish, maintain and keep under review a programme for workplace monitoring under the supervision of a radiation protection officer or qualified expert.

“3.97. The type and frequency of workplace monitoring:

(a) Shall be sufficient to enable:
  (i) Evaluation of the radiological conditions in all workplaces;
  (ii) Assessment of exposures in controlled areas and supervised areas;
  (iii) Review of the classification of controlled areas and supervised areas.
(b) Shall be based on dose rate, activity concentration in air and surface contamination, and their expected fluctuations, and on the likelihood and magnitude of exposures in anticipated operational occurrences and accident conditions.

“3.98. Registrants and licensees, in cooperation with employers where appropriate, shall maintain records of the findings of the workplace monitoring programme. The findings of the workplace monitoring programme shall be made available to workers, through their representatives where appropriate.”

The key criteria for operational control are:

(a) Responsiveness and availability: Results need to be available to operators in a timely fashion. For process control this is likely to include real time monitoring.
(b) Clarity and simplicity for managers and workers: To facilitate control by operators, operational monitoring results need to be available in a form that provides clear information about the status of processes and the working environment.

5.3.3. Purpose of contamination monitoring

The main purposes of contamination monitoring are as follows:

(a) To verify the efficiency of engineered controls in the plant and process;

(b) To confirm good housekeeping practice;
(c) To confirm area designations;
(d) To identify contaminated areas and the level of contamination;
(e) To identify the spread and buildup of contamination;
(f) To monitor items and people exiting designated areas.

5.3.4. Assessment of occupational exposures

Requirements 20 and 25 of GSR Part 3 [10] state:

> "**The regulatory body shall establish and enforce requirements for the monitoring and recording of occupational exposures in planned exposure situations.**
>
> ....
>
> "**Employers, registrants and licensees shall be responsible for making arrangements for assessment and recording of occupational exposures and for workers' health surveillance.**"

5.3.4.1. Criteria for determining techniques

The key criteria for monitoring that need to be considered are similar to those for other compliance monitoring (see Section 5.3.1). In addition, dosimetry service providers are expected to be approved by the regulator, and exposure records are to be maintained.

5.3.4.2. Similar exposure groups

Similar exposure groups (SEGs) are groups of workers who have the same general exposure to sources of radiation. They are identified to determine occupational exposures based on workplace environmental monitoring and occupancy, to assess doses and to analyse exposures, trends and operational performance. In defining SEGs, the following are considered:

— The similarity and frequency of the tasks they perform;
— The materials, processes and proximity to radiation sources in their work;
— The similarity in how they perform the tasks.

Because of the relative ease and low cost of assessing external exposure using personal dosimeters (e.g. optical stimulated luminescence dosimeters

(OSLDs), TLDs), the use of SEGs for external exposure groups is less common. However, they can be used for groups less frequently exposed to significant occupational exposure. It would be appropriate to define SEGs where individuals are not likely to exceed a set dose, to demonstrate that no individual monitoring is necessary. These groups can be usefully aligned with industry standard descriptions of uranium worker roles in the comparative assessment of doses and trends.

5.3.4.3. Verification of design basis

The main objective is to assess changes over time, starting with a high level of monitoring to gain confidence in the results and scaling back the programme when the design basis has been verified.

5.3.4.4. Assessment against trigger levels for investigation or intervention

Requirement 16 of GSR Part 3 [7] states:

> “**Registrants and licensees shall conduct formal investigations of abnormal conditions arising in the operation of facilities or the conduct of activities and shall disseminate information that is significant for protection and safety.**
>
> “3.45. Registrants and licensees shall ensure that information on both normal operation and abnormal conditions that are significant for protection and safety is disseminated or made available, as appropriate, to the regulatory body and relevant parties, as specified by the regulatory body. This information would include, for example, details of doses associated with given activities, data on maintenance, descriptions of events and information on corrective actions, and information on operating experience from other relevant facilities and activities.
>
> “3.46. Registrants and licensees shall conduct an investigation as specified by the regulatory body in the event that:
>
> (a) A quantity or operating parameter relating to protection and safety exceeds an investigation level or is outside the stipulated range of operating conditions; or
> (b) Any equipment failure, accident, error, mishap or other unusual event or condition occurs that has the potential for causing a quantity to exceed any relevant limit or operating restriction.

“3.47. The registrant or licensee shall conduct an investigation as soon as possible after an event and shall prepare a written record of its causes, or suspected causes, including a verification or determination of any doses received or committed and recommendations for preventing the recurrence of the event and the occurrence of similar events.

“3.48. The registrant or licensee shall communicate to the regulatory body and to any other relevant parties, as appropriate, a written report of any formal investigation relating to events as prescribed by the regulatory body, including exposures giving rise to doses exceeding a dose limit. The registrant or licensee shall also immediately report to the regulatory body any event in which a dose limit is exceeded.”

5.4. GENERAL DOSE CONSIDERATIONS

5.4.1. Limitation of radiation doses

The dose limits reaffirmed by the ICRP [19] and established in Schedule III of GSR Part 3 [10] apply to all dose assessments at mines (see Table 1 and Box 1).

5.4.2. Dose assessment for routine monitoring

A method for the routine assessment of the radiation dose received by workers needs to be developed which utilizes data from a statistically valid

TABLE 1. DOSE LIMITS

	Occupational	Public
Effective dose	20 mSv per year averaged over five consecutive calendar years	1 mSv in a year
Annual equivalent dose in		
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	—
Lens of the eye	20 mSv averaged over five consecutive years, 50 mSv in any one year	15 mSv

BOX 1: DOSE LIMITS FOR PLANNED EXPOSURE SITUATIONS

OCCUPATIONAL EXPOSURE

III.1. For occupational exposure of workers over the age of 18 years, the dose limits are:

(a) An effective dose of 20 mSv per year averaged over five consecutive years[66] (100 mSv in 5 years) and of 50 mSv in any single year;
(b) An equivalent dose to the lens of the eye of 20 mSv per year averaged over five consecutive years (100 mSv in 5 years) and of 50 mSv in any single year;
(c) An equivalent dose to the extremities (hands and feet) or to the skin[67] of 500 mSv in a year.

Additional restrictions apply to occupational exposure for a female worker who has notified pregnancy or is breast-feeding (para. 3.114 of [GSR Part 3]).

III.2. For occupational exposure of apprentices of 16 to 18 years of age who are being trained for employment involving radiation and for exposure of students of age 16 to 18 who use sources in the course of their studies, the dose limits are:

(a) An effective dose of 6 mSv in a year;
(b) An equivalent dose to the lens of the eye of 20 mSv in a year;
(c) An equivalent dose to the extremities (hands and feet) or to the skin[67] of 150 mSv in a year.

PUBLIC EXPOSURE

III.3. For public exposure, the dose limits are:

(a) An effective dose of 1 mSv in a year;
(b) In special circumstances[68], a higher value of effective dose in a single year could apply, provided that the average effective dose over five consecutive years does not exceed 1 mSv per year;
(c) An equivalent dose to the lens of the eye of 15 mSv in a year;
(d) An equivalent dose to the skin of 50 mSv in a year.

Source: Schedule III of GSR Part 3 [10].

[66] The start of the averaging period shall be coincident with the first day of the relevant annual period after the date of entry into force of these Standards, with no retrospective averaging.

[67] The equivalent dose limits for the skin apply to the average dose over 1 cm^2 of the most highly irradiated area of the skin. The dose to the skin also contributes to the effective dose, this contribution being the average dose to the entire skin multiplied by the tissue weighting factor for the skin.

[68] For example, in authorized, justified and planned operational conditions that lead to transitory increases in exposures.

monitoring programme based on sound measurement principles. The dose estimation is expected:

(a) To follow the procedures, and use computational methods and data, recommended by the ICRP and IAEA;
(b) To use reference or default values of computational parameters unless other values are approved (if measured values are available and provide greater accuracy, they may be used when approved);
(c) To use any protection factor for PPE if worn in an approved manner following a well managed PPE programme.

The dose assessment method needs to be flexible enough to account for the latest knowledge available on the effects of the different radionuclides on the human body or changes in the acceptable physiological standards. The total effective dose assessment method is the sum of the dose from three exposure pathways: (i) external gamma radiation; (ii) inhalation of LLRD; and (iii) inhalation of RDP.

5.4.2.1. External gamma radiation

The doses of gamma radiation for designated workers and the most exposed group of non-designated workers are monitored using dosimeters. Workers who lose their dosimeters, or are present for only a limited portion of the wearing period, are assigned a pro rata dose based on the average for their SEG.

The most common dosimeter used at mines is a TLD. The organization supplying and assessing them is expected to have a TLD system that is traceable to a national standard. The assessed doses are to be reported in terms of the dose quantities $H_p(10)$ for strongly penetrating radiation and $H_p(0.07)$ for weakly penetrating radiation. The ICRP recommends the use of $H_p(10)$ for the dose assessment of whole body external irradiation and $H_p(0.07)$ for the assessment of doses to the skin and to the hands and feet.

5.4.2.2. Inhalation of long lived radionuclide dust

The effective dose due to LLRD is calculated from:

$$H_{\mathrm{LLRD}} = h_{\mathrm{LLRD}} \times \mathrm{RD} \times \mathrm{BR} \times \mathrm{IT} \times \mathrm{PF}$$

where[3]

[3] Alpha disintegrations per second is shortened to αdps.

H_{LLRD}	is the committed effective dose due to inhalation of LLRD (mSv);
h_{LLRD}	is the DCF for relevant LLRD (mSv/αdps);
RD	is the concentration of LLRD in air (αdps/m^3);
BR	is the breathing rate for light activity (assumed to be 1.2 m^3/h);
IT	is the inhalation time (h);

and PF is the protection factor for any respiratory protective equipment effectively worn (the default value is 1). The LLRD is monitored for various occupational SEGs using personal dust samplers. Dose calculations are based on the average LLRD concentration for each SEG and the hours spent performing that task or in that SEG. Depending on the dose assessment being performed, the results are taken from the quarterly or annual summary LLRD records and inserted either in the rolling SEG or the annual dose assessment records.

The breathing rate used for dose assessments for inhaled LLRD for workers originates from the ICRP human respiratory tract model in which a worker who is occupationally exposed while doing light work (5.5 h light exercise + 2.5 h rest, sitting) breathes 9.6 m^3 of air, which is equivalent to a breathing rate of 1.2 m^3/h [20].

In some cases, workers performing tasks in the final product area wear respiratory protection in case there is a malfunction in the engineered controls in that operation. The respiratory devices normally used are classified as powered air purifying respirators (PAPRs) and, when used in conjunction with a PAPR-P3 filter, have a protection factor of 100. This means that when the LLRD effective dose is calculated for those final product recovery operators wearing a PAPR, the result can be multiplied by a protection factor of 0.01 (1/100). The use of this protection factor is governed by the training given to workers in the use and care of their respiratory protection. If workers did not receive this training, then the effectiveness of the protection device could not be guaranteed and the protection factor would not be used.

A periodic dose assessment (quarterly or annual) for an individual will use the average LLRD concentration for the SEG, incorporating any protection factor which was used for each individual sample, along with the appropriate DCF, the default breathing rate and, where available, the individual's working time in that SEG.

5.4.2.3. Inhalation of radon decay products

The effective dose due to inhalation of RDP is calculated from:

$$H_{\mathrm{RDP}} = h_{\mathrm{RDP}} \times \mathrm{RDP} \times \mathrm{IT}$$

where

H_{RDP}	is the committed effective dose due to inhalation of RDP (mSv);
h_{RDP}	is the DCF for relevant RDP (mSv·(μJ·h)$^{-1}$·m^{-3});
RDP	is the RDP concentration (μJ/m^3);

and IT is the inhalation time (h). The DCFs for radon and decay products are derived from epidemiology studies by the ICRP, whereas the LLRD DCFs are derived from the ICRP human respiratory tract model and physical data on the interaction of radionuclides on human tissue [20]. RDP concentrations are measured in various areas around the mine site. The inhalation time is equal to the number of hours worked in each area. The periodic (quarterly or annual) dose assessment for an individual with respect to the inhalation of RDP will be the average RDP concentration in an area multiplied by the occupancy time in that area for the individual, with this then multiplied by the worker RDP DCF.

5.4.2.4. Assessment of total effective dose

The total effective dose received or committed for an individual is the sum of all components and can be described by:

$$E_T = H_p(10) + H_{LLRD} + H_{RDP}$$

where

E_T	is the total effective dose due to all components (mSv);
$H_p(10)$	is the personal dose equivalent due to deeply penetrating radiation during the year (mSv), with a reference depth of 10 mm;
H_{LLRD}	is the committed effective dose due to inhalation of LLRD (mSv);

and H_{RDP} is the committed effective dose due to inhalation of RDP (mSv). A worker's dose assessment for a period will be the sum of the personal TLD results assessed during that period and the sum of each LLRD and RDP dose assessed for that person for that period. If the worker has been involved in an incident in which he or she may have been inadvertently exposed to radiation, then the dose assessed from that incident will also be included in the total dose for the assessment period.

5.4.3. Dose assessment for non-routine monitoring

Sampling for uranium in urine is carried out following an incident where the ingestion or inhalation of uranium bearing material may have or is thought to have occurred. The analysis technique employed, the kinetic phosphorescence analyser method (KPAM), is very sensitive and can detect low levels of uranium in urine that can occur from the ingestion of natural water and foodstuffs. Other analysis techniques may be available, and the main criteria are that they are reliable and are able to obtain consistent results for low levels of uranium. For this reason, baseline sampling can also occur from time to time. This baseline sampling can be conducted on workers before they commence work in the product recovery area and can also be conducted on workers not exposed to uranium at work as a quality control measure. Workers in the product recovery area have the highest potential to be exposed to uranium concentrate. Workers in other sections of the processing plant where uranium concentrate could be present encountered might also require urine sampling following incidents.

Sampling for uranium in urine occurs because a safety process has broken down. It takes place after an event and is therefore not a preventative measure. If it is thought that a worker might have ingested or inhaled a uranium bearing substance, then a thorough investigation needs to be conducted into how this incident might have occur.

This type of sampling is invasive and has to be conducted with complete confidentiality. Workers might worry that tests for other substances will be conducted in their urine and will need to be assured that analysis will only be conducted for uranium. The credibility of the management is at stake and the utmost care needs to be taken.

5.4.3.1. Sampling process

A 24 hour sample is needed, as the collection of urine will be over a full cycle: when a patient first wakes up and voids the bladder of the urine that has collected while sleeping (the most concentrated urine); and then throughout working and leisure time when the patient is hydrating (urine is progressively less concentrated). If spot sampling is conducted (under 24 hours), then a creatinine correction will be required, which adds another source of error to the result. Creatinine levels are affected by general health and can vary from day to day. The samples need to be dispatched to a reputable independent laboratory. Using an independent laboratory, as opposed to site facilities, will prevent any accusations of operator tampering.

5.4.3.2. Assessment of intake

The results from the analysis will then be used to determine a radiation dose from the intake. The parameters required to undertake the assessment are based on ICRP recommendations [21] and comprise the following:

(a) Inhalation or ingestion: The circumstances surrounding the intake will determine the mode of intake.
(b) Solubility: Uranium products are relatively soluble. If the solubility of the source is not known, then medium solubility is assumed.

Using the time after intake that the urine collection started and ICRP data [19], the intake activity can be estimated. Then normal dose assessment techniques for the inhalation or ingestion of product will be used to determine the effective dose from the intake. This dose assessment will then be included in the worker's dose assessment.

5.4.4. Pregnant and breastfeeding workers

In accordance with Requirement 28 of GSR Part 3 [10] and ICRP recommendations, the mine is to have a process whereby [19]:

> "...the employer should carefully review the exposure conditions of pregnant women. In particular, if required, their working conditions should be changed such that, during pregnancy, the probability of accidental doses and radionuclide intakes is extremely low."

5.4.4.1. Declaration of pregnancy

A worker who becomes pregnant while working at the mine is encouraged to declare the pregnancy to the supervisor or the senior radiation person on-site as soon as possible after the pregnancy has been confirmed. The information is to be treated with confidentiality and the worker cannot face discrimination because of the pregnancy. It is important that the mining company knows about the pregnancy as soon as possible, so that the radiation exposure of the worker can be managed to ensure the protection of the fetus from an early stage.

5.4.4.2. Risk assessment

Once a pregnancy has been declared, a risk assessment needs to be performed for the worker's tasks "in respect of occupational exposure so as to ensure that the embryo or fetus or the breastfed infant is afforded the same broad level of protection as is required for members of the public" (see para. 3.114 of GSR Part 3 [10]). The risk assessment is to ensure the well being of the worker and that the radiation exposure of the embryo or fetus or the breastfed infant be less than the limit for a member of the public and be as low as reasonably practicable "such as to ensure that the additional dose to the embryo/fetus would not exceed about 1 mSv during the remainder of the pregnancy" and that "if required, their working conditions should be changed such that, during pregnancy, the probability of accidental doses and radionuclide intakes is extremely low" [19].

Wherever possible, the risk assessment is to be performed with the pregnant worker, the supervisor, a member of the human resources department and a senior member of the radiation section of the mine. The pregnant worker needs to comfortable with this process and afforded the opportunity to be accompanied by another person, if so desired. The employer may wish to seek additional medical advice. The wishes of the pregnant worker with regard to the confidentiality of the confinement (until the worker wishes to declare the pregnancy openly) has to be heeded. The expectation is that members of the risk assessment team will have already signed confidentiality forms and that the pregnant worker will have been informed of this.

The risk assessment will cover the following aspects of the worker's activities and subsequent exposures:

(a) The previous radiation exposures of the SEG to which the worker has been assigned;
(b) The qualifications and experience of the worker, if alternative work is necessary;
(c) The work aspirations of the worker for the remainder of the pregnancy;
(d) Any medical conditions or recommendations that the medical professionals have placed on this worker for the remainder of the pregnancy;
(e) The radiation exposure of other SEGs, or other areas in the jurisdiction of the mine operations where the worker can perform tasks suited to their abilities and where the radiation exposures are acceptable.

A further risk assessment will be required if the worker, on returning, indicates the wish to breastfeed. The risk assessment will need to determine the working conditions to ensure minimal risk of high accidental inhalation or ingestion of radioactive material that could enter the breast milk pathway. The infant is not allowed in the mine, so the mother would have to express breast milk when practicable.

5.4.4.3. Monitoring

The radiation section of the mine is expected to monitor the activities and work locations of all workers in the mine through the radiation monitoring programme. The monitoring programme needs to be able to assess radiation doses of less than 1 mSv/a from all exposure pathways. From the monitoring programme, the radiation section keeps a database of monitoring results and subsequent assessments to enable a risk assessment to be performed. The data required for the risk assessment are the past annual assessments and the immediate past results for the SEG or the pregnant worker's locations. Any trends in the data need to be assessed to identify if there have been any short term fluctuations that could increase a worker's exposure over a short period (less than six months).

As the monitoring of SEGs and locations is already part of the radiation monitoring programme, there is no need for extra monitoring of where pregnant workers are located. The members of the radiation section need to be aware of where pregnant workers might be and if there is any disruption to the monitoring programme, adequate monitoring will be maintained. Surveillance of these areas and the monitoring programme results needs to ensure that any small fluctuations that could increase exposures unacceptably are identified and controlled.

The senior radiation manager of the mine and the pregnant worker are expected to have several meetings throughout the remainder of the pregnancy to review the monitoring results to ensure that the radiation exposures are being managed in accordance with the initial risk assessment. If the medical condition of the worker changes, then this may also necessitate further risk assessments to ensure ongoing protection.

6. RADIATION PROTECTION PROGRAMMES

The radiation protection of workers is an integral part of all stages in the mining and processing of uranium. However, the level and type of radiation protection practices required varies according to the different stages of the operation as well as the specific needs of each individual operation.

The radiation risks associated with handling radioactive ore and concentrates and the means to reduce these risks to as low as is reasonably practicable are addressed in the radiation protection programme. The programme assists all personnel to meet their duty of care with regard to maintaining their obligations in respect to radiation protection [11]. By reducing the radiation risks, the radiation protection programme also provides a mechanism to ensure compliance with regulatory legislation, corporate policies, standards and guidelines.

For each of the major stages of a uranium operation, the radiation protection aspects have been examined in detail. Specifically, consideration is given to:

— Process description;
— Design and operation;
— Principal exposure pathways;
— Control mechanisms;
— Monitoring and dose assessment.

6.1. EXPLORATION

All soils and rock contain naturally occurring radionuclides; many ores and raw materials (e.g. uranium ores, rare earths, mineral sands) contain relatively elevated levels of natural radionuclides. Therefore, workers performing exploration for uranium and other ores containing NORM are at risk of exposure to above background levels of the naturally occurring uranium series radionuclides and radionuclides in the thorium decay chain.

6.1.1. Process description

Exploration usually starts with surface surveys of various types, followed by test pitting and different drilling methodologies at promising locations. Uranium exploration encompasses a broad range of activities, including:

(a) Claim staking;
(b) Geological data interpretation;
(c) Ground and aerial surveys;
(d) Soil and water sampling;
(e) Radiological studies (e.g. radon emanation from soils);
(f) Drilling and core sampling;
(g) Core storage;
(h) Test pitting and trenching;
(i) Construction of adits and shafts for underground exploration;
(j) Extraction of bulk samples for metallurgical testing;
(k) Test mining to verify mining methods and feasibility.

6.1.2. Design and operation

For occupational radiation protection, the critical area is the exploration field work to obtain samples and their subsequent storage, analysis and disposal. If the exploration team is targeting other metals, the presence of uranium might not be fully expected and radiation protection might not have been even considered.

The most common exploration technique is drilling, and the radiation aspects vary depending on the method. For example, diamond and mud rotary drilling are conducted wet and therefore there is very little dust. However, air rotary and air percussion are dry and can generate significant amounts of airborne dust. Other types include auger drilling, reverse circulation drilling, push drilling and sonic drilling. The amount of ore collected and the waste generated during drilling is also important, as the accumulation of mineralized material in sump pits can become a secondary gamma source.

If the ore body is near the surface, just being in the mineralized area can result in increased radiation exposure. In these cases, it is also possible to conduct bulk excavation of mineralized material using techniques such as test pitting, surface scrapes or deep trenching. These can range from small hand excavated pits to large cuts hundreds of metres long and tens of metres deep.

For deeper deposits, it may be necessary to construct a shaft to provide full confirmation of the ore body and to gather sufficient samples for metallurgical and geotechnical testing. A shaft can range from tens of metres to hundreds of metres deep and can be augmented by side drives to explore some distance from the main shaft.

Storage and handling of samples is often a major issue for exploration, as core yards and bulk sample storage can become very large and difficult to manage. These can range from open air racks on which core is sampled to the use of permanent or temporary buildings (such as shipping containers). Over time, large volumes of material can accumulate, and their management and eventual disposal can be problematic.

Once collected, the samples often need preparation in the field, such as crushing, rifling, cutting drill cores and subsequent geological examination. This brings workers into close proximity with the material. If samples are transported to a laboratory for further analysis, it might be performed by workers unfamiliar with radiation protection practices, particularly if the analysis is for non-radiological characteristics such as geotechnical properties. Finally, both ore related and waste related material may need to be disposed of, for example returning the material to the point of origin or building other structures (e.g. deep trenches).

6.1.3. Principal exposure pathways

All of the standard exposure pathways are theoretically applicable to exploration activities. However, the importance of the pathways depends on the method used. Gamma radiation is generallly applicable to all exploration types, whereas the inhalation of LLRD is more likely with dust generating activites (e.g. air percussion drilling). The inhation of radon progeny is generally important only where there is restricted ventilation, such as deep trenches or shafts. However, very high levels of radon can occur where ore samples are stored in fully contained structures (e.g. shipping containers) if there is no ventilation. Ingestion and the potential for wound contamination are not normally a significant pathway, providing normal hygiene practices are in place.

During initial exploration and baseline studies, the radiation hazard will typically be very low, arising mainly from external gamma radiation from mineralized rock outcroppings, boulder trains and samples taken in the field. In diamond drilling, the main hazard is external gamma radiation from the drill core, especially where the core is stockpiled (e.g. core shack, core rack). Exposure to airborne dust is possible; however, modern diamond drills collect the cuttings.

Measures may need to be in place to protect workers from the dust caused by percussion drilling (e.g. drill dust collectors, operator dust masks). Wet reverse circulation drilling necessitates the collection of slurry and the decanting of clean water.

With test pitting, workers can be exposed to airborne dust in addition to external gamma radiation. Since uranium bearing materials are handled and stored in open or well ventilated enclosures, inhalation doses from RDP are expected to be minimal. Where exploration activities go underground (e.g. for bulk sampling), exploration becomes a mining activity and RDP exposures can be significant.

6.1.4. Control mechanisms

A radiation protection programme is always essential for adequate worker protection, including exploration and drilling programmes. Paragraph 1.3 of GSG-7 [11] states:

> "It provides general guidance on the exposure conditions for which radiation protection programmes are required to be established, including the setting up of monitoring programmes to assess radiation doses to workers arising from exposure due to external sources of radiation and from exposure due to intakes of radionuclides. It also provides specific guidance on the

assessment of doses from exposure due to external sources of radiation and from exposure due to intakes of radionuclides.”

It needs to be recognized that the requirements for a radiation protection programme depend on the anticipated characteristics of the deposit (especially grade) and the nature of the proposed exploration programme. Specifically, a radiation protection programme needs to be developed on a case by case basis. The radiation protection programme for underground exploration is generally the same as for underground mining but less intensive. One critical component is an understanding of radiation protection as it applies to uranium ores and to make sure all workers are informed about methods to reduce radiation exposure.

External gamma radiation exposure from uranium mineralization and radioactive sources in exploration equipment present the most significant hazard. Adequate monitoring of areas with above background radiation fields is essential. Prior to the performance of any work, such as drilling and core handling, a gamma survey needs to be conducted and areas with gamma dose rates greater than 1 μSv/h identified and placarded. Previously disturbed areas with significant radiation levels (e.g. historic showings areas and core storage areas) need to be marked with signs warning of radiation.

To apply the as low as reasonably achievable (ALARA) principle and minimize the dose, the three basic strategies of time, distance and shielding are used. Time and distance are the most commonly applied, with personnel reducing their time in, and proximity to, the areas where higher activity materials are located. Shielding may be used for high grade ores with surface mineralization, and this can take the form of a covering of inert material to form the drill pad. Where very high grade core is being stored or examined, for example, a wall mounted monitor can be installed in the core and splitting shacks. The monitor records the gamma radiation levels every hour and provides an LED display of radiation levels in the area and is visible up to 30 m. Backlit indicators warn of low radiation alarm (yellow) to high radiation alarm (red).

The inhalation of radon progeny is expected to be insignificant for most aspects of uranium exploration. The most important exception is for the storage of samples in an area of poor ventilation. Shipping containers are commonly used to store samples. The very poor ventilation, however, can result in very high levels of radon and radon progeny. Occupational exposure can be avoided very easily by ensuring that the containers are well ventilated prior to personnel being allowed inside (i.e. opening the doors well before entry and external fans blowing in fresh air). Radon can also be a factor in deep cuttings in still weather conditions and in underground exploration. The use of forced ventilation in these cases can dramatically reduce the radon exposure.

Similarly, the inhalation of LLRD is relatively easy to control. Ideally, wet based practices are used to minimize occupational exposure (e.g. diamond drilling or wet based core cutting). If dust generation occurs, the use of basic respiratory protection (e.g. disposable P1 dust masks) is general industry practice. Where possible, workers also need to be upwind to reduce any potential for dust inhalation. In sample preparation, the use of ventilation and respiratory protection may be necessary.

Contamination controls are used to prevent the spread of contamination to eating, sleeping or recreational areas. The application of good industrial hygiene practice helps to prevent the intake of uranium contamination via ingestion or direct entry through open wounds. Protective clothing (e.g. cotton gloves) and contamination monitoring minimize the spread of contamination. With standard workplace hygiene practices, there is minimal likelihood of radioactive contamination of workers (mainly hands), clothing or tools. Workers are to wash their hands thoroughly before eating, drinking or smoking. It is not uncommon for geologists to lick the rock for better examination, but this practice is to be discouraged in uranium exploration. Food preparation and eating areas are generally considered to be clean, and policies are commonly enforced to ensure cleanliness, such as changing out of work clothing and showering before eating.

6.1.5. Monitoring and dose assessment

During exploration, access to monitoring equipment might be restricted. Because of the remote nature of the locations and limited personnel, it is unlikely that there will be dedicated radiation protection personnel on-site, and hence the monitoring programme needs to be adjusted based on the site conditions. For gamma exposure, the general practice is to use integrating personal dosimeters, such as TLDs or OSLDs. These provide a low cost, accurate and easily managed means of performing dose assessment on what is generally the most important dose pathway. There is often an electronic gamma detector at exploration sites, such as a scintillation meter, which is used to check samples for uranium content based on gamma readings. These can be utilized to conduct area surveys and identify areas with high gamma exposure.

The lower potential dose from radon and radon progeny generally means little monitoring is undertaken during exploration. Passive integrating radon detectors, such as track etch detectors, are most commonly used, since they can provide sufficient assurance that radon exposure is low without involving detailed monitoring programmes and specialized equipment.

For inhalation of LLRD, the general approach is to integrate it with other occupational hygiene monitoring. If the sites have significant dust generation, area or personal dust sampling can be undertaken on a periodic basis. The samples can be sent off-site for gross alpha counting to assess the potential for exposure.

The potential for exposure due to ingestion and wounds is normally low for exploration activities, so active monitoring programmes are not generally undertaken. If the site has access to a contamination monitor (sometimes needed for sample transport), then it can be used to screen offices and eating areas. Alternatively, swipe testing of important areas can be undertaken periodically, with the swipes being analysed off-site.

6.2. UNDERGROUND MINING

6.2.1. Process description

Underground mining is performed using a variety of mining methods to extract the ore. The mining method depends on the ore geology, which determines the ease of recovery. The following describes the common methods.

6.2.1.1. Room and pillar open stope

An open stope is an underground cavity created by the extraction of ore, which is kept open by means of ground support from unmined pillars of either ore or waste rock. This support often needs to be supplemented with secondary ground support, such as rock bolts or shotcrete. Room and pillar open stope mining is typically used with ore bodies that are large, flat and in competent rock. The mining zone moves along the ore body in a horizontal or low angle direction with solid pillars of rock left in place to provide ground support. Since the stope is horizontal, the broken ore needs to be gathered and transported out of the mine. A major issue with this mining method is the need to provide ground support as the mine expands and that workers are in the ore zone. As the ore grade increases, gamma radiation levels and the radon source term both increase, resulting in additional constraints.

6.2.1.2. Sublevel stoping

Sublevel, longhole or blasthole stoping is usually used with ore bodies that are relatively steeply angled and situated in competent rock. The ore body is accessed through sublevels between the main haulage drifts, from which the ore body is drilled and blasted so the ore can be collected at draw points at the bottom of stope. The development of the sublevels occurs through the ore body, which for uranium deposits places workers near radiation sources. For low grade uranium deposits, radiation control strategies can be relatively simple, but as the ore grades increase, control steps need to be carefully designed. Shotcreting is a common ground support method, which can be used to reduce the gamma radiation levels.

6.2.1.3. Cut and fill stoping

Cut and fill stoping is a flexible mining method well suited for ore bodies with a considerable vertical extent. Mining starts at the bottom of an ore zone and works upwards, and the general approach is to begin by removing 2–3 m of ore from the roof at the drift back. Ground support can then be installed in the back and mining can continue. Ore is removed upwards through the stope, dropping it to lower levels. Once a stope has been mined, it can be backfilled to provide ground support for adjacent stopes. This type of mining places workers in the ore zone, and ventilation has to be adequate to provide fresh air and to control radon progeny. Depending on the ore grade, gamma radiation exposures can also be an issue.

6.2.1.4. Undercut and fill mining

Undercut and fill mining is a selective method of mining a block of ore by starting at the top of the ore zone and working downwards by taking out successive horizontal cuts. While ore recovery is high and dilution can be controlled, it is labour intensive. After a cut of ore has been taken, it is replaced with a cemented backfill. The next cut of ore is taken out underneath the preceding cut. This method places workers in the ore zone, which can increase gamma exposure and makes ventilation very important.

6.2.1.5. Block caving

Block caving is used for massive ore bodies of a certain grade in the right geotechnical conditions and is very efficient. An area under the ore body of sufficient size is excavated for the ore to cave naturally. Caved ore is removed from the bottom and the ore body continues to cave in a controlled fashion until all the ore has been extracted. This type of mining is best suited to ore bodies that are reasonably regular in shape with sides that dip steeply.

6.2.1.6. Non-entry mining

Non-entry mining avoids direct entry into the ore zone and is used for very high grade uranium ore deposits. The several variations typically involve establishing a drift below the ore zone and inserting a device to grind the ore to allow it fall into the drift, where it is collected. Common to all the methods is that the radon and radon progeny concentrations in the mined out cavity can reach extremely high concentrations and a well designed secondary exhaust ventilation system is required to isolate this air from the general work environment (see Section 6.8).

6.2.2. Design and operation

Each underground mining technique has specific criteria for the design and operation of the mine. Access to the ore body is through the development of a vertical shaft or angled decline, and the pathways are through unmineralized zones to reduce exposures. Some operations will develop one or more underground bases of operation, where workers can hold meetings, perform maintenance activities and take rest and meal breaks. It is critical that these areas be developed in unmineralized zones and be well ventilated with first pass air to prevent the buildup of radon progeny. These areas generally service the underground operation and act as the hub for services from the surface.

Development into the ore body is based on the geological plans for mining, which usually target high grade ore close to extraction facilities. As far as practicable, development headings are to be created in low or unmineralized sections. Except for the alternative mining methods described for high grade ores, the other mining methods generally rely on the use of drilling and blasting to release the ore. Heavy vehicles (e.g. loaders, trucks) transport ore directly to the surface or to an ore handling facility for hoisting to the surface.

Ventilation in underground mining operations is critical to control radon and radon progeny and to remove atmospheric contaminants produced by mining equipment (e.g. diesel fumes). This is a specialized field and underground mining operations generally employ specialists to design and implement ventilation plans. Radiation protection through the removal of radon and radon progeny from the work areas needs to be an integral component of ventilation design and operation and to be embedded into standard operating practices.

6.2.3. Principal exposure pathways

The principal exposure pathways in underground mines relate to the extraction of the uranium ore and the proximity of workplaces to uranium ore mineralization. Uranium ore usually contains all members of the ^{238}U and ^{235}U decay series in radioactive equilibrium. This means that uranium ore can result in multiple exposure pathways and can be an airborne hazard and a source of RDP. Any location or activity that directly exposes workers to uranium ore will result in some exposure to gamma radiation. The source term is proportional to the ore grade, and the strength of the gamma field depends on the physical size of the source, its distance and any shielding. Gamma fields can be modelled accurately, and worker dose can be estimated based on time and proximity to sources. Although gamma exposure is one of the largest exposure pathways, it is generally stable over time and can be controlled with sufficient information and planning.

Radon progeny typically comprise a significant fraction of an underground worker's radiation exposure. While the source term of radon depends on the ore grade, physical characteristics have a strong impact on the amount of radon released, and the concentration of radon progeny in the mine atmosphere will greatly depend on the ventilation system. The transport and subsequent release of radon via groundwater can have a significant impact on the amount of radon released. Factors which influence the release of radon and the ventilation rate can be used to make reasonable predictions, and it is important to consider the residence time of the air, as the ratio between radon and radon progeny changes rapidly as the residence time increases. Changes in the ventilation system can give rise to very large changes in radon and radon progeny concentrations in short periods of time and hence real time monitoring and control may be necessary.

There are many possible sources of radon in an underground mine. An inert gas, radon can transport out of the ore matrix through several means. Radon is emitted when uranium ore is directly exposed to the mine atmosphere. This will occur when mine tunnels or excavations encounter uranium ore mineralization, either as part of the main ore body or as peripheral mineralization. Activities that break up the ore (e.g. blasting) release large amounts of radon. As ore is handled and transported through the mine to the surface, it continues to emit radon into the mine atmosphere. Radon can also travel considerable distances via groundwater, and radon bearing water entering the mine can be a significant exposure pathway.

LLRD exposure depends on the ore grade and mining methods, and sources include any handling of uranium ore, such as drilling, blasting and transporting the ore. The resuspension of dust from contaminated travel ways and the maintenance of contaminated equipment are other potential sources. Wet mining methods are preferred because they generate less dust. It is generally difficult to predict the amount of dust generated and practical experience in similar conditions is a very good guide in anticipating the LLRD concentrations that workers may experience. In operations not exposed to high grade uranium, the contribution from LLRD can be kept relatively minor with appropriate controls.

6.2.4. Control mechanisms

The key means for control of exposure using time, distance and shielding need to be incorporated into the operation based on the mining method and ore grade. The implementation of these controls follows the standard hierarchy of control. Controls for the pathways can easily be incorporated into common mining methods and become an integrated part of the operation, meaning that radiation hazards can be controlled similarly to the other hazards associated with mining.

6.2.4.1. Gamma radiation

All development and underground respite, permanent or maintenance work areas need to be constructed in unmineralized zones of the operation to reduce exposures. The planning and construction of development headings through the ore body also need to be performed in unmineralized zones. This level of control either eliminates or minimizes the exposures to all but key operational personnel. Shotcrete is a common form of ground control in underground operations and has been used successfully as an engineered control for shielding gamma radiation. Feedback through the monitoring programme can be used to identify areas in which shielding is needed. Similarly, the use of benign material for the road base can reduce gamma exposure.

General housekeeping of work areas is also a means of minimizing dose. If drill cuttings from ore zones are allowed to accumulate in work areas, this can lead to a significant increase in gamma exposure and removal of the cuttings can control this exposure. The metallic material of mobile equipment cabins offer some shielding from gamma radiation. At sites without mobile equipment, the use of portable shielded control areas can be considered. Administrative controls include the use of job rotation where exposures are assessed as significant to reduce the amount of time that personnel spend in an area. Restrictions to areas may be needed while controls are implemented that, when breached, will trigger appropriate action.

The storage of ore stockpiles, cuttings, core samples or any other sources of gamma radiation should be kept away from work areas to increase the distance from personnel. As the ore grade increases, the control of the spread of contamination becomes increasingly important to limit gamma exposures. Care needs to be taken in controlling spillage from ore haulage vehicles and other systems used to handle and transport ore.

6.2.4.2. Radon and radon progeny control

Minimizing the amount of radon entering the mine atmosphere is the first approach. An important part of this strategy is minimizing how much mine development there is in areas of uranium mineralization. However, the groundwater transport of radon means that even with this strategy, there is no guarantee that there will not be significant sources of radon entering mine workings. In this case, strategies to control the groundwater can be deployed, for example grouting can prevent groundwater from entering a mine. For well defined groundwater sources that have significant concentrations of radon, capturing and diverting the water into pipes or other containment devices can sometimes be effective. Freezing the ground can also be effective at stopping groundwater movement, depending on other considerations, such as mine flooding or ground control. While strategies to minimize the amount of radon that enters a mine atmosphere are important, they will rarely be effective at eliminating all sources of radon.

Once radon has entered the mine atmosphere, the design of the ventilation system becomes critical for controlling radon progeny concentrations. However, the design needs to consider more than simply the volume of air. The longer radon is released into the mine atmosphere, the greater the concentration of radon progeny. Hence, it is important to minimize the time contaminated air remains in active workplaces. Areas with little ventilation rates (e.g. stopes and behind bulkheads) can have very high radon progeny concentrations and generally need to be under some form of negative ventilation directed to the exhaust air system. It is important that the mine ventilation system does not recirculate air, as this can also lead to elevated radon progeny concentrations.

The goal is to maximize the time workers spend in fresh air, upwind of sources of radon. This starts with the proper distribution of fresh air to mine work areas, avoiding unnecessary contamination of the supplied air. It is important to remove the air efficiently once it has become contaminated through dedicated exhaust ventilation drifts and raises. Physical barriers can isolate strong radon source terms (e.g. sumps). Mobile equipment with enclosed cabins and filtered air also helps to control radon progeny exposures, and enclosed cabins provide reasonable protection against many other occupational hazards. Remote controlled equipment can control radon progeny exposures and provide other conventional safety benefits, for example a remote controlled scoop can be used to enter a stope and retrieve ore while the worker remains in a fresh air drift.

In situations where ventilation control cannot be achieved in the short term (e.g. repairing a fan failure) and routine activities such as periodic inspection of areas with high concentrations of radon progeny (e.g. isolated sumps), the use of respiratory protection to control the exposure to radon progeny may be warranted. These well controlled activities need to follow appropriate regulatory requirements and to have a documented programme:

(a) To select the appropriate respiratory protection equipment;
(b) To train and test workers;
(c) To maintain the respiratory protection equipment and to control its use in the field;

(d) To factor respiratory protection into the calculation of worker exposure to radon progeny.

6.2.4.3. Control of long lived radionuclide dust

The activities used to control LLRD exposure are similar to those used in other mines, with the emphasis on limiting the generation of dust. However, many of the design features of the ventilation system to control radon progeny help to control LLRD exposure to some degree. Water is effective at reducing the generation of airborne LLRD, so wet drilling and mining methods are preferred to dry techniques. Minimizing spillages and cleaning and decontaminating equipment are also important to control LLRD exposure. While the potential for receiving significant doses from LLRD is generally lower than that for radon progeny, some situations warrant the use of respiratory protection (e.g. maintenance of difficult to clean equipment). Similar to the control of radon progeny, respiratory protection equipment needs to be used appropriately.

6.2.4.4. Contamination, ingestion, wound contamination and absorption

Good hygiene practices are the best methods to ensure that pathways do not cause significant exposures. Workers need to be trained and supervised to ensure that they wash their hands and face prior to eating, drinking or smoking. It is also common for workers to have to shower and change at the end of a working shift to reduce the risk of exposure. Wound contamination is an unlikely exposure pathway, but care needs to be taken in a similar manner to standard infection controls to ensure that ‘sharps’ (sharp metal and other objects) are managed appropriately and any wounds are dressed prior to work. Cleaning equipment and tools before use limits the potential for workers to be contaminated following an injury. A general cleaning programme for offices, workshops, amenities and meal rooms can reduce contamination as a source of exposure.

6.2.5. Monitoring and dose assessment

The two goals of radiation monitoring are to confirm that the radiation levels remain within the expected range and to assess the dose to workers. Monitoring needs to be in place for all of the exposure pathways and needs to be carried out by competent personnel. Where specific engineered controls are in place, regular monitoring is necessary to review their effectiveness. The type and frequency of the monitoring reflects the risk associated with the exposure pathway, and dose assessment needs to follow the appropriate ICRP methodologies and regulatory requirements.

6.2.5.1. Monitoring of engineered controls

The monitoring programme needs to include a review schedule of the effectiveness of engineered controls. For example, how effective the ventilation system is needs to be reviewed when it is used to control RDP and LLRD. This includes reviewing the preventative maintenance programme, downtime and repair times for the equipment.

6.2.5.2. Gamma radiation

Gamma radiation is relatively straightforward to monitor, and a range of active and passive monitoring equipment is used to perform area and personal monitoring. As a mine is developed, gamma surveys (typically with hand held meters) determine the background radiation levels for a baseline to measure ongoing performance and to identify any unexpected areas of mineralization. Main haul ways and high occupancy areas are also expected to have periodic gamma surveys. In either cases, the goal is to determine whether the controls are working or whether any remedial actions need to be taken.

Personal (electronic) direct reading dosimeters can keep track of doses continuously, which can be when working near strong gamma sources such as in high grade mines. Direct reading dosimeters are generally not used for official purposes; rather they are typically used for tracking and assessing day to day dose control activities. For official dosimetry purposes, the standard practice is to issue a passive integrating dosimeter (e.g. TLD, OSL) for a specific period, typically one to three months.

6.2.5.3. Radon and radon progeny

Radon progeny levels underground can vary rapidly both temporally and spatially, so it is important to have a thorough system for monitoring concentrations. Since radon and radon progeny concentrations can change rapidly, real time monitoring and control approaches may need to be considered. Monitoring of a work area needs to be at a frequency that matches the risk profile: well ventilated locations with low concentrations require a lower frequency of monitoring than poorly ventilated areas.

Grab sampling is useful to determine the atmospheric concentrations of contaminants in an area in the short term and can be compared against set limits. Continuous radon progeny monitors are important in mines and locations with the potential for high concentrations. The placement of continuous monitors needs to take into account factors such as occupancy, visibility, the ventilation system and potential sources of radon. Continuous radon progeny monitors can alert workers to changing conditions, which is important in controlling exposure.

On account of the inherent variability of radon progeny in many underground work environments and the practical difficulties of tracking workers, it is often preferable to use personal monitors to assess worker exposure to radon progeny. An area sampling system that records the time spent in the various work areas and sample areas can be used to calculate a worker's exposure. Naturally, it is very important that sample areas be representative of the worker's actual exposure. For grab samples, choosing the sample location can be relatively straightforward, but the timing of sampling can be more problematic, as it is possible to miss significant short fluctuations in the radon progeny concentrations. Conversely, continuous samplers will account for short fluctuations, but ensuring that the sample location is representative of actual work locations can be more challenging.

6.2.5.4. Monitoring of long lived radionuclide dust

LLRD can be monitored by using personal and area sampling. Personal sampling collects gravimetric dust, then the sample filters are analysed for radioactive activity concentration. Statistically valid sample sizes need to be collected for each SEG that is present at the operation and SEG averages may be assigned to individuals. In higher risk environments, individual dust sampling may be necessary and continuous integrated sampling devices need to be considered.

Where the risk of exposure is lower, and it can be demonstrated that area monitoring represents workers' actual exposures adequately, it is possible to perform area sampling using medium or high volume air samplers and to assign time weighted exposures based on personal area occupancy. The frequency of this monitoring is based on the exposure risk profile. Individual sampling is used where a long term sample is collected and analysed with doses being assigned directly.

6.2.5.5. Contamination, ingestion, wound contamination and absorption

The monitoring programme does not only focus on the determination of dose but also needs to review all relevant controls for exposure reduction. Good hygiene practices are important to control surface contamination, which is a potential source of airborne exposures and intakes via ingestion and wounds. In the case of wounds, attention needs to be given in cases where workers are injured by contaminated equipment and the skin barrier is seriously compromised.

Feedback on the effectiveness of the various control practices provides appropriate recommendations for corrective actions to be implemented in a timely manner. Practices such as routine contamination surveys and screening urine bioassay programmes provide information on the effectiveness of the controls. Dose assessments from these pathways can be assessed through bioassay of urine samples. These are typically only needed for specific incidents where there has been a serious failure of the various control mechanisms.

6.3. SURFACE MINING

6.3.1. Process description

Surface (or open cut) mining extracts the ore via surface cutting. It has the largest surface signature because of the high ratio between waste rock and ore, the latter of which can be of radiological concern.

6.3.2. Design and operation

Surface mining utilizes a range of different techniques and methodologies dependent on local site specific factors such as topography, geology and geomorphology. The term surface mining can be misleading, as some surface mines are very large and can extend over a kilometre in depth. Other mines might only be surface scrapes and not extend any significant distance into the underlying strata. Some surface operations become hybrid mines as they are transformed into an underground mine because of the depth of the ore body (or some other topographical constraint).

Open cut pits are used when the ore extends from the near surface down to depth. The typical design is based on there being several benches around the perimeter of the main pit, with mining occurring both downwards and laterally. The design of the benches depends on the nature of the rock, geological factors such as local faulting and the scale of the operations. Bench height and angle are generally altered to address local conditions. The overall depth of the pit is determined by the nature of the ore body but other factors can limit the depth, such as groundwater inflow. Within the pit, there are haul roads to transport ore and waste rock to the surface. Adjacent to the pit are waste and ore stockpiles, the location of which is generally guided by the optimization of cost and how the mine develops, and so they are often close to the haul road exits. Other features include ponds for the storage or evaporation of surface water and groundwater from the pit and rock pile surrounds.

The general mining methodology for open cut pits is a combination of drilling and blasting followed by extraction and transport. During drilling, sampling is usually taken for grade control purposes. Ore and waste rock is extracted by using shovels to lift the blasted rock into trucks for haulage to the surface. Some operations use in-pit crushers to reduce the size of the blasted rock and skips or conveyors to transport the material to the surface.

Near surface mining (strip mining) is used when the ore body does not extend to a significant depth. For some operations, the process involves a continuous mine and fill process, in which, after an area is mined, it is progressively filled by the overburden from newly mined areas. Tailings can also be deposited as part of this process. This adds greatly to the complexity of the mining operation but reduces the impact on the surface (e.g. it minimizes surface facilities such as waste rock piles) and the potential for long term legacy issues.

One form of surface mining is where the uranium mineralization only occurs directly on the surface. Although rare, this does occur; and in such cases, mining can be as simple as extraction of only the uppermost layer of the soil (<1 m).

6.3.3. Principal exposure pathways

For surface mining, occupational exposure is generally at the lower end of exposures in uranium mining. Doses in the order of a couple of mSv are the norm and higher doses are rare during routine mining operations. The major exposure pathway is generally direct gamma, with a smaller contribution coming from the inhalation of radionuclides in airborne dust. The inhalation of radon progeny is generally only significant in deep pits and where natural ventilation processes cannot remove exhaled radon. For gamma exposure, there is a direct relationship between the uranium grade of the exposed rock in the mine and the time workers spend close to it. The dominant contribution is from the rock directly below the working area, as personnel are generally restricted from working adjacent or in close proximity to the bench vertical faces (due to rock fall risk). The gamma dose to individual workers is easy to predict based on the expected ore grades.

Inhalation of radionuclides in airborne dust is a direct function of the amount of dust generated by mine operations. Some stages are dustier and can require additional monitoring or controls to maintain low doses. Drilling operations generally offer the highest risk from dust owing to a combination of the inherent dust generated by some drill rigs (i.e. percussion, air core, reverse circulation) and the close proximity of the operator to the area being drilled. Drillers often bypass control mechanisms owing to a perceived need to ‘feel’ the drill to maximize performance. Dust may also be an issue during the maintenance of mining equipment, but good practice is for equipment to be cleaned prior to maintenance and practices that generate large quantities of dust (e.g. using compressed air to clean air filters) may be restricted.

Inhalation of radon progeny is generally a minor pathway for surface mining. Natural dispersal of radon exhaled from the ore is normally sufficient to keep occupational exposures low. The exception is where natural ventilation is curtailed by either pit design, surrounding structures or meteorological conditions. Deep pits are the most likely to be affected, as the air in the bottom might not have sufficient circulation, which results in a layer of high radon and radon progeny concentrations. Where atmospheric temperature inversions occur frequently (e.g. arid regions), it may be necessary to consider the impact of reduced radon dispersal on occupational exposure.

6.3.4. Control mechanisms

As the radiological risk associated with surface mining is relatively low, control mechanisms are usually incorporated into controls for conventional hazards. Radiological specific controls are generally only necessary for mines with very high ore grades or activities with very close and continual interaction with the material.

For direct gamma exposure, the most common control mechanisms are the physical shielding and distance from the rock surface provided by the mining equipment and reducing the time spent in active areas. For the excavation and haulage of blasted rock (mechanical shovels), the operator can be over 5 m from the rock surface and shielded by several centimetres of steel. In high grade operations, further shielding can be added at low cost if gamma becomes a significant pathway. Workers such as geologists, explosive charge hands and, to a lesser degree, drillers work directly on the surface of the material. In these cases, active controls are minimal and focus on minimizing the time spent over higher ore grades and the distance from vertical faces. In particularly high grade areas, a cover of inert material can be placed over the ore (~0.5 m) to reduce the gamma field at the drill location.

One critical lesson from past practices is to ensure that non-mining facilities (e.g. offices, workshops, cleaning bays) are kept remotely from the ore stockpiles. Historically, they have often been placed near the active mining area, with mine material being sometimes used as the building base. The enhanced exposure can mean that the clean area has similar gamma dose rates to the active mining area. Positioning auxiliary structures on low dose rate areas can result in a significant decrease in potential occupational exposures. This will also reduce the number of monitored workers and provide a safe work area for personnel with special requirements, such as apprentices and pregnant workers.

To reduce exposures to radionuclides in inhaled dust, the usual control methods are to minimize the amount of dust generated, restrict access during dust generating conditions or provide filtered air to worker cabins. Dust is often an issue for surface mining and can be critical for a range of non-radiological aspects (e.g. environmental damage, dispersal, silica exposure). Controls include: wetting or dust resistant agents on roads; altered blasting to reduce dust; stockpile design to reduce dispersion; wind breaks; and minimized drop heights during loading. These controls are generally applied irrespective of radiological risk and sometimes it is necessary to prevent access to the mining area. Blasting is almost universally dust generating, so personnel are restricted from accessing the area until the dust settles. During high dust levels, drilling personnel can remain upwind of the dust plume. Most modern mining equipment (e.g. shovels, trucks, drill rigs, cars) have air-conditioned cabins for the operator. Appropriate filtration of the intake air can significantly reduce potential exposure and improve the comfort of the operator. The use of PPE (e.g. respirators) is generally only necessary when there are other non-radiological requirements or there is a particularly dusty operation.

Control of RDP exposures is very rarely needed in surface mining operations. Natural ventilation processes, aided by the increased air movement caused by vehicle heat and movement and ground–air temperature differentials, are almost always sufficient to prevent the buildup of RDP to significant levels. Higher radon gas levels may be found in deep open pit mines under temperature inversion conditions, and it may be necessary either to limit access or use full cab filtered ventilation.

6.3.5. Monitoring and dose assessment

The monitoring approach in surface mining is similar to that used in all other stages of uranium mining. For gamma exposures, normal practice is to use either individual personal dosimeters (e.g. TLDs, OSLDs, electronic personal dosimeters, EPDs) or workgroup SEG averaging of personal dosimeters. Electronic dosimeters are likely to be only necessary in areas of either high dose rates or for non-standard work tasks. The work area can be surveyed periodically and the results used for future mine and exposure planning. The correlation between ore grade and dose rate can enable the ore grade to be used as a surrogate for direct gamma surveying.

For dust, personal (on a workgroup averaged basis) or work area sampling is normal practice. For jobs that involve the frequent movement of workers, personal dust sampling is appropriate; for jobs which are mainly cabin based (e.g. shovel operator, truck driver), an in-cabin sampler may be better. However, if in-cabin monitoring is required, it may be necessary to check that the behaviour of the operator is consistent with remaining in the cabin — drill operators can often leave cabins (or lean out of the door) to be closer to the rig.

For RDP, periodic area monitoring can be enough to confirm that it is not a significant exposure pathway, employing: passive sampling (e.g. track etch monitors); grab sampling (e.g. Rolle, Borak); or electronic sampling. From the dosimetry standpoint, the only variation from other stages of uranium mining is that equilibrium can be assumed in almost all cases for radionuclides in airborne dust (except for radon and radon progeny). However, there are rare cases where this might not apply, such as in an active roll front deposit.

6.4. IN SITU LEACH MINING AND PROCESSING

6.4.1. Process description

An ISL operation comprises a well field with associated infrastructure to pump lixiviant into and out of the mineralized zone and a processing facility to extract the uranium from the lixiviant and to produce the desired final uranium product. ISL currently accounts for most of uranium production in the world and is regarded as a cost effective and environmentally acceptable method of uranium production. Uranium deposits typically amenable to ISL methods are usually associated with relatively shallow aquifers (about 30–150 m subsurface[4]), confined by non-porous shale or mudstone layers [22]:

> "Uranium was transported to the present locations over geologic time as soluble anionic complexes by the natural movement of oxygenated groundwater. Uranium deposition occurred in areas where the groundwater conditions changed from oxidizing to reducing. This produced a roll front deposit with uranium concentrated at the interface between the oxidized and reduced sandstones. This interface is commonly known as the Redox Interface ([Fig. 4]). A schematic of a typical uranium roll-front deposit showing the basic solution mining approach to uranium recovery is depicted in [Fig. 5]."

Uranium is recovered in ISL operations with alkaline or acidic solutions, known as lixiviant, which are pumped into the mineralized zone to mobilize the uranium into a solution for recovery from wells [8]. Lixiviant solutions

[4] This is the typical depth range of applicable to US sandstone deposits; the depth can be deeper elsewhere (e.g. typically up to 800 m depths for geologically similar deposits in Kazakhstan).

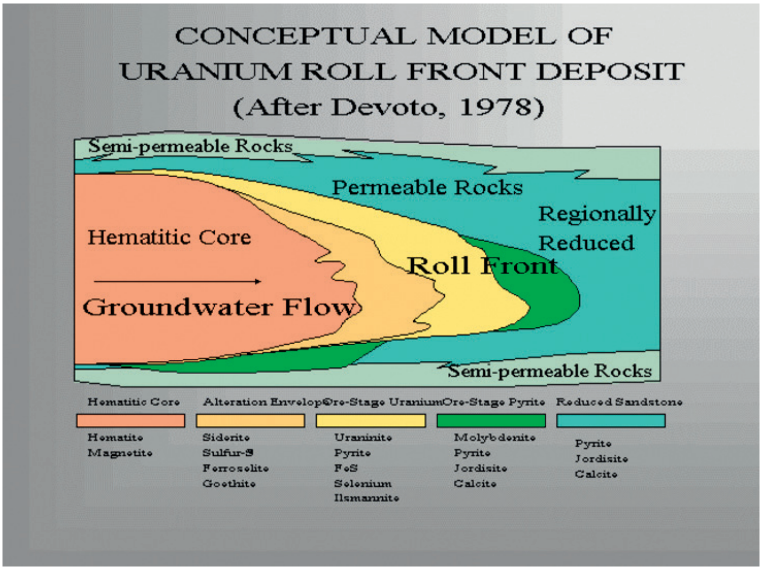

FIG. 4. Redox interface showing a roll front deposit [23] (fig. 1 of Ref. [22]).

FIG. 5. Basic approach to the in situ uranium mining method (fig. 1-2 of Ref. [24]).

are stripped of uranium at the surface in the processing plant and the solution is recycled through the process back into the well fields. The uranium in the lixiviant solution is extracted using ion exchange resins in the majority of ISL operations or directly through solvent extraction [8]:

> "The uranium is chemically stripped from the ion exchange resin...and precipitated from the eluate. In recent designs, the resin may be eluted directly in the ion exchange vessel or transferred to a separate elution column or tank. The uranium precipitate, formerly ammonium diuranate (e.g., using sodium or ammonium hydroxide) or more recently uranyl peroxide (using hydrogen peroxide) is conveyed to a product drying/packaging area where it is converted to the final uranium oxide product. At facilities using high temperature calciners (800–1000°C), final products are typically U_3O_8 and/or UO_2. In designs using lower temperature vacuum drying (e.g., 300–400°C), the final products are typically uranyl peroxide (UO_4) uranyl trioxide (UO_3), their hydrates and/or combinations thereof...."

Some ISL process strategies involve a final product of loaded resin, or an intermediate precipitate or slurry (produced in a satellite plant), which is then shipped to another uranium recovery facility for final processing [22]. A schematic of a typical US ISL uranium recovery process is presented in Fig. 6. Similarly, Fig. 7 depicts the typical ISL process as used in Kazakhstan. Aerial views of ISL mines showing a central processing plant, an industrial area and extended well fields are shown in Figs 8–10.

6.4.2. Design and operation

The design and operation of an ISL mine and processing plant depend on the nature of the mineralization of the ore body, which determines whether an acidic or alkaline solution is used for extraction. Well field design is determined by local conditions, such as permeability, thickness, deposit type, ore grade and distribution. Well fields are typically designed in spot patterns, with injection wells in the centre, or lines of wells alternating between injection and extraction. In most cases, wells will be used for injection and extraction to maximize uranium recovery throughout the life of the mine.

Compared to normal uranium mining methods, the processing plants for ISL mines are significantly smaller as they have no ore handling, crushing, grinding and recovery processes. In turn, this reduces the risk from some exposure pathways, namely LLRD and RDP. However the design of the operation still needs to take into account radiation risks to ensure adequate controls. The

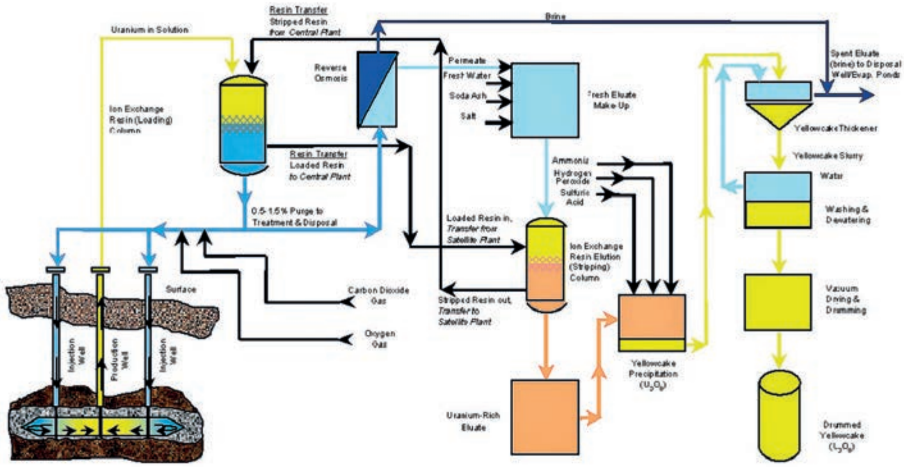

FIG. 6. Alkaline ISL process schematic (United States of America) [25] (fig. 3 of Ref. [22]).

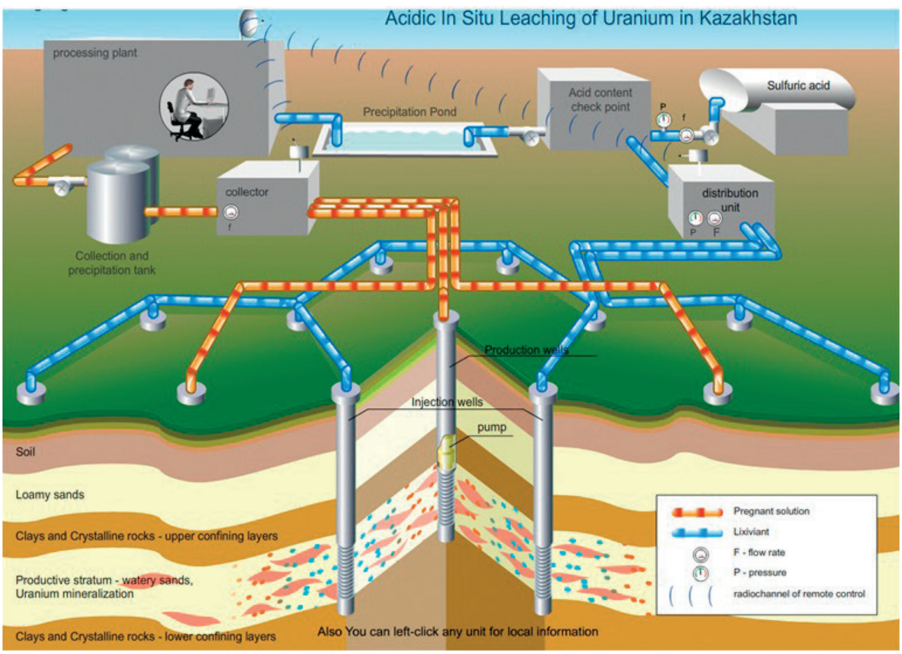

FIG. 7. Acid in situ leach process schematic (Kazatomprom, Kazakhstan).

FIG. 8. Uranium ISL (South Australia, fig. 6 of Ref. [7]).

FIG. 9. Central Mynkuduk uranium ISL complex (south Kazakhstan).

FIG. 10. Wyoming uranium ISL complex (United States of America, fig. 4 of Ref. [22]).

specifics of radionuclide mobilization are important in defining the design and operational parameters, namely:

(a) The radionuclide mixture brought into the processing plant that can become airborne and/or produce surface contamination resulting in potential worker exposure to LLRD and RDP;
(b) The resulting external exposure sources due to concentrations of ^{226}Ra and progeny in process components (e.g. valves, pipes, tanks, filters, clarifiers) and associated wastes (e.g. impoundment areas).

Based on early studies performed at US alkaline ISL mines, Brown [8] reports a relatively small percentage of the uranium progeny in the ore body is mobilized by the lixiviant as the majority of equilibrium radionuclides remain in the host formation [26, 27]. Such values may be process specific (e.g. alkaline versus acid leach) and depend on the age of the facility. It appears that the ^{230}Th equilibrates and very little is removed by the process. The majority of the mobilized ^{226}Ra (80–90%), estimated at 5–15% of the equilibrium radium in the host formation, followed the calcium chemistry in these processes and resulted in radium carbonates or sulphates in calcite slurry bleed streams and associated wastes (see Tables 2 and 3) [8, 27].

TABLE 2. RADIONUCLIDE COMPOSITION OF ALKALINE LEACH LIXIVIANTS (*table 2 of Ref. [27]*)

Lixiviant type	Concentration (Bq/L)		
	^{230}Th	^{226}Ra	^{210}Pb
Pregnant (returning from underground)	56–93	10–150	<1
Barren (being reinjected)	48–81	1.9–4.4	<1

TABLE 3. RADIUM AND RADON CONCENTRATIONS IN PROCESS STAGES (*table 3 of Ref. [27]*)

Process stage	Concentration (Bq/L)	
	^{226}Ra	^{222}Rn
Circulating lixiviant	3–20	300–7000
Calcite in clarifiers	30–100*	n.a.**
Evaporation ponds (in solution)	20–30	Equilibrium assumed
Evaporation ponds (sludge)	30–45	Equilibrium assumed

* Bq/g.
** n.a.: not applicable.

Furthermore [8] (see also Refs [26, 28, 29]):

“The ion exchange (IX) resin used in United States ISR facilities is specific for removal of uranium. Appreciable amounts of thorium and other progeny are not expected in the process downstream of the IX columns (e.g., elution, precipitation, and drying circuits). The radionuclide mixture that can potentially become airborne and result in personnel exposure and area or equipment contamination in the precipitation, drying and packaging areas would be expected to be primarily a natural uranium isotopic mixture with a relatively small progeny component. Although in growth of the first few short-lived progeny (e.g., thorium 234, protactinium 234) is occurring, the in-process residence time is small relative to radionuclide half-lives and therefore time required for appreciable ingrowth. Accordingly, little contribution from these primarily beta emitters is experienced in the radiological aspects of in process materials [and therefore needs little consideration for radiation control design].

"In areas where solid wastes are processed, stored or during maintenance (resin tanks and columns, fabric and sand filters, clarifiers, etc.), mobilized radium 226 associated with calcium and carbonate chemistries may be an important external exposure and/or contamination source [requiring additional design or operational controls (see Appendix IV)].

"During some maintenance activities when systems need to be opened and/or penetrated, aged process material may be encountered containing scale and/or precipitates in pipes, tanks, pumps, etc., which can exhibit elevated beta activity due to ingrowth of short lived thorium 234 and protactinium 234.

"Finally, large quantities of radon 222 gas can be dissolved in the lixiviant returning from the formation is brought to the surface. That portion of the total dissolved radon which is above the solution's saturation value is released when encountering atmospheric pressures and temperatures and can also be released during the decay of radium contained in waste products (e.g., $CaCO_3$/gypsum) being processed and stored at the surface".

The plant design therefore needs to ensure that lixiviant return streams are in low occupancy zones and appropriately ventilated.

At the Honeymoon ISL in Australia, it is reported that concentrations of mobilized radium greater than 100 Bq/g can be associated with the $CaCO_3$ removal process that produces gypsum wastes. This can result in external exposure from radium decay products within precipitated $CaCO_3$ and $CaSO_4$ solids in storage ponds, mixer cells and clarifiers.

The circumstances of in situ mobilization associated with the Kazakhstan acid leach process appear to be similar. The Institute of Nuclear Physics of the National Nuclear Centre of Kazakhstan conducted research to assess the radionuclide composition of the LLRD in the processing plants [30]. Air samples collected in the worker breathing zone indicated that the primary radionuclide components of the LLRD were uranium and ^{226}Ra. On an activity basis, the ^{230}Th concentrations were less than 10% of the total uranium concentration and less than 5% of the ^{226}Ra concentration. Typical radionuclide mobilization reported

TABLE 4. TYPICAL RADIONUCLIDE COMPOSITION OF KAZAKHSTAN ACID LEACH PROCESS SOLUTIONS

Process solutions	Gross alpha activity (Bq/L)	Contribution to radionuclide activity (%)				
		U*	^{230}Th	^{226}Ra	^{210}Pb	^{227}Th
Production solutions (pregnant lixiviant)	840–1350	31–68	19–57	0.5–4	2–15	2–4
Leaching solutions (barren lixiviant)	572–1273	1–5	35–84	2–7	16–24	3–7

* Containing a naturally occurring isotopic mixture of ^{238}U, ^{235}U and ^{234}U.

for the Kazakhstan acid leach processes, based on relative contribution of alpha activity in solutions, is shown in Table 4 [31].

6.4.3. Principal exposure pathways

6.4.3.1. External exposure (gamma)

Radiological sources which can cause elevated external exposures are primarily associated with radium concentrates in certain process components and wastes. As with any uranium mill, there is also the external exposure associated with back end process areas, where large quantities of yellowcake concentrates are produced, packaged and stored (precipitation, drying, packaging). There can be extremity exposure from beta activity associated with the first few ^{238}U progeny as well (^{234}Th, ^{234}Pa), particularly during maintenance activities involving the penetration of systems, and this needs to be evaluated on a case by case basis.

6.4.3.2. Inhalation of radon and radon progeny

The importance of radon gas and its progeny for occupational exposure in underground mines at conventional uranium recovery facilities is well documented in the history of uranium mining [32–34]. In solution mining processes [22]:

> "It appears that the majority of radon which is released at the surface is not, as at a conventional mill, a result of on-surface decay of radium over time. The radon is brought to the surface dynamically, dissolved in the lixiviant

returning from underground. Just as dynamically, that portion of the total dissolved radon which is above the solution’s saturation value is released when encountering atmospheric pressures and temperatures”.

Radon gas is also released during the decay of radium. Accordingly, radon and its progeny may be present where waste products (e.g. $CaCO_3$) are being processed and stored at the surface. Depending on the plant design, the concentrations in occupied areas can be of significance in the absence of adequate ventilation. However, radon progeny concentrations may be low because of the disequilibrium with the fresh radon resulting from the time needed for ingrowth from the radon parent [27]. Since radon can be released from the lixiviant and radium can buildup in pipework and vessels, maintenance activities inside vessels could result in exposure to radon and radon progeny.

6.4.3.3. Inhalation of long lived radionuclide dust

This pathway is almost exclusively associated with the yellowcake drying and packaging areas, since up to the drying step, the ISL process is essentially aqueous and the risk of significant dust generation elsewhere in the process is low. However, there is a risk of exposure to LLRD anywhere in the process if spills of process materials are not expeditiously and adequately cleaned up before they dry.

6.4.3.4. Internal exposure via surface contamination

Similar to conventional mills, surface contamination can become a potential inhalation or ingestion exposure pathway owing to poor housekeeping and allowing spilled solutions to dry and resuspend material into the air. Accordingly, standard contamination controls, radiological surveys and a rapid response to process spills or other loss of containment events reduce the potential for this pathway.

6.4.4. Control mechanisms

The key design considerations for ISL mines are not much different from those for conventional uranium mills for controlling worker exposures in accordance with ALARA principles. Specific considerations for ISL mines, however, also include:

(a) Maintaining adequate ventilation in general process areas, including consideration for local exhaust on vessels and tanks, to contain and remove potential releases of radon (minimizing the potential for ingrowth of radon progeny) and LLRD from process vessels and systems.

(b) Minimizing worker time in process areas and in a practical way maximizing the distance between workers and large sources of radioactive materials such as:
   (i) Ion exchange columns;
   (ii) Solvent extraction circuits;
   (iii) Solution clarifiers and filters in which large quantities of radium can collect;
   (iv) Yellowcake areas, including precipitation, drying and packaging areas.

(c) Providing adequate containment in the event of spills and leaks (sumps and berms adequate to contain associated maximum tank or vessel volumes), given the aqueous nature of ISL processes.

(d) Possessing methods to quickly wash down and remove spilled process materials to minimize airborne releases via the resuspension of dried dusts.

(e) Providing adequate ventilation and dust control in yellowcake areas (precipitation, drying, packaging).

6.4.4.1. External exposure

As noted previously, gamma radiation is present as a hazard in the drying, packaging and storage areas of an ISL operation. This can be controlled through the facility design by making these locations low occupancy areas and ensuring that the product is stockpiled far from work areas in a secure facility with restricted access. In addition, owing to the potential for radium to build up within the pipework and vessels in the aqueous portion of the plant, controls include appropriate cleaning and purging of these systems. Work permit procedures need to review the gamma radiation dose rates at any work area where the risk of gamma radiation exposure from scale has been identified as a potential hazard. Depending on the process location and the specifics of the process chemistry, these scales and residuals can contain beta emitting radionuclides as well as radium precipitates.

6.4.4.2. Radon and radon progeny

Radon gas exposures in front end process areas arising from radon bearing lixiviant returning from underground can be controlled by limiting worker occupancy [8]:

> “Depending on design specifics, ...local exhaust systems on front end tanks and vessels are sometimes necessary to collect and remove the fresh radon

gas before significant progeny ingrowth can occur in work areas. Most of the gas is released within the first few process areas, wherever first exposed to atmospheric pressure. Depending on design specifics, this can be at surge ponds and tanks, at the tops of the ion exchange columns and/or at the interface between resin loading and elution processes. Process tankage and piping may need to be enclosed and maintained under negative ventilation where practical. In warm climates..., surge ponds located outdoors and/or open top ion exchange columns are often used and therefore most of the gas is released outside of enclosed process areas. In colder climates..., the solutions are piped under pressure directly from enclosed well field valve stations and surge tanks to in plant recovery vessels including the IX tanks themselves. Some of the first generation ISR plants (1970s) used in plant IX surge tanks and up flow, open top IX columns requiring use of local exhaust systems to remove the gas from the vicinity of in-plant vessels before progeny ingrowth became an occupational exposure concern. Recent designs tend towards use of enclosed, pressurized systems for lixiviant recovery and ion exchange using local exhaust on the vessels themselves to remove radon prior to significant progeny in growth. This greatly reduces the potential for radon/progeny exposure in plant areas."

6.4.4.3. Long lived radionuclide dust

Since ISLs are essentially an aqueous process until drying and packaging, Brown [8] reports that control and containment of spills in the process areas via design is essential to reduce the risk of LLRD. During operations, it is also important to rapidly wash down and clean up spills to minimize the formation of dried material, which can become an inhalation hazard via resuspended dusts [8]. As is the case for any uranium mill, enclosure of and adequate ventilation for all drying and packaging circuits and areas is the best control method to reduce exposure to LLRD in the end process sections of the ISL operation.

6.4.4.4. Surface contamination, ingestion, wound contamination and absorption

Standard contamination controls, radiological surveys and a rapid response to process incidents involving spills or other loss of containment events minimize the potential for this pathway. In addition, Brown and Chambers [35] note that given the almost exclusive use of peroxide precipitation and low temperature vacuum dryers in ISL mines in the United States of America in recent years (as opposed to ammonia precipitation and the much higher dryer temperatures used in the past, i.e. in calcining plants), a much more soluble product is being produced by these facilities. Modern peroxide precipitated products dried in low temperature vacuum dryers appear to be quite soluble and meet the ICRP [36] criteria for the type F (fast) absorption category [8, 35]. For these products, chemical toxicity comprises the predominant worker risk from intake, not the radiation dose [35, 37–39].

6.4.5. Monitoring and dose assessment

The characteristics of the radiation protection programme at an ISL facility are very similar and, in many cases, identical to those of a conventional mill. In some important aspects, however, the ISL radiation protection programme needs to be modified. This is primarily due to the specifics of radionuclide mobilization in situ and the general design characteristics of ISL mines that define the radiological environment at the surface. The radiation protection programme elements, including the special considerations for ISL mines are described in the following.

6.4.5.1. External (gamma radiation)

External exposure (particularly extremity exposure) from short lived beta emitting uranium progeny (^{234}Th, ^{234}Pa) can occur during maintenance activities when systems are penetrated or opened [8]. Therefore, beta dose rates have to be measured prior to entry to assess the severity of these potential hazards to extremities [8]:

> "External exposure monitoring...is required primarily in areas in which large quantities of uranium concentrates are processed, packaged and/or stored. Additionally, depending on importance of calcium chemistry in situ and therefore radium mobilization, radium build-up can occur in resin tanks and columns, filter membranes from reverse osmosis water treatment units, fabric and sand filters, clarifiers, etc., where large quantities of radium bearing calcite wastes are precipitated, processed and stored. This can result in requirements for control and monitoring of external exposure during work near these processes, during filter changes and/or maintenance of these systems."

6.4.5.2. Radon and progeny

Airborne monitoring for both radon gas and progeny in occupied plant areas needs to be conducted at locations and at frequencies based on the plant design and measured concentrations. General area monitoring for radon gas, in addition to progeny, is typically necessary to evaluate engineering and radiation protection conditions within general plant areas due to the disequilibrium that can occur between fresh radon and progeny, which was regularly observed in early ISL plants [23]. Appendix III presents methods for radon and progeny measurement and the associated assessment and assignment of resultant dose.

6.4.5.3. Long lived radionuclide dust

Airborne monitoring for LLRD is necessary in some process areas. ISL is essentially an aqueous process until the precipitate slurry is produced. Accordingly, LLRD exposure potential is primarily associated with the precipitation, drying and packaging areas. The monitoring techniques can include combinations of grab sampling, breathing zone sampling and continuous monitoring based on job functions and related radiological and work conditions [8].

6.4.5.4. Surface contamination and control

Contamination surveillance and control is necessary in both plant and non-plant areas. In addition, workers may need to be monitored; and monitoring is also necessary for the release of equipment and materials for unrestricted use into the public domain. Appendix V presents methods for assessing contamination, conducting surface contamination surveys and establishing control limits for contamination.

6.4.5.5. Dose assessment and bioassay

Bioassay programmes have to be designed and executed according to the characteristics of the uranium products to which workers are potentially exposed, since product specific solubility characteristics can have metabolic implications for bioassay and dose assessment. This is discussed in detail in Appendix IV.

6.5. HEAP LEACHING

Uranium is recovered from crushed ore heaps by using a leaching solution applied in situ. This is an alternative first stage of ore processing compared to the more traditional treatment, in which the ore is fed continuously into a chemical engineering process where leachate is contained within recovery tanks. While most of the radiation protection considerations applicable to heap leaching are similar to those for other uranium mining and processing activities, some need particular attention, as outlined in this section. The principal concerns requiring assessment relate to exposure to ore dust during the construction and subsequent removal of the heap, exposure to gamma radiation and the inhalation of RDP for workers who carry out maintenance tasks on the heap during the leaching period.

6.5.1. Process description

Heap leaching involves the application of a leaching solution to the top of a heap of crushed ore to extract the metal contained within (see Fig. 11). Metals that are soluble in the leaching solution (typically an acid) are drawn into solution as the liquid percolates downwards through the heap. The metal bearing solution, or leachate, is collected at the bottom of the heap, where it meets an impervious base, and then pumped away to be reapplied or, eventually, to be further processed to separate out the metal. This process is slow and has to be continued for a long period in order to extract as much of the available metal as possible. For heap leaching of uranium ore, a continuous process of many months may be needed, using dilute sulphuric acid.

6.5.2. Design and operation

Crushed ore may be placed in discrete heaps, with each being leached in sequence, or a continuous process may be adopted by progressively constructing a linear heap with the leaching process following construction (see Fig. 12). The leaching solution is applied through a network of slow release drippers at the top of the heap. An impervious pad at the base of the heap has to be constructed to ensure that leachate does not percolate to the underlying ground. This may include a clay base, for example, covered with a plastic membrane, and may be slightly contoured to allow the leachate to run to the drainage pipework. To protect the membrane and to allow leachate to be drawn off from the base of the heap, a layer of screening material can be used to host the pipework for leachate transport. In

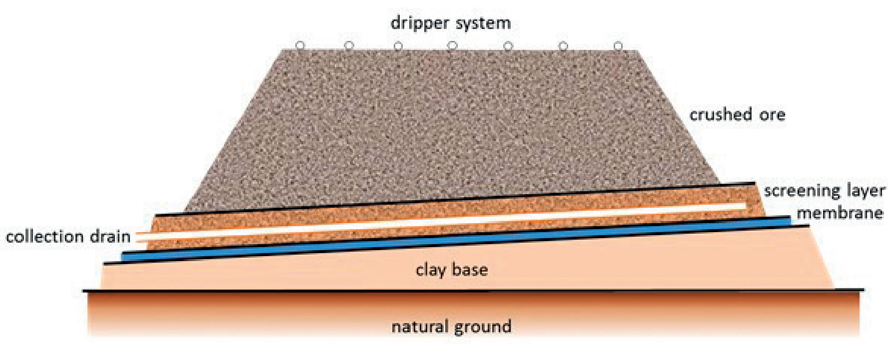

FIG. 11. Heap leaching construction (simplified schematic).

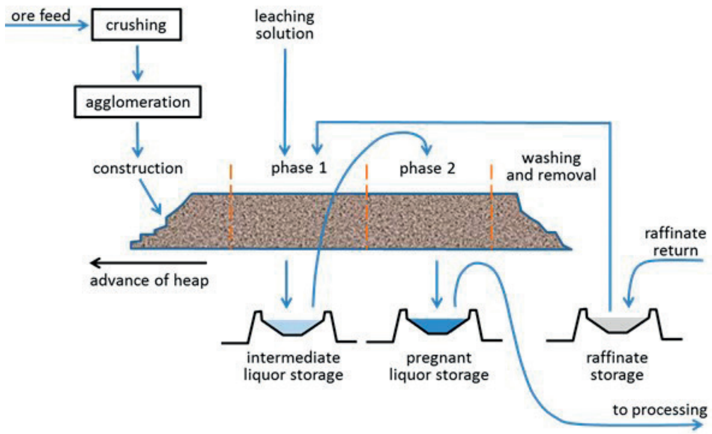

FIG. 12. Heap leaching process (simplified two stage schematic).

addition, some heap leaching processes may employ positive pressure aeration from the base of the heap to improve the leach rate; the pipework for this can also be embedded in the screening layer.

Additional infrastructure is needed for the operation of a heap leaching process. The supply of fresh leaching solution involves a storage and delivery network. The intermediate solutions (leachate that is partially loaded with uranium and which will be reapplied) and pregnant liquor (fully laden leachate) require impermeable retention ponds. Provision also needs to be made to handle natural rainfall, including containment within the site of unusual rainfall events. In the simplest designs, the pregnant liquor will be pumped to a separate processing plant for treatment and the production of uranium oxide concentrates. Some preliminary processes, such as solvent extraction of the uranium, may be carried out within the heap leach area.

6.5.3. Principal exposure pathways

In addition to the more commonplace health and safety concerns relating to heap leaching, such as the potential for physical injury during building and removing the heaps, working at heights and on uneven and unstable surfaces, and handling pumped acidic solutions, the leaching of uranium ore raises radiation protection issues, which are discussed in the following.

6.5.3.1. Exposure to external radiation

The intensity of gamma radiation depends on the uranium ore grade. Typical exposure rates of ore stockpiles lie between a few μSv/h for low grade ore (below ~0.1%) and a few tens of μSv/h for higher grade ores (~1%), and they vary with the area, depth and geometry of the heap. There is little that can be done to restrict exposure to external gamma radiation other than to control the amount of time that workers need to spend on, or close to, the heap, although the cabins of the heavy vehicles used in construction and removal operations afford a degree of shielding for the driver. Optimizing protection from this pathway focuses on restricting the time spent on, or close to the heap.

6.5.3.2. Exposure from inhalation of radon and radon decay products

The rate radon gas diffuses from a heap of uranium ore depends on factors such as ore grade, crushed rock size, moisture content of the ore, meteorological conditions and, where applicable, the rate of any aeration applied. Under dry conditions, exhalation rates are around 50 $Bq\cdot s^{-1}\cdot m^{-2}$ per % ore grade; under normal operation, with the heap saturated with leaching solution, the exhalation rates will be an order of magnitude lower. When aeration is applied to the heap, exhalation rates are expected to rise.

Due to natural dispersion processes and dilution of the exhaled radon, the exposures of persons remote from the heap will usually be negligible. However, some workers carry out periodic inspection and maintenance tasks for the dripper system at the top of the heap, and drivers of vehicles engaged in constructing or removing the heap will be in close proximity to the ore. Optimization of protection will focus on limiting the time spent on, or close to, the heap and on providing filtered air cabins for vehicle drivers.

6.5.3.3. Exposure from inhalation of radioactive material

Once constructed and in operation, an ore heap is kept wet by applying the leaching solution, and ore dust from the heap is minimal. Hence, inhalation of ore dust will only be significant if there are interruptions to the feeding of the leaching solution or breakdowns in the feed pipes, which can lead to the core drying out. However, the potential for inhalation of ore dust will need to be addressed during construction of the heap or its removal on completion of the leach cycle. Continual wetting of the heap surface at the point of delivery or removal can be part of a strategy for optimization of protection, as can the use of filtered air cabins for ore handling and ore transport vehicles.

6.5.3.4. Exposure from ingestion of radioactive material

Ingestion of radioactive material is not expected to be a significant pathway of exposure, provided good occupational hygiene practices are followed, such as no eating, drinking or smoking while working directly on heap management operations.

6.5.4. Control mechanisms

A heap of uranium ore in the open presents a large source of relatively low concentration radioactive material for which little can be done in the way of shielding from external radiation or of mechanical containment of any emissions. The control of occupational exposure will depend primarily on restricting the time spent on, or close to, the heap and on ensuring that the heap remains saturated to restrict the emission of radon and ore dust.

During construction of the heap and its removal (e.g. using haul trucks and front end loaders), vehicles need to be fitted with filtered air cabins, and drivers have to avoid opening windows and doors as far as practicable. At these times, site access other than in filtered air vehicles needs to be controlled, and dust masks worn to restrict dust intake. Workers who perform maintenance and inspection tasks are expected to organize their work to restrict the time spent on the heap by careful planning prior to access. Where working conditions create a need for frequent hydration, provisions for drinking from uncontaminated water bottles or water fountains need to be made.

6.5.5. Monitoring and dose assessment

A risk assessment and exposure pathway analysis needs to be performed to establish the types and frequency of monitoring required to demonstrate compliance with health and safety standards and with the principle of optimization of protection. Provided that good occupational hygiene practices are observed, intakes of radioactive material other than by inhalation are expected to be negligible. The three key pathways of exposure that require attention are thus external gamma radiation, inhalation of radon and RDP and inhalation of ore dust. If chemical processing of the leachate takes place near the heap, additional monitoring may be necessary.

Prior to construction of the heap, estimates of the exposure conditions likely to be encountered need to be made based on earlier experience within the operation or from other sources, including a knowledge of the ore grade and construction method. As a precaution, some personal monitoring is advisable for all three pathways of exposure in the initial stages of construction until reliable data on exposure conditions become available, although this does not need to be done for every worker. Similarly, during the initial operation of the heap with the application of leaching solution, personal monitoring will assist in establishing an appropriate monitoring programme for subsequent routine operation.

For exposure to RDP, it may also be necessary to carry out an intensive area monitoring programme (in a representative area) at the start of leaching operations to establish the radon exhalation characteristics of the heap and to provide information on the variation of radon concentrations with height above the heap surface. Some of the maintenance work on the dripper feed system for the leaching solution will involve crouching close to the heap surface. The radon dispersion and dilution levels may be lower near ground level than at the breathing zone when standing, although this is unlikely to be significant, except in very still air conditions or during atmospheric inversions. Furthermore, if personal monitoring of RDP shows intakes to be small, more comprehensive monitoring might not be needed.

For external gamma radiation in routine operation, personal dosimeters are readily available for the relatively few workers who need to work on, or close to the heap and the cost will be modest. All workers can be issued with personal dosimeters and their external dose records maintained. For routine monitoring of the inhalation pathway, the situation is more complex. While personal monitoring equipment is available, its use can be complicated, cumbersome and moderately costly, and it is unlikely to be necessary for every worker to carry personal monitoring gear. For workers in the cabins of construction vehicles, monitoring within the cabin can provide a good alternative to wearing personal monitoring equipment. Given the proximity to the surface exhalation of radon, the disequilibrium of RDP can vary considerably, depending on factors such as location and wind conditions. Hence, a radon decay product monitoring technique that accounts for disequilibrium is preferable.

The results of the initial monitoring and dose assessment programme will allow the subsequent routine programme to be designed and implemented. For example, decisions can be taken on the fraction of the workforce who needs personal monitoring to be confident that the results could be used for the dose estimation for the whole group. Similarly, the extent and frequency of any area monitoring that is required can be determined.

6.6. PROCESSING FACILITIES

6.6.1. Process description

Once uranium ore has been mined from an ore body, it requires additional processing to concentrate it and remove impurities to then produce the final product. In general, uranium processing facilities contain many circuits, each of which has its own specific radiation concerns. These can vary greatly depending on many factors, such as age, the expected composition of the uranium ore to be processed, and environmental constraints. However, there are general features which are common to all. Figure 13 provides a simplified flow chart of a uranium extraction process while Fig. 14 provides a more specific flow chart for the McClean Lake mill in Canada [39].

6.6.1.1. Ore handling and preparation

Ore blending may be necessary when a uniform grade is required for processing. In anticipation of processing, ore is often stockpiled on a pad, where it can be mixed, as needed. Uranium ore is mechanically reduced in size to increase the efficiency of extraction, and the processes can involve crushing, ball mills, rod mills, or autogenous or semi-autogenous grinding processes. In cases where slurry is created directly from an underground mine, or after the grinding process has been completed, material is pumped into storage tanks and held in preparation for blending and leaching. Slurry density is often adjusted in thickener tanks to prepare it for processing.

6.6.1.2. Uranium leaching into solution

Ore slurry is transferred from storage vessels to the extraction circuit. Uranium is leached from ore using either acid or alkali leaching processes, largely depending on the geochemical properties of the ore. Leaching vessels are typically connected in series, with one tank feeding another. Chemical reagents are mixed into each tank, as needed.

6.6.1.3. Classification and liquid–solid separation

After extraction, material is transferred into a series of tanks designed to separate the uranium bearing solution from the remaining solids and extract any residual uranium. Solid material is directed towards the tailings circuit, while the uranium bearing solution is directed towards the concentration and purification circuit.

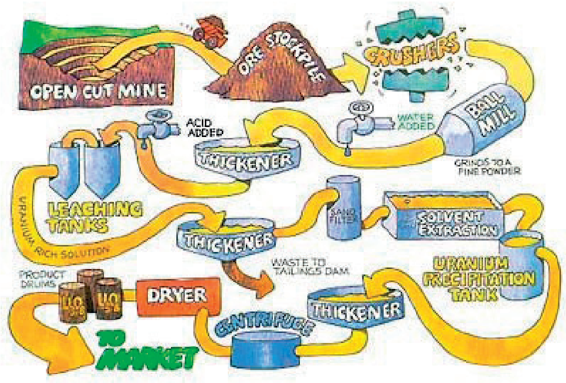

FIG. 13. A simplified uranium processing flow chart (see www.chemcases.com/nuclear/nc-06.htm).

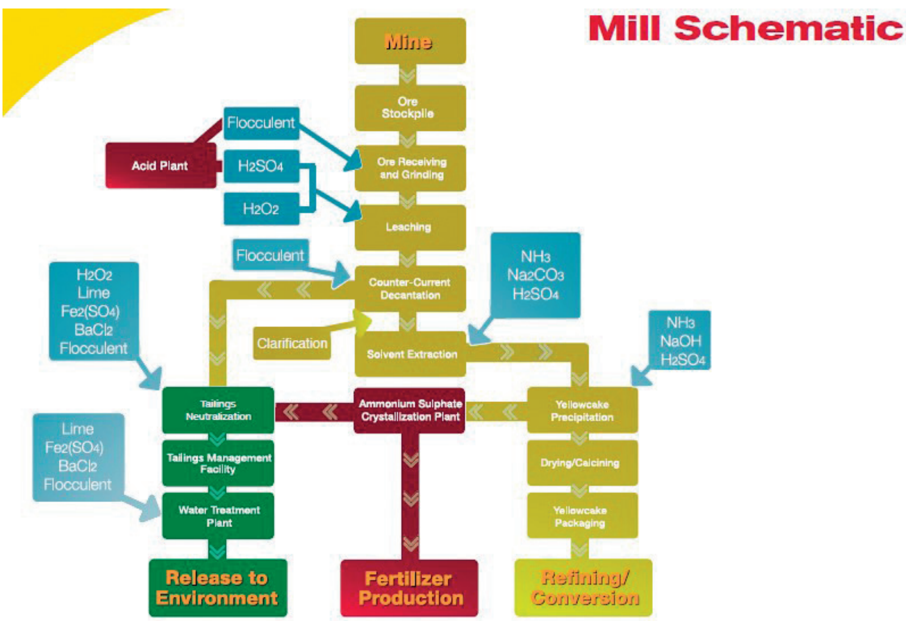

FIG. 14. Specific schematic of the processing (courtesy of D. Chambers, SENES Consultants).

6.6.1.4. Concentration and purification

To remove any remaining suspended solids, the uranium bearing solution is passed through a collection of tanks and filters. Once filtered, the solution is sent to the extraction circuit, while the solids are returned for further separation. The uranium bearing solution undergoes a series of chemical transformations to produce a more concentrated solution. Common techniques include solvent extraction and ion exchange. Once most of the impurities have been removed, the solution is sent for precipitation, where the uranium is chemically changed into a solid. After the uranium has been precipitated it is allowed to settle out in solid form. The solid material is sent to a thickener tank to increase its density. This solid uranium compound is then sent to a drying circuit.

6.6.1.5. Drying and packaging

The final step in the process is drying and packaging. Excess liquid is removed prior to drying by using filters or centrifuges. Drying is performed with either a low temperature dryer or a high temperature calciner. The chemical composition of the final product depends on the temperature at which it was dried. In a low temperature dryer, solid uranium compounds are dried at around 300°C and transformed into a soluble uranium final product. In a high temperature calciner, solid uranium is dried at around 800°C and transformed into an insoluble uranium final product. Once the uranium product has been dried, the product is packaged into drums for storage and transport. Ideally, the product packaging stage is carried out using an automated, ventilated drum filler to reduce occupational exposures.

6.6.1.6. Final product storage and shipping

Uranium final product drums awaiting shipment need to be stored in a secure, clean area with restricted access. A typical storage arrangement could be a separate building or shipping containers packed and awaiting final shipment. Owing to the ingrowth of decay products, uranium product stored for an extended period will gradually emit increasing amounts of gamma radiation.

6.6.1.7. Tailings preparation and storage

Waste streams from every part of the process are concentrated and treated in tailings preparation tanks. There are typically multiple treatments due to the variety of materials in the waste streams. Once treated, the tailings are thickened and deposited for long term storage. Treated tailings need to be stored in a manner that reduces the potential for negative consequences to the environment and the general population in the long term. They are often stored in specifically constructed cells, mined out surface pits or mined out underground drifts in such a way that they remain isolated, contained and chemically inert.

6.6.1.8. Water treatment

Water used during uranium processing usually requires treatment before release into the environment. Part of the treatment process can involve the removal of radioisotopes and other pollutants through precipitation. In the case of radium removal, the potential for RDP generation and localized gamma dose rates needs to be addressed in the monitoring programme.

6.6.2. Design and operation

The design and operation of a processing facility depend on local site specific factors. Factors such as the grade of the ore, the type of mineralization, the availability of reagents, the availability of waste disposal facilities and the volume of ore to be processed are critical in the design of the facility. External factors such as the topography of the region, the weather, water availability, the amount of land available and nearby public populations can also influence the design of the facility.

Most uranium processing plants are designed for the most efficient extraction. This generally means that the distances between plant sections and the amount of crossing over between the sections are minimized. Sometimes local topography is used to allow gravity to assist in the flow of material within the process. The ability to change or expand the process is a critical design decision and plants have experienced significant difficulties by not considering this in the design phase. Consideration of maintenance needs is also critical during the design phase and aspects such as access for heavy lift cranes need to be assessed. As uranium operations can be in remote areas, associated infrastructure such as power, water and transport are also critical.

Consideration of radiological aspects during design is not always a priority for the design engineers. Historically, this has led to increased occupational doses during either operations or maintenance. During design, radiation exposure may be one of the key considerations, depending on the ore grade and processing techniques. For example, an aspects to be considered is the proximity of large volumes of ore or waste to personnel (e.g. in stockpiles, processing tanks, tailings storage). The ore stockpiles are often located adjacent to the processing plant for efficiency, and this can result in increased occupational exposures.

Potential exposures can be greatly reduced at the design stage by proper consideration of engineered controls. As most of the processing plant is wet, ease of cleanup and containment of spills can offer the dual benefit of lower doses and more efficient plants. For areas where there is higher potential for exposure, such as during uranium final product packaging, additional engineered controls can be incorporated, such as negative pressure rooms and automated drum filling and cleaning.

Processing uranium ore is normally relatively easy to control and as the material is contained within the plant, occupational exposures are generally stable and well defined. However, unexpected sources of exposure can occur that were not considered in the process design or when the plant does not operate as designed. These can arise from changes in the plant (e.g. leaking pipes or changed ventilation), changes in personnel practices and changes in the ore composition, as a result of changes in reagents or as the result of material accumulation over time (e.g. scale in pipes and tanks). The impact can be significant for occupational doses if they are not detected by the monitoring programme. Maintenance is also a critical consideration for occupational exposure at uranium processing facilities. Activities involving vessel entries, scale removal, tank cleanout, ventilation repair and baghouse filter changes have a high potential for occupational exposure. Ideally, both the plant and the task will have been designed with dose minimization in mind.

An important radiological consideration in the design and operation of the processing facility is potential disequilibrium across the circuit. For most plants, there is extremely good information on the behaviour of uranium (^{238}U, ^{234}U, ^{235}U), since uranium is the target ore and it is relatively easy to measure using conventional chemical instruments. However, the behaviour and disposition of the other radionuclides (^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po) are far less well known and can change the potential for occupational exposure. The general approach is that the material can be considered to be in equilibrium prior to the addition of water in the grinding phase. After this point, the various radionuclides in the uranium series behave according to their chemical and physical properties. After leaching, it can be assumed that the liquor has enhanced uranium and the solids have reduced uranium, and that only uranium isotopes are present in the final product recovery area. Care needs to be taken with this general approach; performing a radionuclide balance on the process is the best way of ensuring that the behaviour of all radionuclides is understood.

6.6.3. Principal exposure pathways

For most processing plant workers, the principal exposure pathway is external gamma radiation because most processing is in the form of a liquid or saturated solid and the material is fully contained in the process equipment. In these cases, the exposure from inhalation of both long lived alpha emitters in airborne dust and radon progeny is negligible. However, there are many exceptions, such as initial ore crushing, cleanup of spills, maintenance activities and activity in the product packaging area. Radon gas is released during the processing of the ore and if there is insufficient ventilation (either natural or forced), radon progeny exposure can become significant.

The amount of gamma exposure in a facility will depend on the uranium ore grade, the quantity of ore and the proximity of ore to the general work areas. Beta radiation can also pose a hazard in a processing facility, particularly to the eyes. Ore stockpiles and tanks are often the largest source of gamma radiation. Over time, tank liners can become entrained with gamma emitting radionuclides, which cannot be easily removed. Material buildup in back end processing tanks and recycled process water piping can result in steadily increasing gamma radiation exposure rates due to the ingrowth of uranium decay products. Even when emptied and flushed, tanks can be significant sources of gamma radiation, and the dose rate will depend on the size of the tank and the ore grade being processed. Any work done to repair tanks or tank liners needs to be closely managed, with gamma radiation monitoring, including EPDs, where appropriate.

Initial ore crushing is generally performed on relatively dry material, so dust is likely to be generated. Control mechanisms such as water sprays, ventilation and the exclusion of personnel from the area can reduce this potential pathway.

The cleanup of spilt material can give rise to enhanced gamma exposure and has the potential for dust generation and subsequent inhalation. Where possible, wet cleaning methods, such as hosing into sumps, are to be used. Another area of cleaning is the collection of accumulated dry material, such as spilt material from conveyors and accumulated material around deteriorating tanks and piping. Cleanup of this material may need to take place in dry conditions, so PPE precautions against inhalation may be warranted.

During maintenance activities the inhalation of both radon progeny and dust needs to be considered. Enclosed vessels or areas can have elevated radon gas levels and a good standard practice is to perform a radon or radon progeny measurement before any vessel or confined space entry. Radon exposure also needs to be considered in other areas of poor ventilation, such as reclaim tunnels under ore stockpiles. A good practice is to flush with clean air prior to personnel entry. Inhalation of radionuclides in airborne dust is possible when dry operations are being performed. Water based cleanup is to be used, where possible. The potential for inhalation of dust needs to be considered for any maintenance work which is either in inherently dusty areas (e.g. ventilation system maintenance, filter changes) or directly generates dust (cutting, grinding).

In most processing plants, the highest potential exposure is associated with the inhalation of uranium isotopes in airborne dust within the final product packaging area. This is due to a combination of the material being dry and hence able to become airborne and the far higher specific activity compared to elsewhere in the processing plant. Special monitoring and control mechanisms are usually put in place in the packaging area to control this potential dose. The greatest risk of internal exposure occurs when process material is released from containment. In the precipitation and solvent extraction circuits, material is more readily inhaled or ingested after it has been dissolved into water used for cleaning. Mist escaping from tank hatches can also contain soluble radioactive material.

6.6.4. Control mechanisms

Ideally, radioactive material is contained to minimize exposure to the general workforce. This is especially true when large quantities of material are being stored or transferred. Secondary containment such as enclosures or bunded or bermed areas is extremely effective at isolating material from the general work areas when primary containment fails or has to undergo maintenance.

In a processing facility, gamma radiation is often considered to be the primary radiation hazard. Significant quantities of product need to be stored away from personnel, and any work done in a storage areas minimized. If gamma radiation dose rates are expected to be higher than workplace objectives, placing tanks within well shielded enclosures needs to be considered. If work takes place near large sources of gamma radiation for an extended period, shielding can reduce gamma dose rates to acceptable workplace levels.

Slurry or tailings transfer pipes need to be located a reasonable distance from general walkways and work areas. When this is not feasible, localized gamma radiation can be controlled by wrapping pipes with a shielding material, such as lead. Care needs to be taken to ensure that piping can withstand the increased weight of any added shielding.

Well designed ventilation systems may be needed to control worker exposure to airborne radiation hazards. Where there is a high potential for exposure, storage and processing tanks can be ventilated individually and the air exhausted away from working areas. If possible, the tank process exhaust will have redundant fans to maintain ventilation in case of a primary fan failure. The tanks can be negatively pressurized to prevent radon and radon progeny from escaping in the event that the tank hatches are opened for inspection or sampling.

Buildings which house the majority of the processing equipment can benefit from a single-pass ventilation strategy, such that clean air is loaded with contaminants of increasing concentration before being exhausted. In buildings with multiple floors, air needs to be drawn down to lower floors before being exhausted, as radon will naturally collect in low lying areas. It is especially important that the building exhaust location is carefully selected so that the ventilation intakes are unlikely to recirculate contaminated air and to ensure that outdoor work areas are not in the exhaust stream.

Offices and control rooms are generally considered to be clean areas, free of radioactive contamination, and need to be isolated from the main processes of a facility. When this not possible (e.g. control rooms are usually in, or close to, the work area), routine workplace cleaning of floors, tables, desks and computers can help to reduce exposure. Care is needed to ensure that contaminated PPE is cleaned or removed before entering or working in an office or control room. When offices or control rooms are located near gamma radiation sources, shielding can ensure that dose rates are within workplace objectives. Positive pressure ventilation can ensure that offices and control rooms are kept free of airborne radiation hazards.

Although ventilation is less of a concern in open air facilities, it is important to identify the location of all source terms with respect to regular working areas. In the case of open air ore and slurry storage, it is possible to experience larger than expected concentrations of radon and radon progeny under calm weather conditions.

A wide range of administrative controls can minimize doses within a processing facility, including the use of safe working levels, controlled and supervised areas, and restrictions on access and the consumption of food and water. An appropriate level of training for all staff and feedback to them on the radiation levels in work areas can prove very effective at reducing doses. This training can include detailed information about the specific radiation risks in an area, particularly for higher potential exposure tasks and areas such as final product packaging and maintenance operations. External factors also have to be considered, such as the impact of weather: rain, temperature inversions, still winds and hot and cold spells can all effect radiation exposure.

A key aspect of the facility waste management programme is to develop a system whereby contaminated items are collected and stored separately from clean items. Special bins for contaminated waste need to be readily available wherever waste is generated. In certain locations, waste disposal may be frequented by wildlife foraging for food, so any edible waste can be isolated from contaminated waste to prevent the ingestion of radionuclides by wildlife. Incinerating food waste may need to be considered if segregation is ineffective.

A uranium operation is expected to consider all potential accident situations when developing an emergency response plan. In most operations, the potential radiation exposure is not significant enough to prevent emergency responders from performing their duties. This is not necessarily the case in very high grade uranium processing operations and a more thorough analysis is necessary. Some accidents can also result in significant contamination with radioactive liquids and slurries, which has to be addressed in the emergency response plan, along with the appropriate protective measures.

6.6.4.1. External exposure

External exposure to gamma radiation is controlled by time, distance and shielding. The time spent near localized gamma sources needs to be minimized or the work needs to be performed at a distance from significant gamma sources. Fixed work stations ought to be in low dose rate areas. The use of modern EPDs can be very effective in controlling and reducing gamma doses.

6.6.4.2. Radon and radon progeny

If there is not sufficient natural ventilation, radon and radon progeny can increase in concentration in enclosed areas. Fresh air drawn into the facility needs to move through areas in order of increasing radon concentrations. If possible, air should be moved through the facility with a single pass. Process tanks can be ventilated so that radon gas does not build up in the work areas. Exhausts need to be suitably diluted and discharged away from all fresh air intakes to reduce the likelihood of recirculation. A separate fresh air supply to control rooms can ensure that radon and progeny concentrations are minimal. By ensuring that the control room is positively pressurized, airborne contaminants cannot build up past the concentrations present in the air being supplied to the room. The ventilation system is expected to have the capacity to increase the number of air exchanges in working areas if needed.

6.6.4.3. Long lived radionuclide dust

The primary control of LLRD is through proper containment. Exposed ore fines with the potential to become airborne are to be kept wet to prevent suspension in the air. In the drying and packaging areas, automated, ventilated drum packaging equipment is expected to be installed and controlled from a positively ventilated control room.

Specialized PPE, including respirators, needs to be used when handling dry uranium concentrate. Exposed yellowcake needs to be contained in separate enclosures with negative ventilation to prevent contamination of the general workplace. Exhaust scrubbers are to be used to prevent yellowcake dust from contaminating the environment surrounding the facility.

Having the capacity to increase the number of air exchanges in working areas will help to reduce LLRD concentrations if they become elevated due to an abnormal operating condition. If such ventilation is available, care needs to be taken to ensure that pressure balancing and direction of airflow is maintained. This will ensure that contaminated air is not transferred to cleaner areas, especially control rooms and offices. If work has to be performed in elevated dust conditions, respirators are to be used as a last resort (e.g. vessel entry).

6.6.4.4. Internal exposure

The most effective way to prevent internal exposure is to prevent direct contact with radioactive material. All preventative measures used to protect workers from elevated LLRD can prevent other internal exposures. If workers are directly exposed to soluble forms of uranium, additional PPE such as disposable coveralls, respirator, or splash shield needs to be used. Tanks containing soluble radioactive material have to be ventilated to prevent uranium bearing mist from escaping tank openings. If the sampling of soluble radioactive material is necessary, a sealed sampling port needs to be installed that prevents direct contact with the material. Sharp contaminated objects need to be moved with remote equipment whenever possible. If this is impractical, puncture and cut resistant PPE needs to be made available.

6.6.5. Monitoring and dose assessment

6.6.5.1. External exposure

For monitoring individual external exposure, the most common technique is the use of TLDs or OSLDs, which provide a cheap, reliable and accurate means of monitoring individual exposure over longer periods of up to a month. Workgroup averaging can be used to determine the external dose. For higher exposed individuals, EPDs can help to determine time of exposure and to provide improvements in dose control. Gamma dose can be estimated from area monitoring and time occupancy data.

Monitoring work areas helps to ensure that daily exposures to gamma radiation are within acceptable workplace limits. Sampling frequencies are determined based on area occupancy and the variability of gamma exposure rates in the area. Where gamma radiation dose rates fluctuate significantly, continuous monitors (EPDs) can be installed to warn workers when workplace exposure levels are elevated.

Beta radiation monitoring is rarely necessary in a uranium processing facility, where workers wear conventional PPE, including coveralls, gloves and safety glasses. In unusual circumstances, beta monitoring might be advisable if there is concern about exposure to the eyes.

6.6.5.2. *Radon and radon progeny*

Routine monitoring for radon and radon progeny is performed to ensure concentrations are within acceptable workplace limits. The monitoring frequency depends on the workplace occupancy and the likelihood and levels of contamination. Where radon and radon progeny concentrations fluctuate significantly, continuous sampling, alarming monitors can warn workers when workplace concentrations are elevated. Radon monitoring in process ventilation streams can identify the most significant radon sources in the facility. Prior to undertaking maintenance operations, such as vessel entries, it may be prudent to perform radon progeny monitoring.

Area monitoring of radon and radon progeny concentrations can be used along with workplace occupancy to estimate the total effective dose. This method is adequate when airborne concentrations are relatively consistent in most work areas. However, this method is the least accurate for determining radon and radon progeny exposure and is best used when exposures are low. For more personalized and accurate readings, personal alpha dosimeters can be considered.

6.6.5.3. *Long lived radionuclide dust*

Regular monitoring of the workplace can help to ensure that exposure to LLRD is well controlled. The monitoring frequency depends on workplace occupancy and the likelihood of airborne contamination. Where spontaneous dust generation is likely to occur, or where the risk of LLRD exposure is significant, continuous monitors can be used to warn workers when concentrations are elevated.

Area monitoring of LLRD concentrations can be used along with workplace occupancy to estimate total effective dose. This method is most effective when airborne concentrations are relatively consistent in each area. It is typically the least accurate method for determining LLRD exposure and is best used when exposures are low. For more personalized and accurate readings, personal monitoring needs to be considered.

6.6.5.4. *Internal exposure*

The potential for internal exposure can be monitored and controlled using a programme of contamination monitoring and administrative controls. If there is significant potential for internal exposure, bioassay monitoring might be appropriate when workers have direct contact with radioactive material. In vitro bioassay, in particular urinalysis, is used in some uranium processing facilities to monitor radioactive intakes. In vivo measurements, such as lung counting, can be useful for acute exposures or routine long term monitoring of workers. Bioassay may also have a role following an emergency or non-routine exposure.

6.7. NON-CONVENTIONAL URANIUM EXTRACTION

6.7.1. Process description

The majority of global uranium production is from mines where uranium is the only product, and include open and surface mines, ISL and heap leach operations, and a variety of extraction and processing methods. However, uranium has also been produced as a by-product from other types of mine and process, such as:

(a) Copper mines (Australia, South Africa, Zambia);
(b) Gold mines (South Africa);
(c) Nickel mines (Finland);
(d) Phosphate mines (Egypt, Islamic Republic of Iran, Jordan, United States of America);
(e) Vanadium mines (United States of America);
(f) Silver mines (Czech Republic, United States of America);
(g) The treatment of water containing uranium (Canada, France, Germany, Hungary).

Uranium has also been produced as a by-product of other metalliferous mines for over sixty years. In addition, over the past fifty years many operations have produced small quantities of uranium as a by-product of the treatment of mine water. Other operations (particularly in South Africa) have reprocessed old slimes dams to produce uranium and gold. By-product recovery of uranium accounted for approximately 5% of total global production in 2016.

6.7.2. Design and operation

The design and operation of the uranium extraction and production plants is similar to those described in detail for the major producers elsewhere in this publication. Many of the by-product plants produce small amounts of uranium in the range of 10–150 t/a. As a result, the uranium extraction sections are usually significantly smaller than those of the major producers.

6.7.3. Principal exposure pathways

The principal occupational exposure pathways during non-conventional extraction of uranium is very similar to the main methods of mining and extraction. In most cases, the major exposure pathway will involve gamma radiation and the inhalation of long lived alpha emitters in the extraction plants. Radon gas exposures will be insignificant in surface operations but may be a significant dose contributor in some underground operations. By-product mines tend to have very low uranium ore grades, resulting in very low occupational exposures in those parts of the operation leading up to the uranium extraction and recovery stage.

6.7.4. Control mechanisms

Owing to the small production quantities and low ore grades in by-product mines, annual exposures can be lower than those prevailing in the major producers; however, in the uranium extraction and product sections, a similar level of control is necessary compared to major producers.

6.7.5. Monitoring and dose assessment

The monitoring and dose assessment programmes in by-product facilities are site specific; however, in the uranium extraction and product sections, a similar level of control is necessary compared to major producers.

6.8. HIGH GRADE ORE MINING AND PROCESSING

6.8.1. Process description

In some areas, uranium has naturally concentrated to present very high ore grades. At these high grades (a few to tens of wt% of uranium), the controls and the associated monitoring programmes are significantly more rigorous than for lower grades. However, the general approaches to monitoring and control still apply.

The high concentration of uranium and its decay products in the ore means that all exposure pathways become far more significant. In particular, high gamma radiation fields will be present in areas close to the ore and any airborne dust can have significant radioactivity. The shielding of plant items and entry restrictions for certain areas become important control mechanisms. A key objective is to isolate workers from the high grade materials. Radon concentrations during entry into areas of mineralization or those impacted by radon contaminated water can become significant. Furthermore, contamination control to prevent the potential for accidental intake through ingestion, inhalation, or wounds (i.e. wounds directly contaminated with radioactive materials) become far more important.

In high grade ore mining, more stringent controls on the handling and disposal of waste materials may also be necessary. Tailings retain most of the radioactivity of the ore and the waste rock can still retain significant quantities of uranium.

6.8.1.1. Underground mining

For underground high grade deposits, the general approach is to use non-entry mining methodologies (see Section 6.2.1.6). Three common mining types include boxhole boring, raise boring and jet boring.

Box hole boring uses a boring machine to grind out a cylindrical section of the ore body. The machine pushes the reaming equipment from below, leaving the cuttings to fall through the reaming head into the collection system installed below. The box hole machine and associated ore collection system needs to be ventilated adequately to contain RDP and LLRD, typically under negative pressure from a secondary ventilation system — radon and radon progeny can reach significant concentrations. Once a box hole chamber has been mined, it is backfilled so that a new box hole can be mined next to it.

Raise boring also involves using a large cutting drill to bore a cylinder through the ore zone. The main difference is that drifts are established above and below the ore zone and the raise boring machine pulls the drill head from the bottom chamber up through the ore zone. Similar to box hole boring, the raise bore machine in the upper chamber needs adequate ventilation to control RDP and LLRD. The mined out raises are backfilled.

Jet boring is conceptually very similar to box hole boring and can be a suitable alternative, depending on the local geological conditions. From a tunnel below the ore zone, a pilot hole is drilled up to the ore, through which a high pressure water jetting tool is installed. This water jet cuts out a cavity within the ore, and the ore cuttings and water drain to the drift below and are collected in a system that is attached to a secondary ventilation system to contain RDP and LLRD. The cavity is then backfilled before the next cavity is mined.

6.8.1.2. Surface mining

For high grade surface mining, it is more difficult to isolate the worker from the high grade ore, as the intervening waste rock cannot be used as a shielding material. The mining methods used are based around restricting the time over high ore grades and by maximizing the distance of the worker from the ore. Remote controlled equipment can be used for drilling, charging, excavation and transport. Shielding can be used if access to a mineralized area is necessary (e.g. by placing a cover of clean rock material over the surface of the ore) or within the equipment used to extract or transport the material (e.g. shielding between the driver cabin and the ore transport area). Radiometric sorting and control of the material being extracted can be a component of a surface operation.

6.8.1.3. Processing

The processing of high grade ores is chemically similar to other uranium processing methods but generally involves much smaller volumes of ore. Hence, the processing equipment is generally smaller and more compact and the overall size of the processing plant is reduced. Shielding and restriction of access to areas containing high grade ores are an integral part of the plant and process. Special attention is needed to minimize exposures during non-routine work such as maintenance.

6.8.2. Design and operation

Radiation protection and safety is an integral part of the design and operation for high grade operations, the requirements of which can determine how an operation is performed and might be a limiting factor for some design decisions. Design and operation methodologies from the nuclear fuel cycle are sometimes used in these operations owing to the high levels of containment needed.

The key control aspects for underground high grade operations are non-entry mining and isolation of personnel from the ore zone. This helps to limit direct exposure to gamma radiation from the ore and to minimize radon sources in the workplace. Additional practices to limit the movement of radon rich groundwater, such as grouting and freezing, can be important. The ventilation system is a critical control method in limiting exposure to radon progeny. Control of spilled material and the use of wet based loading and transport all contribute to reducing exposure. Non-routine work such as maintenance is generally performed in low background areas or, where this is not possible, in a controlled manner to minimize exposure.

The design of a high grade surface mine is generally determined by the geology of the deposit and how to utilize mining techniques to limit exposure while optimizing production. Different approaches may be needed for near surface rather than deep pits. In near surface mining, it is often appropriate to keep personnel at a distance from the high grade areas to minimize exposure. As depth increases, however, it is likely that work areas will be more restricted and there is increased potential for personnel to be working on or near the ore. For tasks that involve working directly on the ore, such as drilling or explosive charging, remotely operated equipment may be justified. The use of large earthmoving equipment can provide sufficient distance and shielding to control doses for operators, but additional cab shielding may also be a viable dose optimization practice. There may also be concerns relating to radon in deeper pits, particularly during still or inversion conditions.

The standard uranium plant design is unlikely to be appropriate for the processing of high grade ores. One solution is to use blending or downgrading of the plant feed to enable conventional plants to process higher grade ore. Care needs to be taken around the blending facilities to ensure that the higher potential for exposure from the high grade ore is addressed. The processing plant can also be designed specifically for the processing of high grade ores. Because of the comparatively low volume throughput, it is possible to design a plant with radiation control mechanisms as an integral part of the design. This can include the shielding of vessels which contain significant quantities of ore, and dedicated ventilation systems to keep vessels under negative pressure and exhaust any generated radon. This process can also be applied to non-routine and maintenance tasks where design and work practices can assist in dose control. Examples include the use of quick decoupling systems to minimize change out times for critical equipment (e.g. pumps) and increased slope on bonded areas to speed up the wash down of collected slurries.

6.8.3. Principal exposure pathways

Due to the higher concentrations of uranium, all exposure pathways have increased significance when handling high grade ores. While doses that are well over the limit are possible, experience has shown that good design and operating practices can reduce doses to levels that are comparable to those of low grade mines. With high grade ore, gamma doses in excess of 1 mSv/h are possible, so both passive and active controls are likely to be necessary. Irrespective of the process, the isolation of personnel from the ore (or tailings), as far as is possible, will assist in dose minimization. The amount of material that can give rise to significant doses is also greatly reduced, which means that more work areas are likely to need control.

Radon generation from the ore will be higher than for lower grade ores, but due to the range of factors influencing radon exhalation into the workplace, the range of potential conditions is highly dependent on site specific conditions. Furthermore, because less material is being handled, it is possible to design more efficient ventilation systems and keep air residence times low (thereby decreasing the ingrowth of radon progeny). However, the potential for rapid changes in airborne concentrations remains and needs to be considered in the design, operational monitoring and work practices.

The potential dose from the inhalation of LLRD increases with ore grade and hence is of more significant concern at high grade operations than those processing low grade ore. For example, in a low grade deposit (~100 ppm U), a worker would need to inhale in the order of 10–100 g to reach the occupational dose limit. In practical terms, this would be very unlikely to occur, even with minimal dust control. For a high grade ore (~10% U), however, inhaling less than 1 g of ore dust would be sufficient to reach the occupational limit. This means that control of airborne dust is far more important with high grade operations.

Similarly for ingestion and wound pathways, situations normally not important become more significant when handling high grade ore. For low grade ores, these pathways normally become significant when handling the final uranium product. For example, a wound directly contaminated with tens to hundreds of milligrams of high grade ore that is not cleaned out could result in an appreciable dose (i.e. >1 mSv). The potential for appreciable doses from wounds contaminated with low grade ore is significantly lower. Even for high grade operations, the ingestion of uranium ore would normally be a minor radiological issue and the dominant concern is likely to be a chemical toxicity issue, as when handling the final uranium product.

6.8.4. Control mechanisms

The primary control method for the mining and processing of high grade ores is isolation of the material from the workforce. In practice, this means a strong commitment to radiation protection being an integral part of both the design and day to day operation of the facility. However, a lack of appropriate controls has the potential to result in situations where doses approaching or exceeding the occupational dose limits could occur in a relatively short period of time (e.g. days to weeks). Hence, it is important that the proper design, operational and administrative controls are in place.

Shielding and separation of the workforce from the ore and waste materials is commonly used to control exposures. For mining, non-entry or remote mining become the most appropriate methods, while active ventilation and dust controls are also used. Mine planning is the key to dose control and having a strong knowledge of the geological distribution of the high grade ore is often the key to controlling doses. Ore handling is generally performed using wet material to minimize dust, and material to be transported may need additional shielding to protect the driver. Ventilation and isolation of ore areas are often the best means of ensuring that radon progeny exposure is minimized. For open cut operations, natural dispersal might be sufficient, but there may be a need for forced ventilation or work restrictions during periods of still air.

Worker access in close proximity to vessels containing ore has to be controlled. Gamma dose rates in the mSv/h range are possible, so access control is a key safety component. Areas where worker occupancy is higher may need shielding or, alternatively, the ore vessels may be shielded.

With respect to maintenance, these activities are usually planned, and dose assessments are used to optimize exposures. Good design features which reduce either the need or the time required for maintenance can have strong benefits for reducing doses. For example, having pumps outside of the tank area can enable maintenance to be performed in a lower dose area. Quick release fittings and pre-existing lifting and attachment systems can greatly reduce the time for removal of equipment. Easy to clean, hoseable surfaces can increase the speed of the cleanup after spillages and increase the distance of the worker from the spilt material (a small change in the slope of sumps can greatly affect the cleanup speed). Administrative controls to authorize entry into areas containing ore are also used to control and minimize dose.

6.8.5. Monitoring and dose assessment

Monitoring programmes in high grade mining and processing are like those used in all other stages of uranium mining, with the exception that there may be more use of real time monitoring (such as EPDs for gamma dose and real time RPD monitoring in critical airways). For gamma monitoring, the use of individual personal dosimeters (TLDs, OSLDs, EPDs) is normal practice. For workers close to the ore, alarm electronic dosimeters might be necessary. In some high grade mines, workers wear personal dosimeters that record radon and thoron progeny, gamma and dust exposures in one unit.

For radon progeny exposure, a combination of real time area and airway monitoring and personal monitoring can be used. The real time monitoring is used to confirm that ventilation systems are operating as designed and to allow quick response in the event of any change in exposure conditions. Personal monitoring of RPD is likely to be used due to the high potential for variation in both radon concentration and equilibrium factors in underground situations.

Personal monitoring of dust is likely to be the monitoring method for LLRD exposure. This personal sampling may be combined with the RPD monitoring (and gamma monitoring). Area sampling may be utilized to confirm that dust control mechanisms are effective. In the event of any increase in dust exposure, additional sampling may be performed to identify the source of dust.

6.9. URANIUM TAILINGS FACILITIES

6.9.1. Process description

Tailings are waste products generated from the processing of mined ore and contain up to 85% of the initial radioactivity of the ore. The physical and chemical processing change the radionuclides in the tails and they may become more mobile as a result. Tailings typically contain heavy metals and other compounds potentially harmful in high concentrations. Tailings management facilities are meant to act as repositories for waste products and act as long term containment after the mine is closed.

Generally, waste material from a milling process is collected and treated according to the composition of the original ore body and the types of process used for extraction. It is then impounded into a suitably isolated repository. Tailings need to be treated so they are chemically inert and placed in such a way as to provide maximum long term physical stability.

Mine operators can employ many tailings management strategies, including: tailings thickening to help to ensure physical stability after deposition; dewatering; backfilling of tailings underground; desulphurization of tailings to reduce the likelihood of acid generation; and blending tailings and waste rock to reduce pore space and lower hydraulic conductivity. Wet or dry tailings covers can secure the facility once impoundment is complete.

Local site specific factors often drive the choice of the most appropriate tailings disposal methodology. Given that tailings facilities have to be designed for site specific environmental conditions (e.g. ore type, geochemistry, topography, rainfall, other constraints), no single solution can guarantee sufficient containment in perpetuity. Uranium tailings have the added risk of being radioactive, which makes their management more difficult owing to the risks of ionizing radiation.

6.9.2. Design and operation

All tailings management facilities need to be designed to minimize contamination of the local environment and need to address the potential for acid generation, metal leaching and contamination of surface water and groundwater. A well developed tailings management strategy can mitigate harmful effects on vegetation, wildlife and the public. The economics of remediation have to encompass the lifetime of the facility in order to assess properly the cost to the operation. Occupational exposure is generally a lesser concern for tailings disposal compared to mining and processing activities.

6.9.2.1. Site selection and construction

There are a variety of containment options for tailings storage, including structures such as dams, dykes and berms; natural landforms such as lakes and valleys; and mined out open pit and underground mines. The type of tailings facility largely depends on terrain, environmental considerations and cost. Increased scrutiny from regulatory bodies and the public means that tailings impoundments are often expected to develop tailings management plans which encompass every stage of a facility's life cycle.

When operating tailings facilities above ground, a water cover can provide shielding from gamma radiation and reduce radon emanation and dust releases. However, this might not be possible in low rainfall areas, and other control mechanisms, such as a waste rock or soil cover, need to be used.

6.9.2.2. Treatment

Tailings are often composed of multiple waste streams created throughout the milling process. If necessary, they are to be rendered chemically inert before deposition. This is especially true when contaminants are released to the environment. Pretreatment of tailings can reduce acid generation and prevent leaching of contaminants into the environment.

6.9.2.3. Thickening

Controlling the physical properties of tailings can increase the effectiveness of long term storage and isolation. By managing tailings density, consolidation after impoundment can be improved, thereby reducing hydraulic conductivity. This will ensure that contaminants are released to the environment in a slow and controlled manner.

6.9.2.4. Deposition

The deposition of tailings needs to be managed in a controlled way to improve their storage and long term isolation. Depending on the type of facility, this can be achieved by continually varying the location of deposition to obtain an even tailings deposit. The even deposition of tailings helps to improve consolidation and physical stability, which is especially true when tailings deposition occurs under a water cover.

6.9.2.5. Backfill

Sometimes a proportion of the tailings is used to backfill underground voids. To ensure structural integrity, often only the coarse grain (sands) fraction are used for this purpose, as fine grained material might not dewater sufficiently and may lack the necessary structural integrity for use underground (e.g. liquefying under vibration from blasting). The tailings fraction is normally mixed with other material (e.g. fly ash, cement) to improve its physical properties and is then pumped or trucked for disposal underground (e.g. via boreholes from the surface).

6.9.2.6. Long term storage and isolation

Strategies for containing radioactive and non-radioactive tailings are similarly dependent on the mineralogy of the mined ore and host rock, the materials used for blending purposes and the type of chemical extraction used for processing. For surface facilities, a tailings cover can provide a barrier between the tailings and its surroundings. The choice of cover will depend on local topography and the type of facility. For wet covers, tailings are continuously submerged in water. For dry covers, solid material such as soil or some other membrane is used to keep tailings sequestered. Due to the presence of ^{230}Th, with its long half-life (75 000 years), and the subsequent ingrowth of ^{226}Ra (1600 years), radon emanation, and its subsequent decay into progeny, can be a concern long after the facility has been decommissioned. Radon exhalation into the surrounding environment can be effectively reduced to zero by installing an adequately thick and impermeable cover. Any tailings cover also needs to provide adequate shielding to ensure that the resulting gamma exposure rate conforms to regulatory requirements for exposure to the public.

6.9.3. Principal exposure pathways

6.9.3.1. External exposure

Once the majority of the uranium has been extracted from the ore, the waste products will contain residual gamma emitting radionuclides from the uranium decay series. Gamma exposure will occur when the workers are on or near tailings. Particular attention is to be given to tailings thickener tanks, tailings transfer lines and pumps, and deposited tailings.

After three to four months, the total activity in a deposit will be reduced by 20–25% owing to the decay of ^{234}Th and ^{234}Pa. Since covered tailings deposits are usually well shielded, they present a low risk for gamma exposure. For open air tailings, the deposit will remain a gamma exposure risk for workers nearby. Most uranium mining operations exploit low uranium grades and, as a result, the potential gamma exposure from the tailings is relatively low (i.e. usually <1–2 mSv/a for 2000 h of occupational exposure). As the ore grade increases, the potential gamma doses will increase, resulting in a need for more monitoring and dose tracking.

6.9.3.2. Inhalation of radon and radon progeny

As radium decays, it produces radon, which quickly decays into radon progeny. For adequately covered tailings facilities, the increase in radon and radon progeny concentrations is expected to be minimal compared to the naturally occurring radon background concentrations. For water covered tailings, surface disturbances caused by wind can result in a rapid degassing of radon. In open air facilities, the risk of exposure is increased. Radon and radon progeny can become elevated in low lying areas during calm weather. Generally, natural air dispersal is sufficient to ensure that occupational exposures due to radon progeny are usually very low.

6.9.3.3. Inhalation of long lived radionuclide dust

If tailings remain adequately saturated, LLRD concentrations will remain controlled. Open air facilities are at the greatest risk for elevated concentrations of LLRD. For dry tailings storage, such as those used in arid areas, dusting can become a significant exposure pathway. The tailings often form a crustal layer of dried salts on the surface, which may be resistant to dust dispersal. However, if the tailings are disturbed or there are high wind speed events, significant quantities of tailings can become airborne. Due to the low uranium grades exploited by most uranium operations, the inhaled dust pathway is a minor exposure pathway in most cases.

6.9.3.4. Internal exposure

The risk of internal exposure is proportional to the amount of direct handling of tailings material during tailings treatment, thickening and deposition. Given the low uranium grades exploited by most operations, this pathway is usually a negligible contributor to occupational dose.

6.9.4. Control mechanisms

The control mechanisms for operational work at a tailings facility depend on the ore grade, the strategy employed for long term storage and the current stage of the facility's life cycle. If the tailings deposition is being performed underground, a full radiological survey and hazard assessment will need to be conducted before any work commences. An appropriate control and monitoring programme is then implemented to keep doses ALARA. The primary method of radiation control underground is adequate ventilation to remove RDP.

6.9.4.1. External exposure

In most operations, the gamma radiation levels on tailings are usually very low and can be monitored by routine area monitoring programmes. With higher grade tailings, the gamma exposures can be an order of magnitude higher or more. The main form of control is then to limit the time spent on the tailings and to implement a monitoring and control programme (e.g. area and personal monitoring, as appropriate). In underground backfill operations, the main form of gamma exposure mitigation is to restrict access to the backfill work areas.

Covered tailings facilities are generally not significant sources of gamma exposure, whether they are active or not. Provided that the cover has adequate thickness, no additional work controls are necessary. The cover thickness will need to be adjusted if area monitoring reveals gamma exposure rates above operational limits.

6.9.4.2. Radon and radon progeny

On account of the low uranium grades exploited by most operations, the RDP exposure pathway is usually a minor one. Natural air movements, dispersion, dilution and low uranium grades usually ensure low RDP levels. In underground tailings backfill operations, the RDP exposure pathway can become significant and need to be monitored and controlled. The main control mechanism is to limit occupation times at the operations and to ensure adequate fresh intake and exhaust ventilation.

6.9.4.3. Long lived radionuclide dust

Because of the low uranium grades exploited by most operations, the LLRD exposure pathway is usually a minor one. Wet tailings and underground backfill operations have virtually no dust release potential. In high grade dry tailings operations, the LLRD exposure pathway may need to be monitored and assessed. If significant exposures are indicated, the main control mechanisms include wetting down the work area, limiting the occupancy factors and wearing an adequate form of respiratory protection.

6.9.4.4. Internal exposure

To prevent internal exposure, radioactive material is not to be handled directly. Appropriate PPE needs to be worn to protect against splashes, cuts and punctures.

6.9.5. Monitoring and dose assessment

6.9.5.1. External exposure

Gamma area surveys of tailings and backfill workplaces are needed to assess dose rates and to determine the need for personal dosimetry. In most cases, routine area monitoring results can be used with area occupancy records to estimate worker exposures. If personal monitoring is necessary, EPDs and TLDs can be used to determine individual worker exposures.

6.9.5.2. Radon and radon progeny

Surveys of tailings and backfill workplaces are needed to assess RDP concentrations, estimate exposures and doses, and determine the need for personal dosimetry. The most efficient method is to use radon gas monitors over a one to three month exposure period to determine the long term average radon concentration. The annual dose can be estimated from this value (after a background radon gas correction). For most surface tailings workings, it is very unlikely that there be a need for personal dosimetry and, routine long term area monitoring of radon gas concentrations will be sufficient.

6.9.5.3. Long lived radionuclide dust

Monitoring for LLRD exposure is only necessary where there are operations utilizing dry tailings. LLRD concentrations can be initially evaluated through static dust samplers and small personal air samplers. The results are then used to determine the monitoring and control programme. In most cases, routine area monitoring will be sufficient.

6.9.5.4. Internal exposure

It is very unlikely that there will be a need for bioassay investigations of tailings intakes because of the low grades of ore exploited by most operations. Most operations produce tailings with low levels of uranium radionuclides and significantly higher levels of their decay products, radium, polonium and lead radionuclides. Therefore, bioassay measurements have to be tailored to these other elements in the uranium decay chain.

6.10. MATERIAL IN TRANSPORT

6.10.1. Process description

A uranium mining operation can involve a wide variety of radioactive materials, including ore, ore concentrates, intermediate products, final product, wastes and contaminated items, which may need to be transported by road, rail and sea on private and public roads. Examples include the following:

(a) Transport of final product to the customer;
(b) Transport of ore and ore concentrates from the mine to the processing plant;
(c) Transport of intermediate process materials to a central processing facility (e.g. a central ISL plant);
(d) Transport of contaminated scrap items to recyclers or smelters (all types of metal scrap);
(e) Transport of contaminated plant items for refurbishment (e.g. valves and fans);
(f) Transport of contaminated plant items for use in a uranium or other processing plants (e.g. larger plant items such as stainless steel tanks, valves, pipes);
(g) Transport of contaminated plant items for decontamination.

The final product can be in many chemical forms, including U_3O_8, UO_4, UO_2, ammonium diuranate or a combination of these, depending on the process. The chemical form of the product can change the packing density (and hence the gamma signature) and solubility of the product.

There are a range of options for the transport of ores or liquids between mining and processing operations. Transport may be fully contained within the site boundary of the operation or may occur on dedicated transport routes or on public roads. Material can be transported by rail, road and conveyors, or by pipelines, depending on the distance and the physical form.

Uranium product is usually packed into metal drums and then stacked into a shipping container for transport. The most commonly used packages are industrial package Type IP-1 steel drums (~200 L), which are secured into the shipping containers. However, alternatives such as industrial package Type IP-1 bulka bags are being considered by some operators because of improved economics, reduced waste and the ability of the bags to handle shipping container movements. From the occupational exposure standpoint, the type of package does not significantly change the radiation protection requirements.

The transport requirements for all types of radioactive material (including uranium and other forms of NORM) are laid out in the IAEA Safety Standards Series No. SSR-6 (Rev. 1), Regulations for the Safe Transport of Radioactive Material, 2018 Edition [40]. One of the national regulators is appointed as the national competent authority for the transport of radioactive materials.

6.10.2. Design and operation

After filling, the drums are cleaned and monitored to ensure that they are not contaminated. They are then moved to a clean area away from the final product section and stored until transport. The initial stage of transport ensures that packages meet the specified requirements for transport (e.g. packaging type, cleanliness, labelling, sealing). The packages are then loaded into a shipping container (generally using forklifts) and secured with strapping or dunnage. The containers might be stored for a period prior to bulk shipment.

There is a wide range of options for transport from mine to mill, and range from conveyor belts, roll conveyors and uncovered lorry loads of low grade material within the site boundary to fully enclosed, specially designed transport containers for high grade ore material on public roads. Liquids can be transported in specially designed tankers or directly by pipe networks.

6.10.3. Principal exposure pathways

Under routine transport conditions, the only exposure pathway of significance is direct gamma exposure. Prior to transport, the exterior of the container and the interior of the cab is monitored. Dose rates are taken on contact and at 1 m. One of the most significant areas for potential underestimation of the occupational exposure is the ingrowth of progeny from the parent uranium isotopes. When uranium product is produced, it generally has a high degree of purity and only the uranium isotopes (^{238}U, ^{234}U, ^{235}U) are present. However, shorter lived decay products immediately begin to grow in and this can change the gamma signature of the package significantly. The uranium isotopes have a relatively weak low energy gamma signature, so fresh uranium product will generally be a low gamma emitter, but over the next few months the gamma dose rate will increase significantly as the gamma emitting progeny grow in. The increase in the gamma dose rate is due to the decay of the ^{238}U to ^{234}Th, which is a gamma emitter. The ^{234}Th comes into equilibrium with the ^{238}U after about two to three months, so the gamma dose rate ceases to increase significantly after this time (see Fig. 15).

In the event of an accident during transport, additional pathways, including the inhalation of LLRD, ingestion, wounds and skin adsorption, may need to be considered. Of importance for LLRD inhalation is the particle sizing and solubility of the product. Typically, the uranium product has a large particle size and a high density, so it is not overly prone to dusting.

In the transport from the mine to the processing plant, the gamma pathway and the inhalation of radionuclides in airborne dust needs to be considered. For higher grade ore, the gamma dose rate can become a very significant exposure pathway. During the transport of liquids in pipes, the critical pathways are likely to be gamma radiation from the buildup of radium scale on pipework and the inhalation of RDP due to degassing from the liquor upon discharge into the processing plant.

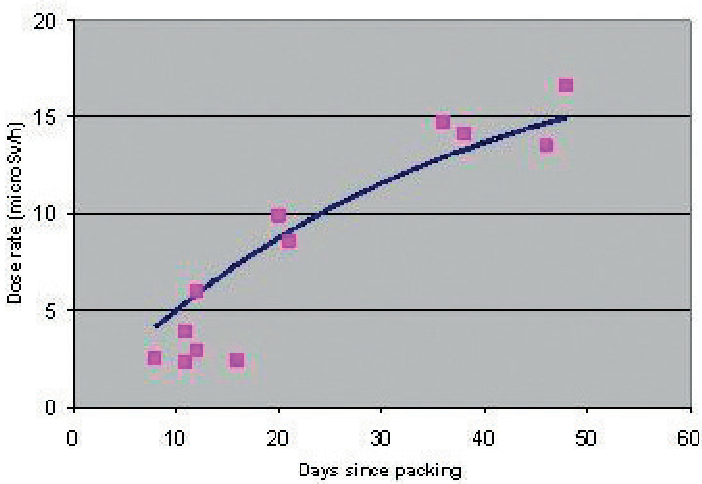

FIG. 15. The increase in gamma dose rate from uranium product due to ^{234}Th ingrowth.

6.10.4. Control mechanisms

For the routine transport of uranium product, the normal control practices of time, distance and shielding apply. Limiting the time of exposure to radiation is generally the most commonly applied and the most effective control practice. Each year, many hundreds of drums have to be prepared for transport and this includes cleaning the exterior, weighing and labelling the drums, and packing them into a container. This takes time and the workers are in close contact with the drums and exposed to gamma radiation. Simple practices, such as automated drum cleaning and pre-printing the labels onto the drum surface during manufacture, can significantly reduce occupational doses. The packing and securing of the ISO containers needs to be planned and optimized to reduce the time spent in contact with the drums. The container placards need to be put in place prior to drum loading.

Packed ISO containers may be stored for a considerable period whilst awaiting shipment and the placement of the containers is important to prevent increased dose rates in nearby work areas. Locating the container loading and storage area well away from high occupancy areas is good practice.

An emergency plan is required in case of an accident during the transport of radioactive materials. The transport crew need to be trained in accordance with the arrangements for emergency response. In the event of an accident, there may be a risk of the inhalation of LLRD and environmental contamination. The use of personal PPE (i.e. respirators, disposable overalls, gloves) in emergency situations is standard procedure for most hazardous materials (including uranium). The transport of ores from the mine will also benefit from this control system. If the ore is being carried uncovered, wetting or wind deflectors can significantly reduce dusting. In addition, any spilt ore at the loading area needs to be removed promptly.

For liquor transfers, periodic monitoring of the gamma dose rates adjacent to pipework can provide an early indication of the buildup of radium scales and any deviation from operational norms. Possible corrective actions to reduce dose rates include warning signs and, as a final resort, the descaling of the pipes. If process liquids are being transferred into vessels or ponds, any contained radon will be degassed (this is particularly important for ISL operations). The degassing area may need to be well ventilated, or an upstream remote degassing area could be used to prevent radon buildup in work areas.

6.10.5. Monitoring and dose assessment

The gamma exposures associated with the transport of uranium product are usually low. A variety of methods can be used to estimate the exposure of driving crews. In many operations, only a few trips are made each year. The primary workplace (e.g. truck cabin) can be surveyed to measure the gamma dose rate and, the dose can be estimated by multiplying the dose rate by the number of hours spent in the driver's position. Another method is to issue the driver with an EPD and record the total dose per trip. Many modern uranium operations issue the driving crews with EPDs as part of the emergency response kit.

Workers loading the packages and preparing the containers can be assessed by many methods, including SEG averaging and the use of EPDs, TLDs or OSLDs. Electronic dosimeters are useful to estimate the dose of individuals performing specified tasks. The storage and loading area needs to be surveyed on a regular basis for dose estimation, to assist in control and to detect any surface contamination.

In emergency situations involving transport, monitoring may be required for gamma dose rate, LLRD and surface contamination. The potential LLRD exposures of the workers and members of the public can be assessed through bioassay techniques such as urine and faecal analysis and lung and whole body counting. There may be a need for periodic monitoring of RDP where the degassing of process liquors occurs.

6.11. DECOMMISSIONING

6.11.1. Process description

The decommissioning of a uranium operation is a combination of plant demolition and disposal, large scale earthmoving, stabilizing the surface waste facilities (e.g. waste rock stockpiles, evaporation ponds, tailings structures) and rehabilitation of the surface areas. Exploration decommissioning involves the removal and remediation of any surface structures (e.g. drill casings, scraps, pits) and the disposal of wastes and unwanted core and cutting samples.

6.11.2. Design and operation

In exploration decommissioning, the amount of material and the operational areas are usually very small, so the potential for occupational exposure is generally not significant. In the decommissioning of uranium mining and milling operations, the critical decision is how and where to dispose of the waste products arising from the operation. This depends on a range of factors, including the type of operation, the amount of waste, topography, hydrogeology, climate, future land use and regulatory requirements. The scale of the decommissioning operations can range from relatively small ISL operations to extensive surface mining operations. Important aspects of the process include the clearance and removal of non-radioactive material, the isolation of radioactive waste material and the incorporation of controls for non-radiological impacts, such as acid rock drainage. The three major tasks of decommissioning include the demolition of the processing plant and other facilities and structures, the disposal of tailings material and other wastes (including evaporation and holding ponds), and various remediation activities. Waste rock can be a useful resource during decommissioning, as it can provide a benign cover material for the final landform. Secondary remediation activities may be necessary due to the need to access resources for the primary decommissioning (e.g. the remediation of the surface excavations used to extract clay for tailings capping). Other activities include the backfilling of underground mine workings, the closure of entry points to mines and the stabilization and isolation of surface mining areas.

6.11.3. Principal exposure pathways

The principal exposure pathways for occupational exposure during decommissioning activities are gamma exposure and the inhalation of radionuclides in airborne dust. Radon progeny are unlikely to be a significant source of exposure unless there are specific situations where ventilation is not present, such as during vessel entries and during work in confined spaces and underground areas. The ingestion of radioactive materials and the contamination of wounds by radioactive materials is usually a very minor pathway.

During exploration, decommissioning the total volume of radioactive material is usually small and of low grade, therefore the occupational doses are unlikely to be of significant concern unless very high grade ores are involved. Prior to decommissioning, the processing plant needs to be shut down, the insides of the process vessels and pipes emptied and flushed, and the rest of the plant washed down. Not doing this will result in significantly higher occupational doses during decommissioning.

Removing the contents of the process vessels and pipes lowers the gamma radiation levels significantly. The remaining gamma sources then comprise localized areas of internal contamination (e.g. radium scales) inside pipes and vessels. These areas can be identified and marked during a radiation survey prior to demolition.

Plant and structure demolition are for the most part a low exposure task. The risks for higher exposure are generally limited to a small number of specific tasks, such as cutting plant items that are internally contaminated (e.g. the final stages of the uranium production area and localized radium contaminated hotspots). During this part of decommissioning, the most important exposure pathways are gamma radiation from radium scales and the inhalation of LLRD. Due to the variation in the type and level of radionuclides across the plant (e.g. uranium and various progeny mixtures), it will be beneficial to compartmentalize the work based on the radiological risk, as this will define the control measures to limit occupational exposures.

The decommissioning and rehabilitation of tailings facilities (including evaporation and holding ponds) will be the most significant part of the decommissioning process for most underground and surface mines. Tailings can be disposed of on the surface during operations (i.e. in situ disposal) or returned to the open pit or underground workings. If dry tailings are to be moved, then the exposure pathways will include gamma radiation and the inhalation of radionuclides in airborne dust during excavation, transport and final placement. If the tailings are to be disposed of in situ, then once an initial covering layer has been applied, these exposure pathways will be of less significance.

Uranium radionuclides are severely depleted in the tailings; most of the radioactivity comprises ^{230}Th and its decay progeny. Although the bulk of the tailings will be close to equilibrium from ^{230}Th, some material may be in extreme disequilibrium. For example, the upper crustal layer of the tailings may be enhanced in activity by over an order of magnitude compared to the rest of the material, and this crust, once disturbed, can be very prone to dusting. Similarly, the residues in evaporation ponds can have a much higher activity and a totally different mixture of radionuclides compared to the tailings. For example, residues from acidic evaporation ponds can have concentrations of ^{230}Th that are three orders of magnitude higher than those in the tailings.

The movement and stabilization of waste rock and other surface structures are unlikely to have significant occupational radiation protection impacts. The exposure pathways are similar to those for the movement of tailings, but the radioactivity and exposures will be substantially lower. Although ISL operations do not produce tailings, they do produce smaller quantities of other solid and liquid radioactive wastes. These wastes include ion exchange resin, sludges, precipitates, contaminated soils and contaminated plant items.

In higher grade uranium mines, the decommissioning of the tailings and waste rock stockpiles involves significantly higher radiation exposures and therefore requires more rigorous control programmes.

6.11.4. Control mechanisms

Due to the comparatively small volume of material being handled during exploration decommissioning, the occupational exposures are not usually significant, provided that basic radiation protection controls are implemented. In particular, dust generation during sample handling needs to be minimized and personal hygiene measures used to prevent inadvertent ingestion of material.

If dusting is observed and cannot be prevented by wetting down, then basic respiratory protection can be used to reduce exposures (e.g. P2 disposable dust mask). High grade ore sample stockpiles can produce localized gamma dose rates which can be significant. The main control method is to identify these areas and materials and to plan for their removal to ensure the shortest occupancy factor for workers.

Demolition of the processing plant facilities can result in significant occupational doses. Demolition may occur well after the operation has been completed and information concerning the localized high dose rate and high activity areas may be lost. A gamma radiation survey carried out before decommissioning to identify the higher dose rate areas can significantly aid decommissioning planning and facilitate dose reduction. In addition, a thorough wash down of the plant followed by a surface contamination survey is useful to identify areas and items contaminated by fixed contamination. Vessels, equipment and piping associated with uranium product or radium scales need to be identified and made subject to rigorous controls to reduce occupational doses. The remaining areas of fixed contamination on floors, walls and vessels can be significantly reduced by ultra-high-pressure water jetting. These simple washing practices can significantly reduce gamma and LLRD exposures during the demolition activities.

The identification of clean items and areas (i.e. not contaminated) is also essential to minimize the total amount of waste material classified as radioactive. Items such as footings, support girders, fencing and poles can be cleared for off-site disposal or potentially sold as scrap metal following suitable clearance practices.

Gamma exposures can be substantially reduced by area classification, warning signs, restricting access and removing fixed contamination from surfaces. During the demolition process radioactive material will be found inside pipework and vessels. If this material cannot be removed easily, the item will need to be sealed and disposed of as radioactive waste. The use of large demolition equipment (e.g. loaders, shearing equipment, bulldozers) can significantly speed up the demolition process whilst minimizing the dose due to the time, distance and shielding concepts. Where cutting is necessary, care needs to be taken to prevent injury and wound contamination due to the presence of sharp edges coated with radioactive materials.

Tailings disposal has the potential to become a strong dust source, resulting in the inhalation of LLRD. The tailings material may be very dry and prone to dusting, and water for dust control might not be readily available. Where possible, dusting is to be minimized, but if this is not possible, then other approaches need to be taken to minimize the inhalation pathway (e.g. dust masks, respirators). The use of earthmoving equipment with ventilated cabins is a successful means of dose control. Minimization of work during high wind speeds or when the wind direction is towards other work areas may be necessary. Owing to a higher propensity for dusting and higher radioactivity levels, some areas may need specific dust minimization controls, such as crustal layers in the top layer of the tailings and on the residual precipitates in the evaporation ponds. The radiation controls during the decommissioning of waste rock stockpiles and other surface facilities are like those for tailings, but the level of protection needed is likely to be less due to the lower radioactivity levels.

6.11.5. Monitoring and dose assessment

Gamma surveys with portable instruments are used to identify localized areas of elevated dose rates. Worker doses can be assessed by many methods, including SEG averaging and the use of EPDs, TLDs or OSLDs. Electronic dosimeters are useful to estimate the dose of individuals performing specified tasks. The inhalation of LLRD can be assessed through area monitoring and occupancy factors. Personal air sampling may be appropriate for activities with a high risk of inhalation (e.g. cutting activities and dry, dusty operations).

Appendix I

SURVEY OF THE INFORMATION SYSTEM ON URANIUM MINING EXPOSURE (UMEX)

I.1. INTRODUCTION

UMEX was initiated in 2011 to strengthen occupational radiation protection for workers in the uranium mining and processing industry, increase opportunities for the optimization of workers' exposure and support quality assurance programmes across the industry. To support this broad objective, the following key activities have been identified:

(a) To develop an information system for occupational exposure in uranium mining and processing;
(b) To obtain a global picture of occupational radiation protection experiences in the uranium mining and processing industry;
(c) To identify both leading practices and opportunities for improvements and to derive actions to be implemented where appropriate for assisting the industry, workers, regulatory bodies and other stakeholders in implementing the principle of optimization of protection and safety.

In 2012, the IAEA developed a questionnaire (see Annex) which was distributed to uranium producing countries. Responses were received from 36 operating facilities (covering approximately 85% of global uranium production) in 2013. This appendix provides an analysis of the results and includes summaries of current practices for monitoring exposures and reporting doses for the various mining and processing techniques, as well as summarizing the exposures and doses reported for 2012 for the same operations.

I.2. OCCUPATIONAL EXPOSURE

The current focus is on occupational exposures associated with the operation of a uranium mine or processing facility, namely external gamma and inhalation of LLRD and RDP. The dosimetric information requested included the exposure pathway as well as the total effective annual dose. Provision was also made in the survey for dose data and supporting information to be made available by workgroup. At a later stage, this could be expanded to all life cycle activities, from exploration to closure and surveillance.

The monitoring practices and the dose calculation procedures and assumptions used to estimate worker doses vary from operation to operation and by jurisdiction. Doses can be assessed, for example, from area monitoring and estimates of occupancy times or be based directly on individual dose measurements. The procedures and assumptions for dose assessment affect not only the estimation of dose by pathway, but also the total dose. Thus, it is important to document any assumptions made in estimating and reporting the dose and the values of key parameters. An example is the use of PPE such as respirators and the protection factor assumed during their use.

I.3. RESULTS OF THE ANALYSIS OF MONITORING AND DOSIMETRIC PRACTICES

I.3.1. External gamma exposure

I.3.1.1. Summary of monitoring approaches

The monitoring of occupational gamma doses across worldwide uranium operations was dominated by the use of TLDs as the primary monitoring methodology (i.e. personal dosimetry) (see Fig. 16). Some sites utilized area monitoring or workgroup monitoring to determine gamma doses and other sites used a combination of the two methodologies for personal monitoring of some individuals and area or workgroup monitoring for others, as shown in Fig. 17.

Background subtraction was also undertaken at approximately half of the sites for the determination of the occupational gamma doses. The remaining operations indicate that they did not perform a background subtraction, which would indicate that the doses might be overestimated in these cases. The TLDs accumulate natural background radiation continuously (see Fig. 18); if control badges or other correction methodologies are not used, then the occupational contribution will be overestimated. The overestimation will include all the natural background contribution, as well as any additional exposure that the TLDs receive in transit. This overestimation is likely to be in the order of 1 mSv/a and will vary depending upon the location.

I.3.1.2. Dosimetric aspects

Due to the predominance of TLDs, the dosimetric characteristics of the gamma radiation are closely aligned with the characteristics of the TLD. It is assumed that the data used would be $H_p(10)$ equivalent, but this was not defined in the survey.

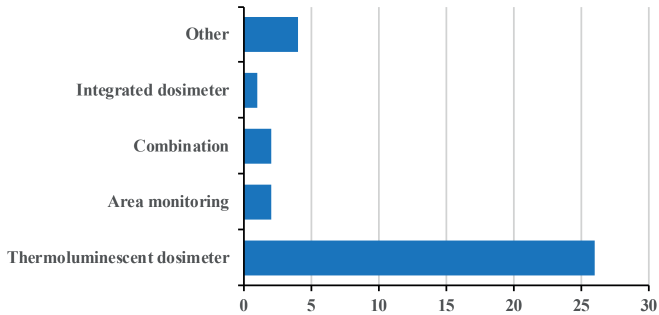

FIG. 16. External exposure monitoring approaches.

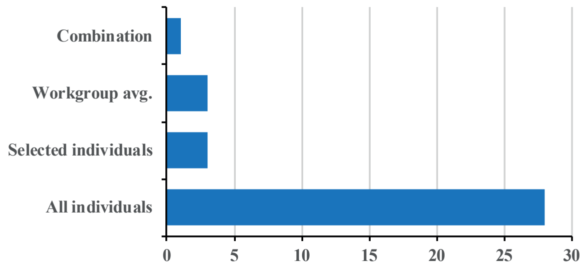

FIG. 17. Individual monitoring methodologies.

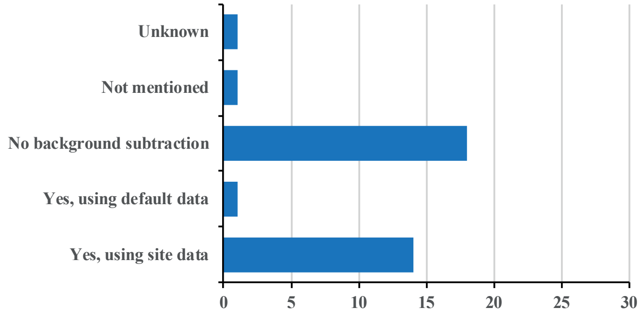

FIG. 18. Background subtraction during external exposure assessment.

I.3.1.3. Common and divergent aspects

With respect to the methodology, the approach used was very consistent with the predominance of TLDs and individual monitoring. However, the survey results indicate that there is a major divergence concerning the use of background subtraction, with an approximately equal split between sites using background subtraction and not using it. This could imply that approximately half of the sites overestimate the occupational exposures, but this is unlikely to be significant in terms of demonstrating regulatory compliance.

I.3.2. Inhalation of long lived radionuclide dust

I.3.2.1. Summary of monitoring approaches

The two dominant methodologies used for the determination of LLRD doses are personal dust sampling and area dust sampling (see Fig. 19). In both cases, the collected filters are usually analysed using gross alpha counting. Alpha spectrometry and radionuclide analysis are not often used for occupational exposure determinations, although two sites did use these techniques (as the underlying isotopic composition of the dust is important for dosimetry) (see Fig. 20). Although not noted in the questionnaire responses, it is assumed that the dust samplers are size selective and that dust measurements reflect respirable dust.

With respect to monitoring frequency, the three methods used are workgroup average, periodic monitoring and permanent individual monitoring (see Fig. 21). Where the collection of dust was incorporated into a dosimeter which had a combined monitoring functionality (i.e. with other dosimeters for RDP and gamma dose) and operated continuously for an individual worker, it is defined as 'individual permanent'. The background contribution to the occupational dose is likely to be insignificant due to the small contribution of LLRD to natural background exposure.

I.3.2.2. Dosimetric aspects

Direct bioassay or other internal dosimetric measurements are not generally used by the surveyed uranium operations (see Fig. 22). However, six operations use the assessment of uranium in urine as an analysis technique, with an additional technique using biological monitoring[5] in the event of an incident.

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[5] Biological monitoring can include a range of techniques, such as urinalysis, faecal sampling, radon exhalation in breath and band chest or whole body counting.

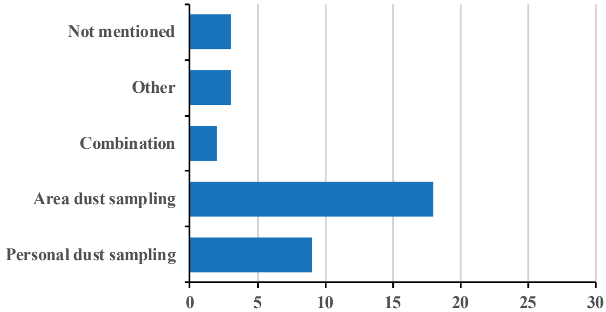

FIG. 19. Method of dust collection.

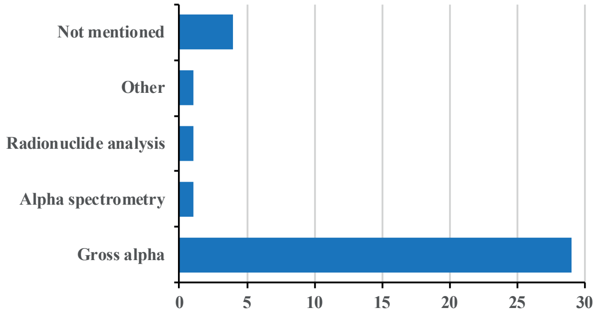

FIG. 20. Method of determining radioactivity.

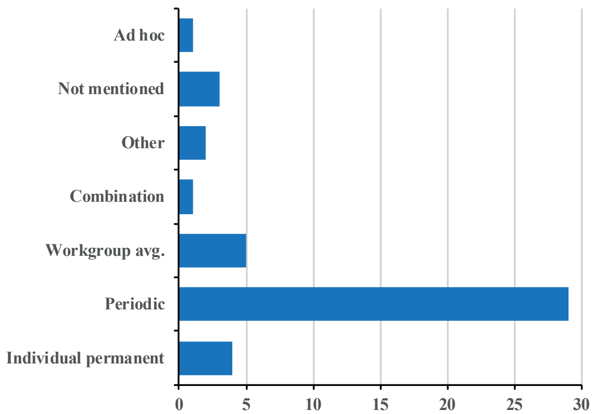

FIG. 21. Monitoring frequency.

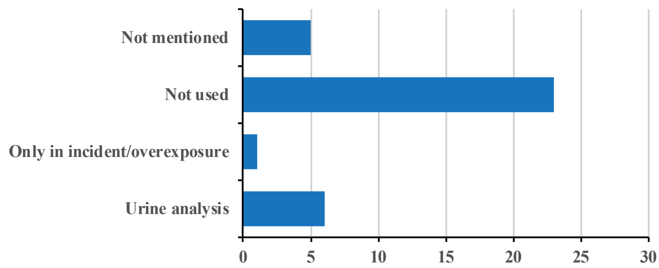

FIG. 22. Application of bioassay techniques for dose evaluation.

The occupancy time is a critical aspect in the case of dose estimation from personal dose sampling, workgroup averaging or area averaging. Timesheets remain the dominant means of determining the occupancy time, although there is an increasing move to electronic measurement of time (see Fig. 23). If timesheets are used for dosimetric purposes, then every effort needs to be made to ensure accuracy, as it has a direct effect on the calculated dose.

The underlying parameters for DCFs also varied across the surveyed operations. Most of the operations used DCFs which were regulator specified, but some used default values based on experience, measured values or the most conservative values. As would be expected, a wide range of DCFs were reported for inhaled alpha activity. This can be attributed to differences in the composition of the material (i.e. ranging from material in equilibrium, such as ore, through material depleted in uranium, such as tailings, to material which is essentially pure uranium in final product). There is even wide variation (by over an order of magnitude) in the DCFs reported for final product. This might be due to specific studies at some operations on aerosol particle characteristics, such as particle sizing and solubility. Dose variation can also result from differences in assumptions, such as the fraction of radon progeny retained in a collected dust sample and hence the number of long lived alphas contributing to the direct alpha measurement. A few operations also included the contribution of the actinide series to dose.

I.3.2.3. Common and divergent aspects

The most significant variation in the calculation of the dose from LLRD is seen in the DCFs. The wide range of values used would have a significant influence on the calculated dose. In particular, three operations included a very low DCF for non-calcined ammonium diuranate, although whether this

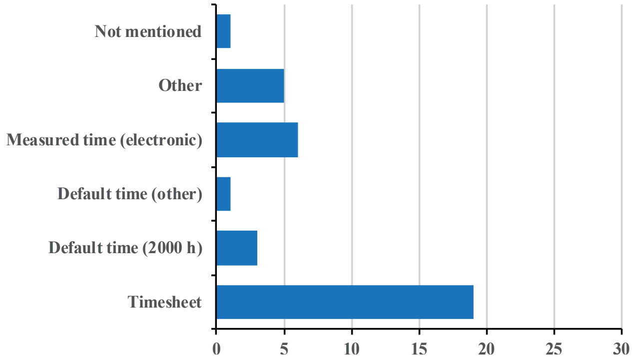

FIG. 23. Use of occupancy time in estimating inhalation dose.

is used in practice is unconfirmed. In the operations in question, the DCF only has a small impact on the reported LLRD dose due to the limited potential for airborne exposure.

I.3.3. Inhalation of radon decay products

All of the mining operations measured radon or its progeny for occupational exposure assessment and dose estimation. The various approaches to estimating exposure are illustrated in Figs 24 and 25.

For the sites that do not have background subtraction for RDP, it is likely that the operational dose assigned to this pathway will be overestimated. The overestimation would be in the order of 25% of the natural background dose from RDP, which varies by location but is likely to be in the order of 0.3 mSv/a (i.e. approximately 25% of local natural background currently defined by the United Nations Scientific Committee on the Effects of Atomic Radiation [41] as about 1.2 mSv/a).

If timesheets are used for dosimetric purposes, then every effort needs to be made to ensure accuracy, as it has a direct effect on the calculated dose. Because RDP exposure is heavily dependent on the type of mining operation, RDP monitoring is discussed for each type in the following sections.

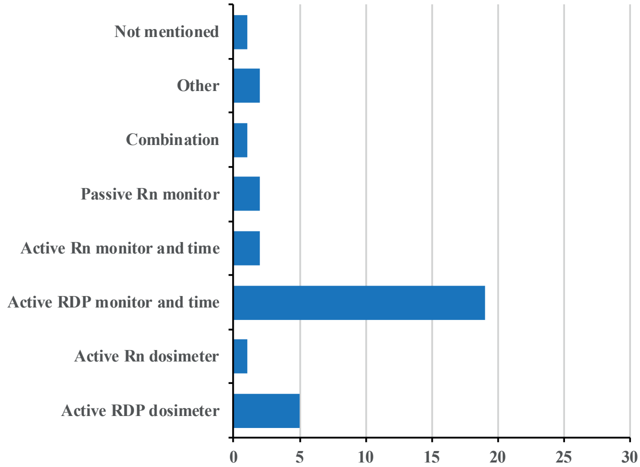

FIG. 24. Types of monitor for radon and radon decay products.

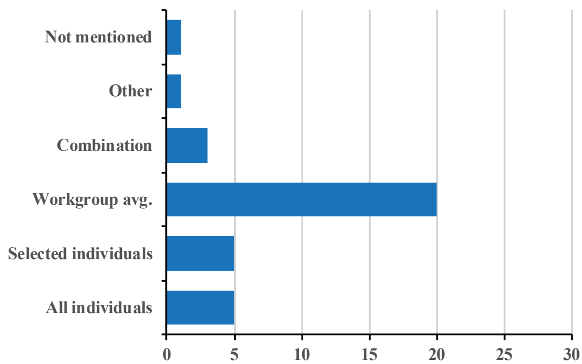

FIG. 25. Methodologies used for exposure assessment from radon decay products.

I.4. UNDERGROUND MINE EXPOSURE

I.4.1. Approaches for exposure assessment

Six underground mining operations responded to the questionnaire. There is consistency in the methodology used for exposure assessment. The latest information shows that active dosimetry measurement is the method of choice. In five of the six mines, all personnel had both personal and area monitors. Two mines measured radon gas rather than the decay products and applied an equilibrium factor (of 0.3 and 0.5) to obtain working level (WL) values. One mine used undefined measurement techniques, but all personnel was monitored. Personal and area monitoring was full time and personal exposure was based on occupancy time.

I.4.2. Dosimetric aspects

There is consistency in the calculation of dose in that an effective dose of 5 mSv per working level month (WLM), based on ICRP recommendations [3], was used. Two mines stated that they assumed a particle size but this was not used in any calculation of lung dose.

I.4.3. Common and divergent aspects

All but one site did not utilize background data to subtract from the monitoring measurements. One mine had site measurements and used this data for subtraction. The active instruments used for area and personal monitoring are turned off after the work shift, and background is not thought to be a substantial contribution to exposure.

I.5. OPEN CUT MINES

I.5.1. Approaches for exposure assessment

Six open cut mining operations responded to the questionnaire. Five mines had active area decay product monitors and two also had active personal dosimeters. One open cut mine had undefined monitoring techniques. In one open cut mine, all personnel were monitored; in one mine, selected individuals were monitored; and workgroup averaging was used in four mines.

I.5.2. Dosimetric aspects

There is consistency in the calculation of dose across five of the mines, in that an effective dose of 5 mSv/WLM, based on ICRP recommendations [3], was used. One mine assumed an equilibrium factor of 0.4 and employed a DCF of 5.56×10^{-6} mJ·m^{-3}/(Bq/m^3). Two mines stated that they assumed a particle size but this was not used in any calculation of lung dose.

I.5.3 Common and divergent aspects

Five sites did not utilize background data to subtract from the monitoring measurements. One mine had site measurements and used these data for subtraction.

I.6. IN SITU LEACHING

I.6.1. Approaches for exposure assessment

Four respondents representing 18 ISL operations (one of the operations represents 15 separate sites) replied to the questionnaire. One operation reported the use of area radon monitors combined with estimates of time spent in workplaces to estimate exposures; one reported the use of passive radon detectors and estimates of time spent in workplaces to estimate exposures; and the remainder reported the use of area RDP monitors combined with estimates of time spent in the workplaces to estimate exposures. Two operations reported estimating radon exposures for all individuals; 15 operations reported estimating exposures by workplace average; and one reported the use of a combination of the two methods. One facility reported employing background subtraction using site specific data; 16 operations reported that background was not subtracted; and one facility provided no information.

I.6.2. Dosimetric aspects

Fifteen operations reported calculating the effective dose using the DCF of 5 mSv/WLM recommended by the ICRP [3]. Two operations reported using a radon DCF of 0.001 4 $mSv \cdot \mu J \cdot m^{-3} \cdot h^{-1}$ and one operator reported using an equilibrium factor of 0.4. The remaining operation reporting a measurement of RDP used a DCF of 8 $nSv/(Bq \cdot m^{-3} \cdot h^{-1})$.

I.6.3. Common and divergent aspects

One site reported the use of area radon measurements and the remaining sites reported the use of area RDP measurements to estimate individual exposures.

I.7. OTHER

Three quite varied operations are included: a site undergoing rehabilitation; a uranium leaching (toll milling) facility; and a water treatment facility.

I.7.1. Approaches for exposure assessment

No information was provided by one facility on how exposure estimates are developed. Two facilities reported the use of active RDP dosimeters and one operation reported using active radon monitors. Two operations combined time spent in workplaces with either the radon or RDP measurements to estimate workgroup average exposures; the third facility reported using a combination of individual and workgroup average estimates. One facility reported subtracting site specific background.

I.7.2. Dosimetric aspects

One facility reported using the DCF of 5 mSv/WLM, recommended by the ICRP [3], to estimate effective dose. The other facilities providing information on dosimetry used equilibrium factors of 0.2 or 0.4 and different DCFs, neither of which were fully defined in the questionnaire response. None of the operations reported the measurement of particle size.

I.7.3. Common and divergent aspects

One site reported the use of area radon measurements, with the remaining sites reporting the use of area RDP measurements to estimate individual exposures.

I.8. ANALYSIS OF DOSES

A number of factors are important in estimating exposures and doses, including the measurement method (e.g. individual or workplace average), the time spent in each workplace and whether or not background is subtracted. The number of employees is critical to the data analysis, as the average for the combined operations is weighted based on employee numbers (see Fig. 26).

Operation 2 dominates the employee numbers, with 10 987 personnel. The dose histogram for this particular operation indicates that approximately three quarters of the personnel received occupational doses of less than 0.5 mSv/a and therefore might not be representative of workers who are more closely associated with radioactive material. It is also critical that the data from Operation 13 are the amalgamated data for 15 operations which report though a single organization. It is thus included in subsequent data analysis as 15 different operations.

The reported occupational doses in each operation are shown in Fig. 27. The average occupational dose for all operations is below 5 mSv/a. The maximum annual doses vary considerably, but for all but two of the operations they were below 10 mSv. One operation reported a maximum annual dose of over 30 mSv. However, on examining the supplied data, this entire dose was from the gamma component, it was for a final product recovery worker, and all the exposure for this single worker was in one quarterly TLD issue period. Given this, it is suspected that the supplied maximum may be an error due to an incorrectly exposed TLD, erroneous reporting or some other non-operational reason.

The suspected erroneous reading was reported back to the relevant regulator and operator. Since the initial reporting of data to the IAEA, the single gamma reading had been found to be in error, removed from operator and regulator records, and replaced with the workgroup average. With this one result discounted, the maximum dose dropped to below 10 mSv/a (see Fig. 28). Operation 4 reported a maximum dose of above 10 mSv/a, which appears to be more consistent with the data, with exposure across all three pathways. The maximum dose remained below 20 mSv/a in this case.

Of the operations which supplied data, most provided information on all three exposure pathways (see Figs 29 and 30). Operation 10 did not provide any information on the inhalation of LLRD in airborne dust and Operation 1 only provided the gamma dose. Operation 13 (15 separate ISL operations) stated that they did not use background subtraction for gamma exposure. Given that TLDs record background continuously, this could lead to an overestimation of this pathway by up to 1 mSv/a.

The average dose components for each exposure pathway in different types of mining and processing are shown in Figs 31 and 32, which represent two ways of looking at the contributions of the three exposure pathways to the total dose. The first shows the contribution (in %) by pathway to total dose and the second shows the absolute contributions of the three exposure pathways to total dose. There is considerable variation in the relative contribution by exposure pathway across the various types of facility.

The data for the various operations were amalgamated into four mining methodologies: underground (U/g), open cut, ISL and other. The underground and open cut categories were further separated into mining personnel and processing personnel. The 'other' category included uranium recovery from rehabilitation, wastewater treatment and toll milling.

The average doses for the underground category were greatly influenced by Operation 2 owing to the large number of personnel recorded for this particular operation. Similarly for the open cut category, Operations 3 and 15 had the most

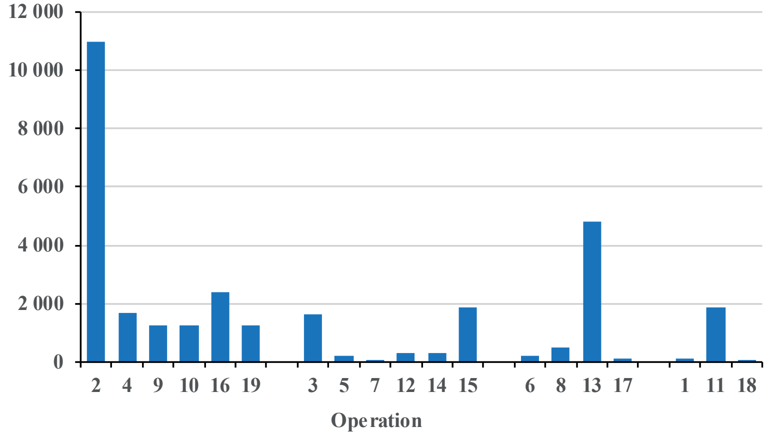

FIG. 26. Number of occupationally exposed workers in each operation.

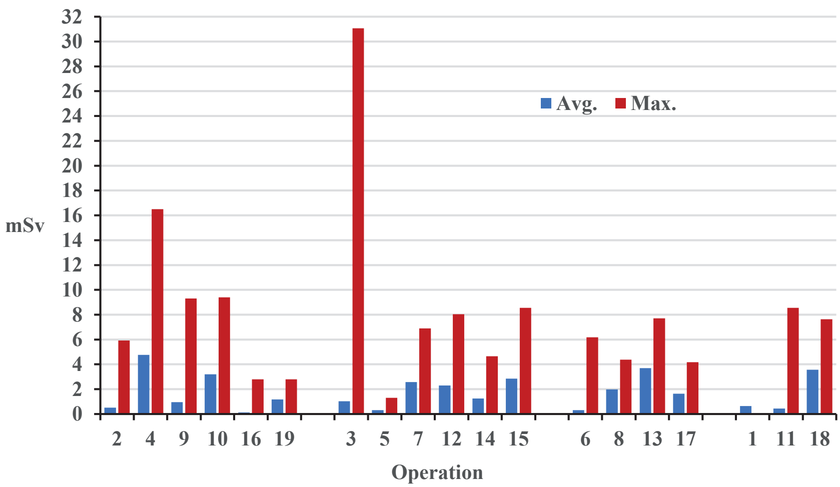

FIG. 27. Occupational dose as originally reported.

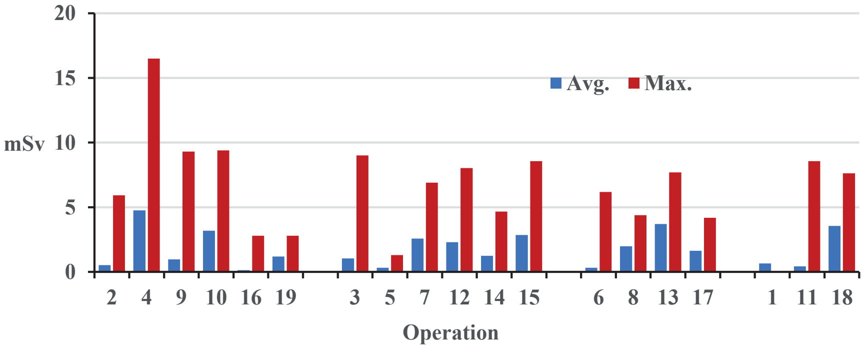

FIG. 28. Occupational dose after removal of the erroneous measurement.

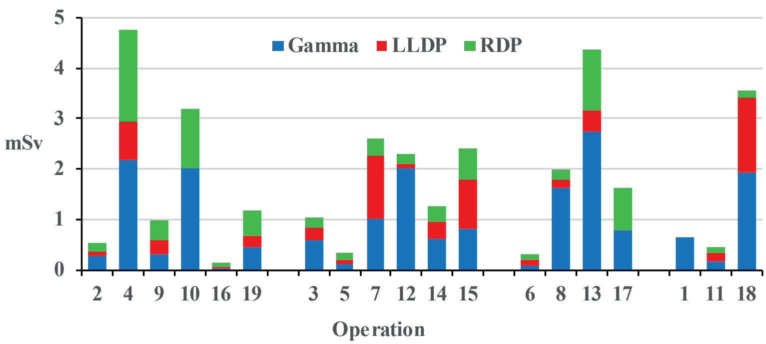

FIG. 29. Average dose contribution of each exposure pathway.

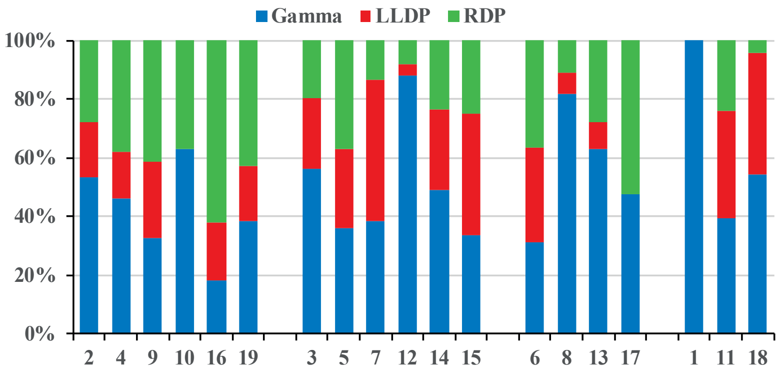

FIG. 30. Percentage dose contribution of each exposure pathway.

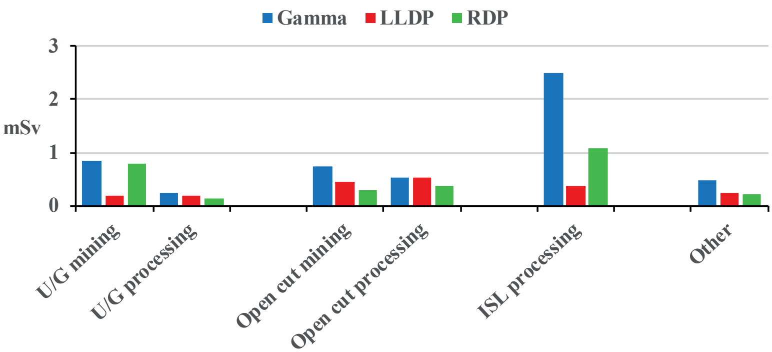

FIG. 31. Average dose with respect to different types of mining and processing.

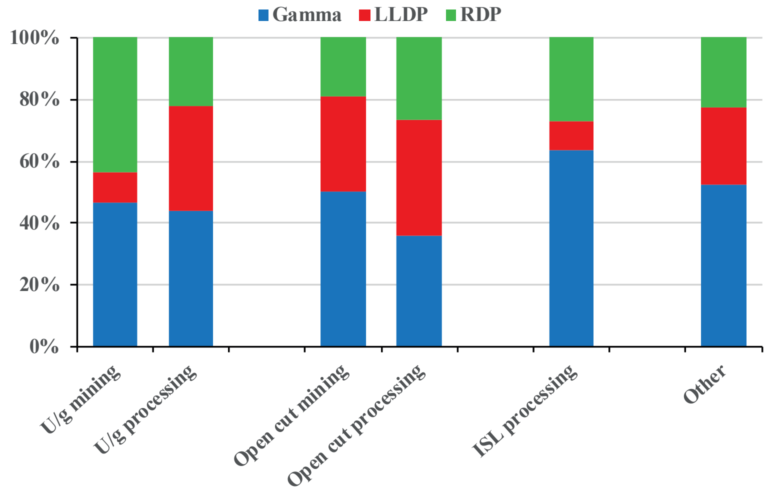

FIG. 32. Percentage dose for each pathway in different operations.

employees and hence had a strong influence on the average dose recorded. In the ISL group, Operation 13 was dominant in terms of employee numbers, but as this represents the amalgamation of 15 different operations, the average is more representative of the data supplied. The distribution of exposure pathways for underground mining and processing, open cut mining and processing, ISL processing and other operations are presented in the following figures.

The distribution of exposure pathways for underground mining is as expected (see Fig. 33(a)). There is approximately the same contribution from gamma (47%) and RDP (43%) and a much smaller contribution from the inhalation of LLRD (10%). This reflects the approaches taken in modern underground mines, including dust suppression, good ventilation and shielding against gamma. For the processing of ore derived from underground mining, the doses from gamma (44%) and LLRD (34%) are approximately the same (see Fig. 33(b)). The contribution from RDP (22%) was smaller but still significant. This may be because background subtraction was not generally used for RDP exposure, so a significant proportion of this pathway might not be operation related.

For open cut mining operations, gamma exposures are dominant, which is as expected for modern mining methods (see Fig. 34(a)). Gamma shielding is not generally possible for open cut methods beyond that provided by the heavy earthmoving equipment that many workers operate. The next most dominant pathway is inhalation of LLRD, mainly from Operations 3 and 15, which are both in semi-arid regions where dusting is likely to be more significant (i.e. there is less water available for dust control and material dries more quickly). The inhalation of RDP is the least significant pathway, which is expected given the natural dispersal of radon within large scale open pits. The relative importance of the different pathways for the processing of ores derived from open cut operations is almost identical to that from underground ore processing (see Fig. 34(b)). This is as expected, given that the processing methodology is generally similar and the means used to mine the ore have no significance in terms of processing doses.

For ISL operations, the gamma pathway is dominant, and this is almost completely due to Operation 13, an amalgamation of 15 different operations (see Fig. 35(a)). It is believed that the dominance of this pathway is in part due to this pathway not being subject to background correction and hence it may incorporate a component of natural background exposure. For the other mines, there was a wide divergence in the relative pathways based on the supplied data (see Fig. 35(b)). Operation 1 only supplied gamma data and hence does not have any LLRD or RDP component. Operation 11 was a toll milling operation and had the dominant number of personnel. Gamma is the dominant pathway and this is as expected, given the nature of a pure toll milling operation.

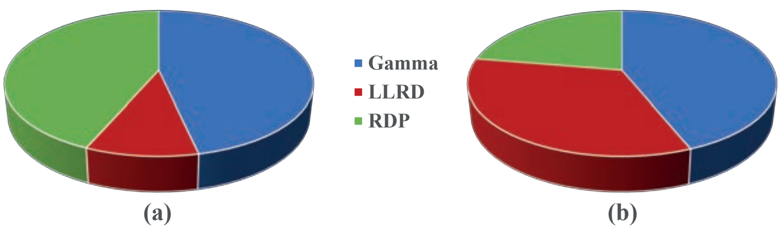

FIG. 33. Occupational exposure contribution from (a) underground mining and (b) underground processing.

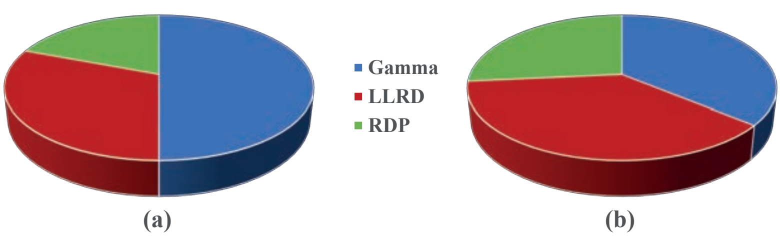

FIG. 34. Occupational exposure contribution from (a) open cut mining and (b) open cut processing.

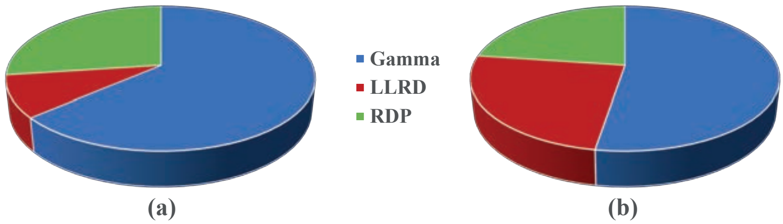

FIG. 35. Occupational exposure contribution from (a) ISL processing and (b) other mines and facilities.

I.9. DOSE DATA

For most of the operations, the available data contain a significant amount of information, including how the dose is distributed within a workgroup, how representative the workgroup is and whether there are potential outliers or individuals significantly different from the group (see Fig. 36).

By examining the total number of personnel in each group and how the data cluster around the low doses, it is possible to determine how representative the dose is of radiation worker exposure. For example, Operation 2 was characterized by many workers, with the majority (>87%) receiving an annual dose of less than 1 mSv. This implies that the data do not focus on workers with higher potential for exposure (i.e. designated workers) but record all workers who entered the controlled areas of the operation. This approach ensures that all potential exposures are recorded, but also biases the average data to very low doses. For other operations, the data focus on a far smaller group of workers and the doses cluster at higher levels of exposure. This implies that the recorded data are more heavily focused on designated workers and hence will have a higher average. Although both methodologies are valid, this highlights the importance of understanding the nature of the data, as just using averages can lead to an incorrect interpretation of the comparative impacts. Operations data can be more directly compared when the data are normalized by dividing the number of workers in each dose range by the total number of individuals (see Fig. 37).

All operations appear to have a similar dose distribution, which is log-normal with a higher number of individuals clustered around the lower doses. Because some operations appear to provide data in different dose ranges (e.g. every mSv/a rather than every 0.5 mSv/a), care needs to be taken in analysing the data. However, there appear to be two distinct groups, with some operations having the maximum number of workers in the very low dose range

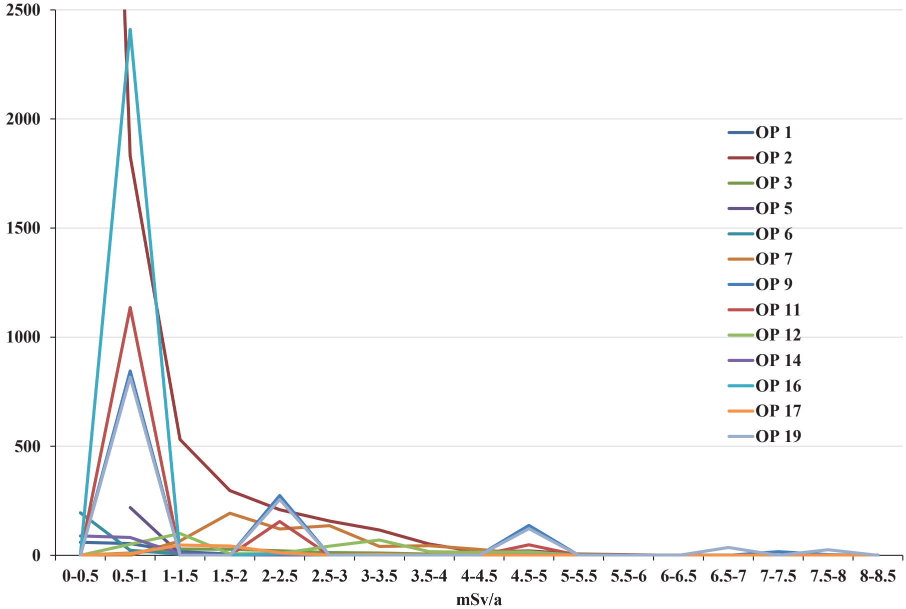

FIG. 36. Number of workers in different dose ranges. Note: For Operation 2, 7749 workers are in the range 0–0.5 mSv/a.

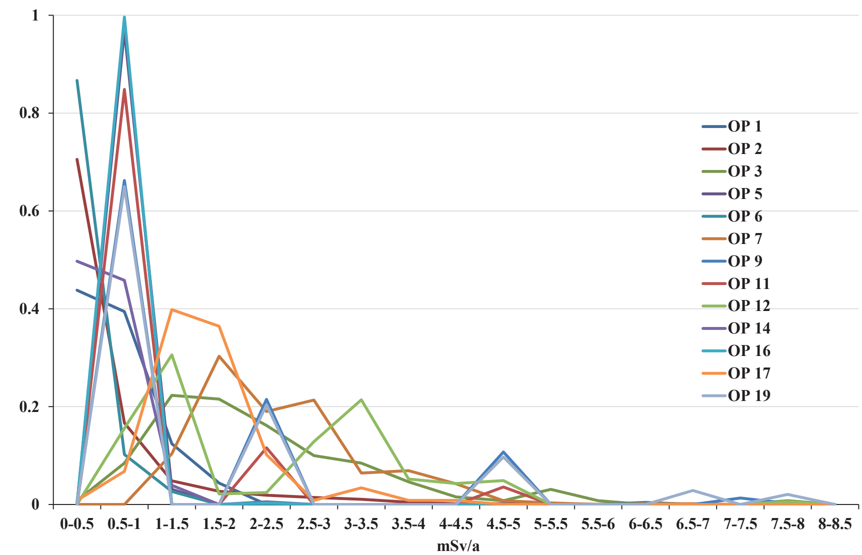

FIG. 37. Normalized dose distribution in different operations.

(0–0.5 mSv/a) and others having the maximum number of workers at higher dose ranges. There are three potential reasons for this:

(a) The data provided were not based on 0.5 mSv/a dose steps, but used a larger dose range;
(b) The selection of workers to be recorded concentrated on workers with the potential for higher exposures, which shifted the distribution;
(c) The data recorded included natural background (particularly for gamma monitoring) and hence included up to 1 mSv/a of background contribution.

The dose data can also be utilized for examining workgroups (see Fig. 38). For a workgroup which is representative of all its members, the resulting distribution generally follows a log-normal distribution. However, it is often common for a workgroup to be a compilation of two or more similar exposed groups, which leads to a bimodal or multimodal distribution. For example, a selection of workgroups has been analysed from Operation 2. The distribution for the electricians, and to a lesser degree the production drillers, is as expected for a group which is internally consistent. However, the distribution for the ore handlers and the raise drillers shows evidence of a bimodal distribution. This is not unexpected if the range of work for the group is considered. For example, raise drilling operations can often be split into a range of tasks some of which have a higher potential for exposure. If the individuals in the workgroup concentrate on one range of tasks (i.e. controlling the drill rather than being at the face changing the rods) then this bimodal distribution could be expected. Similarly, workgroups often incorporate some individuals who, by way of their job specification, will have a different potential for exposure than their peers. The most common example would be for the shift supervisors who may move between operations and be doing more administrative duties and hence could be expected to have a lower potential for exposure.

Dose histograms are an underutilized tool for the interpretation of doses. At the very minimum, knowledge of the nature of the dose distribution is essential to the understanding and the correct interpretation of what average and standard deviations mean with respect to dose. It is also a useful tool for determining whether the members of a workgroup are similarly exposed or if there are members who have significantly different exposure profiles than their peers. As the use of workgroup averaging is a common tool in dose assessment, this understanding of the internal consistency of a workgroup is a means for improving the accuracy of the dose assessment.

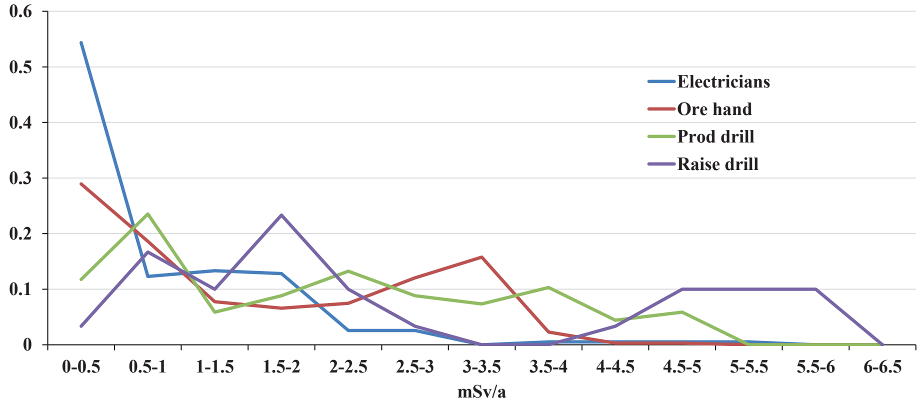

FIG. 38. Normalized dose histogram for selected workgroups.

I.10. FUTURE CHANGES AND IMPLICATIONS

There is currently a projected future deficit of uranium ore in terms of what is needed to maintain existing nuclear power plants and the anticipated growth in the nuclear industry in the future. The requirements for protection and safety in uranium mining and processing plants as planned exposure situations, and the remediation of contaminated uranium legacy sites as existing exposure situations, have become ever more challenging. The UMEX survey on occupational exposure in the uranium mining and processing industry would support the opportunity for the implementation of GSR Part 3 [10] to further strengthen occupational radiation protection for workers, increase opportunities for the optimization of workers' exposure and support quality assurance programmes across the industry. The data demonstrate the feasibility of developing a global information system for occupational exposure in uranium mining and processing. The data as summarized above also provide a demonstration that, although the doses vary by operation and by the relative contributions of the various pathways of exposure, the doses are lower relative to regulatory standards and many cases are indeed within the range of natural background exposures. Notwithstanding the low doses, the survey has identified many opportunities for improvements to radiation protection practice and reporting. The survey results also provide an opportunity to consider, albeit at a high level, the possible implications of proposed new ICRP guidance on the application of radiation protection at uranium mines and mills.

I.11. RADON DOSIMETRY

In the 2009 statement on radon, the ICRP [42] advised that the change in nominal risk coefficient for exposure to radon and progeny “is likely to result in an increase...of around a factor of two.” The ICRP is also planning to move from the current epidemiologically based dose conversion convention approach to a fully dosimetric approach. The DCFs based on dosimetric models depend on a number of considerations, including the site of deposition in the respiratory tract, which in turn depends strongly on the activity and size distribution of the RDP, especially small sized (ultra fine) particles in the range of a few nanometres in diameter (commonly referred to as the ‘unattached fraction’).

The dose per unit deposited activity can vary by much more than a factor of 10 based on particle (activity) size alone, which suggests that uncertainty in the activity size distribution assumed for dosimetric modelling can also lead to large uncertainties in the DCF. The fractional contribution of radon to the total average and maximum doses at the various facilities is shown in Figs 39 and 40. Assuming a doubling of the radon DCF, the contribution from radon to the total dose will increase substantially and, in some cases, has the potential to increase the doses to above 20 mSv/a.

A simplistic approach to determining the potential impact of the proposed ICRP changes is to double the dose contribution from RDP, as illustrated in Figs 39 and 40 for average and maximum doses (note that the single maximum dose in excess of 30 mSv is not included). The average doses, even with doubling the RDP dose contribution, are not greatly affected and, based on the available data, they seem likely to remain under 5 mSv/a. For maximally or highly exposed individuals, however, it is more likely that cases of doses exceeding 20 mSv/a might occur. Additional control measures will need to be implemented to ensure compliance with a new dose limit, in particular in underground operations.

Thus, knowledge of the activity size distribution of RDP will be increasingly important for the accurate assessment of occupational exposure in uranium mining and processing facilities. However, as illustrated by the survey, very few operators measure activity or particle size data. Moreover, equipment to measure activity size distribution in the nanometre range is currently very limited and primarily research oriented.

I.12. LONG LIVED RADIONUCLIDE DOSIMETRY

The ICRP has published a series of reports to provide revised dose coefficients for occupational intakes of radionuclides by inhalation and ingestion (see Refs [43–45]). The revised dose coefficients have been calculated using the

ICRP models. The ICRP has revised many models for the systemic biokinetics of radionuclides absorbed to blood, making them more physiologically realistic representations of uptake and retention in organs and tissues and of excretion.

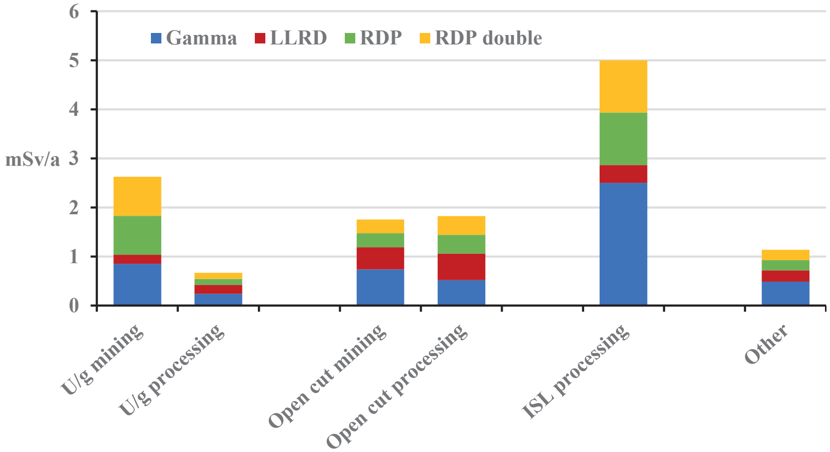

FIG. 39. Fractional contribution of radon and progeny to the total average dose.

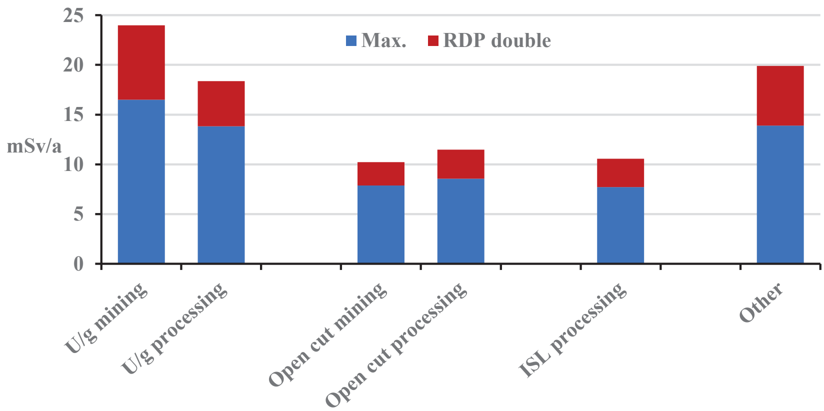

FIG. 40. Fractional contribution of radon and progeny to the total maximum dose.

I.13. EXPOSURE TO THE LENS OF THE EYE

Cataract was one of the earliest pathologies associated with radiation, and it has long been thought that cataracts can only be induced after high dose exposure to the lens of the eye. In 1977, the ICRP [46] stated that “The aim of radiation protection should be to prevent detrimental non-stochastic effects [now referred to as tissue reactions] and to limit the probability of stochastic effects to levels deemed to be acceptable.” In 1984, the ICRP [47] stated:

> “that exposure of the lens to the currently recommended dose-equivalent limit (0.15 Sv) each year for 50 years would not cause a vision-impairing cataract, although it might give rise to opacities that could be detected ophthalmologically in some exposed individuals.”

In 2007, the ICRP [19] noted that “recent studies have suggested that the lens of the eye may be more radiosensitive than previously considered”. In 2012, the ICRP [48] set the ‘threshold’ for cataracts to an absorbed dose of 0.5 Gy, without any indication that fractionation of dose is less harmful than acute exposure and, at the same time, recommended that the annual equivalent dose limit to the lens be reduced from 150 mSv to “20 mSv/year, averaged over defined periods of 5 years, with no single year exceeding 50 mSv.” Accordingly, para. III.1(b) of GSR Part 3 [10] now stipulates the dose limit is “An equivalent dose to the lens of the eye of 20 mSv per year averaged over five consecutive years (100 mSv in 5 years) and of 50 mSv in any single year”.

The external doses reported in the recent questionnaire are assumed to reflect $H_p(10)$ for consideration of whole body dose. Although whole body doses reported in the questionnaire are quite low, further consideration of the dose from photons (gamma radiation) and beta particles arising in the uranium mining and processing activities would be informative with respect to protection of the lens of the eye, for which a dose at 3 mm (i.e. $H_p(3)$) is most relevant.

I.14. MAIN OBSERVATIONS AND CONCLUSIONS

The review of information from the UMEX questionnaire responses has identified many general observations and several observations on the measurement of exposure pathways:

(a) General observations:
   (i) Although a number of processes have been adopted for uranium mining all over the world, the predominant uranium mining process is ISL, followed by underground and open cut methods.
   (ii) The main process for uranium extraction is acid leaching, followed by alkali leaching.
(b) Assessment of external exposure:
   (i) The majority of the operators use TLD methods for the assessment of individual doses.
   (ii) The majority of operators monitor of all individuals, followed by selected group averaging and selected individuals.
   (iii) Approximately half of the operations do not use background subtraction. This may lead to an overestimation of occupational dose.
(c) Assessment of LLRD:
   (i) Approximately half of the operators use area dust sampling and the rest use personal dust sampling.
   (ii) Most operations use gross alpha counting methods to assess the inhaled alpha activity.
   (iii) The majority of operators use periodic monitoring for the assessment of inhaled dust.
   (iv) While the majority of operators do not use routine bioassay, some of the operators use urine analysis.
(d) Monitoring of the inhalation of RDP:
   (i) The majority of the operators use area RDP measurements with time records, followed by active RDP monitoring.
   (ii) The monitoring methodology used by the majority of operators is working group averaging, followed by individual monitoring.
   (iii) The majority of the operators do not use background subtraction, which may lead to some overestimation of the measured dose.
(e) Dose assessment:
   (i) For dose calculations, the majority of operators follow the timesheet method, while most of the remainder use electronic devices for time measurement.
   (ii) Different types of DCF are used by operators. The majority of operators use the DCF of 5 mSv/WLM, recommended by the ICRP [3], for RDP.
   (iii) There has to be a global harmonization of the approach to DCFs in order to allow comparisons to be made.
   (iv) In order to calculate a more accurate inhalation dose estimate, factors such as particle sizing, solubility factors and radionuclide speciation also need to be taken into account in the estimation of the annual dose.

Appendix II

EXTERNAL EXPOSURE TO GAMMA RADIATION

II.1. INTRODUCTION

II.1.1. Gamma emitting radionuclides of the uranium and thorium decay chains

The exposure of the workforce to direct external gamma radiation is often one of the most significant pathways in uranium mining. The uranium and thorium decay chains comprise a mixture of alpha, beta and gamma emitting radionuclides. The dominant gamma emitters are ^{214}Pb and ^{214}Bi (^{238}U decay chain) and ^{228}Ac, ^{212}Pb and ^{208}Tl (^{232}Th decay chain). The uranium decay chain radionuclides ^{214}Pb and ^{214}Bi have gamma emission energies of 242, 295, 352 and 609 keV. The gamma energies of the thorium decay chain radionuclides (^{228}Ac, ^{212}Pb, ^{208}Tl) exhibit both greater abundance and higher gamma energies, in the range of 239–2610 keV.

Gamma radiation is an electromagnetic form of radiation which is capable of penetrating steel and concrete. Localized concentrations of gamma emitting radionuclides in stockpiles or inside the process can therefore result in localized gamma radiation levels several metres from the gamma radiation source.

In most cases, the ore bodies exploited for uranium production contain very low levels of thorium and this decay chain makes an insignificant contribution to occupational gamma dose rates in the great majority of uranium producing mines. Where thorium comprises more than 10% of an exploited uranium ore, this will result in significantly higher gamma dose rates in the mine and plant.

II.1.2. Factors influencing the magnitude of gamma radiation fields

The following factors have a strong influence on the magnitude of the gamma radiation fields and annual occupational doses encountered in uranium mining and milling operations:

(a) Uranium concentration of the ore;
(b) Thorium concentration of the ore;
(c) Quantity of materials involved;
(d) Plant process and chemistry;
(e) Radionuclide composition and activity concentration per gram in the material;

(f) Presence or absence of the radon progeny;
(g) Distance of a localized gamma radiation field from fixed work positions and high occupancy areas.

The average grade exploited in uranium producing mines ranges widely from around 0.02% (200 ppm) at the Rossing mine, in Namibia, to around 20% in the Athabasca Basin, in Canada. As the uranium grade increases, the gamma component of the annual occupational dose will increase in importance, particularly during the mining operations. Exploitation of the high grade deposits presents significant challenges in terms of the very high dose rates encountered close to the ore body. In order to reduce occupational exposures from high grade ores to an acceptable level, specialized mining techniques and engineered controls are needed.

As the quantity of gamma emitting materials at a discrete location increases (e.g. in a stope, an ore stockpile, in the product storage area or in a processing plant tank), the gamma dose rates in the working area close to the material will also increase. The gamma 'shine' will also extend a further distance into the surrounding workplace.

Uranium ore contains a variety of alpha, beta and gamma emitting radionuclides in secular equilibrium. Uranium ores and concentrates can therefore be significant sources of gamma radiation in the mine and process. During the processing of uranium ores the secular equilibrium can be disrupted, giving rise to materials with different radionuclide compositions and gamma emitting potentials. The radionuclide composition of process materials in the process stream will influence the local gamma dose rates and occupational exposures. The extraction of uranium product in the processing plant will result in the product containing uranium and its immediate progeny, which are strong alpha and beta emitters but weak gamma emitters. The remaining radionuclides of the chain are discharged from the process as waste (e.g. tailings). The radionuclide compositions of materials found in uranium processing plants include the following:

(a) Materials containing the uranium decay chain in equilibrium (e.g. ores, concentrates);
(b) Uranium product containing ^{238}U, ^{235}U, ^{234}U and their immediate progeny;
(c) Materials containing the remainder of the decay chain from ^{230}Th to ^{210}Po (e.g. tailings);
(d) Materials comprising ^{210}Pb and ^{210}Po (e.g. precipitator dusts);
(e) Materials comprising ^{226}Ra and its short lived decay products (e.g. surface scales inside the process).

Material in (b) and (d) is a weak gamma emitter; material in (e) is a strong gamma emitter. Scales and deposits inside the processing plant rich in ^{226}Ra will give rise to strong, localized gamma radiation fields; as the activity concentration of ^{226}Ra increases, so do the localized gamma dose rates. The buildup of ^{226}Ra rich scales is process and plant specific and depends upon the process chemistry, the ore mineralogy and plant design. In South African uranium plants, radium rich scales were mainly associated with specific types of stainless steel and rubber compounds used to line the process; significant dose rates on pipes, valves and drum filter cloths of up to 1 mSv or more per hour were encountered in some plants.

Areas of high occupancy or fixed working positions close to elevated localized gamma radiation fields (e.g. at the working face or in the processing plant) can result in significant occupational exposures. A variety of administrative and engineered controls can be used to mitigate occupational doses.

II.2. CONTROL MEASURES

Gamma radiation exposures can be reduced through a wide variety of administrative and engineered control methods. The key concepts for controlling occupational exposure are time, distance and shielding:

— Reducing time spent in gamma radiation fields;
— Increasing the distance from the gamma radiation source;
— Shielding the gamma radiation source.

In underground operations, the gamma dose generally comprises around half of the occupational exposure and in open cut operations it comprises around 70%. In the processing plant, it is generally a smaller contributor to dose.

Control over gamma exposure is amenable to engineering and administrative measures (e.g. planning and control actions). In planning and designing mines and processing plants, it is important to take this into consideration, as it can be difficult to reengineer control measures later in the mine life cycle. The nature of gamma emission from uranium operations means that it is generally a very stable contributor to exposure. Under normal operations, the gamma dose rate at a location will not change over the short term unless there are very significant changes in the process and work area (unlike the radon progeny and, to a lesser extent, dust exposure pathways). In the exploitation of low grade ore bodies, it is rare for there to be any unforeseen high doses arising from gamma radiation during mining or processing, as increases in dose rate (especially in the processing plant) are generally the result of longer term changes (e.g. the buildup of radium scales inside the process). Measures to reduce gamma doses can involve significant changes to either the work area (e.g. the design, increased shielding or the removal of gamma emitting scales from the process internals) or worker interaction with the work area (e.g. access to controls and relocating fixed work positions). In underground operations (in particular those with high grade ores), the nature of the mine, its geology and the working methods can mean that the control options involve significant investment.

The principal means of controlling the gamma dose is by restricting the time that the workforce spends in areas of enhanced gamma dose rates (i.e. minimizing the occupancy factor). A variety of techniques can be used in isolation and together to reduce occupancy factors:

— Planning work tasks to reduce exposure times;
— Knowledge of gamma dose rates (especially localized high dose rates) in all areas of the plant;
— Monitoring and controlling access to high dose rate areas;
— Locating fixed work positions in low dose rate areas;
— Barriers and fences;
— Warning signs;
— Workers issued with EPDs;
— Training of workers.

In a mining and processing environment, the use of distance is often constrained on account of the nature of the facility and the ore body. In the mining environment, simple practices such as ensuring an adequate working distance from the ore face and the siting of high occupancy areas away from areas with high grade ores can result in significant dose reductions. In processing plants, controlling worker access, shielding, reducing occupancy factors, and locating fixed work positions and control rooms in low dose rate areas can be very effective in reducing doses. Simple changes in work practices can be very effective in reducing gamma doses.

During mining activities, the large size and density of the equipment being used can often give a substantial shielding advantage to the worker. In underground mining, additional shielding in the form of shotcrete (spray on concrete on the exposed rock) can result in a significant reduction in dose and decrease the risk of rock falls. In most processing plants, shielding is not necessary due to the low dose rates or because there is sufficient open space in the plant to reduce the radiological impact without the need for shielding.

In mines with very high grade uranium, the shielding design of the mine and processing plant is a vital tool in managing occupational doses. Mining has to be carried out using special methods, remote controlled machinery and handling methods that limit worker occupation in the high dose rate areas. In the processing plant, certain parts of the process will need to be shielded by concrete containment and strict access controls are also necessary.

A key aspect of minimizing the gamma exposure in the workplace is a good knowledge of the gamma dose rates in all work areas through regular surveys and managing them accordingly.

II.3. MONITORING AND DOSIMETRY

The gamma monitoring programme needs to be commensurate with the nature and extent of the gamma radiation sources in the workplace and the annual exposures received by the workforce.

II.3.1. Life cycle aspects of gamma radiation monitoring

Gamma monitoring is not just confined to the operating life of the uranium mining and milling facility between commissioning and termination of the process, it is also needed during exploration activities and baseline environmental studies, prior to hot commissioning, and during operations and decommissioning activities. It is particularly necessary in the collection and sampling of high grade ores, and in the areas where ore samples are stored, prepared and processed for analysis (e.g. laboratories).

A baseline gamma monitoring programme determines the background gamma radiation levels at the plant prior to commissioning. The operational gamma monitoring programme is initiated during hot commissioning and further developed in the initial years after ramp-up to full production. During this period, the monitoring results are regularly reviewed and the operational monitoring programme revised and optimized accordingly, including major and minor maintenance activities. It is common to see a buildup of gamma emitting scales inside the process during the life of the plant.

II.3.2. Purpose and types of gamma radiation monitoring

In a uranium mining and milling operations both area and personal gamma monitoring programmes are needed for the following purposes:

- To measure gamma radiation dose rates in the workplace;
- To measure individual occupational exposures to gamma radiation;
- To detect the buildup of gamma emitting materials (e.g. scales) within the process;

— To verify the efficiency of engineered controls in the plant and process;
— To confirm and verify area designations.

Area gamma radiation monitoring activities need to focus on designated supervised areas and controlled areas, including:

— Underground and surface mining operations;
— Ore stockpiles;
— Processing plant;
— Uranium product section (e.g. product precipitation, filtration, drying, weighing, packaging);
— Milling and crushing areas;
— Product storage areas;
— Scrapyards;
— Tailings.

Other areas of the facility designated as uncontrolled areas can be monitored at more infrequent intervals, such as offices, workshops, eating areas, roads and laboratories.

II.3.3. Workplace monitoring and equipment

Routine workplace monitoring for gamma radiation can be carried out with a variety of portable instruments incorporating Geiger–Müller detectors. The surveys are conducted at defined intervals in a systematic manner in accordance with a monitoring plan. Installed gamma monitoring systems (with readout and alarms) are sometimes used to assess local dose rates at fixed working positions in high dose rate areas. In addition, special monitoring (e.g. during commissioning and after plant modification) and task related monitoring may be necessary, for example during maintenance activities on the mine and plant, such as the replacement of pipes and valves and the cleaning of tanks, in particular where these activities involve entry into the process.

During gamma radiation monitoring, readings are taken on contact and at one metre above surfaces or one metre from discrete gamma sources. Different monitoring strategies are needed for the following situations and activities:

— Routine area monitoring of the workplace (e.g. mine, processing plant, product storage);
— Maintenance activities on the plant (e.g. prior to process entry);
— Monitoring items removed from designated areas (e.g. for repair or refurbishment);

— Monitoring items for clearance from an authorized site;
— Transport of uranium product;
— Identifying the source of any unexplained increase in gamma radiation;
— Monitoring accident situations and contaminated areas (e.g. soil);
— Monitoring prior to and during decommissioning activities.

II.3.4. Gamma radiation monitoring strategies

Monitoring programmes are used to demonstrate that the operational radiation protective measures function as intended, to signal whether further protective measures are to be considered and to audit whether the operations maintain the desired level of radiation protection. In addition to routine operational monitoring, there is usually a need to develop other monitoring programmes with specific objectives. Examples include monitoring for clearance of items from the site, monitoring prior to maintenance activities inside the process and monitoring of non-designated (i.e. clean) areas of the plant and site. These factors have to be considered when the methods, strategy and instrumentation for monitoring are chosen. Developing the monitoring strategy comprises the following phases:

(a) Identifying the areas that need to be monitored;
(b) Identifying the appropriate monitoring equipment;
(c) Determining the temporal frequency of monitoring;
(d) Determining the number of measurements associated with an area or group of items.

Monitoring strategies need to be developed for operational areas, plant items, fixed working positions, maintenance activities and non-operational areas. The monitoring strategies will be site specific. For example, older plants will usually need a more extensive monitoring programme than modern plants due to the buildup of fixed contamination in the plant and process.

The first step in defining the monitoring programme for operational areas is to identify those areas in the facility with the highest probability of gamma radiation fields. These areas will have been identified during the design stage of the project and appropriate designed controls implemented. Initially, the routine monitoring programme focuses on these priority areas of the mine, plant and process. This is determined by carrying out an initial detailed survey of the whole facility to identify the priority areas after hot commissioning of the plant. The frequency of monitoring the priority areas could commence with monthly monitoring for the first 6–12 months of plant operation in order to establish baselines and trends and to confirm the higher dose rate areas. After reviewing the initial results, the programme can be modified to adjust the frequency of monitoring and number of measurements to a more appropriate level commensurate with the occupancy time and potential for occupational exposure.

The remaining areas of the plant (i.e. low dose rate areas) can be monitored at a much lower frequency (e.g. quarterly or annually). Processing plants and their supporting infrastructure (e.g. storage sheds, maintenance buildings and bays, offices, parking areas, loading areas, scrapyards) can extend over very large areas of tens of thousands of square metres. This presents a significant problem in terms of monitoring resources. The majority of the routine area monitoring needs to focus on those areas with a high potential for localized gamma dose rates. These will comprise areas where radioactive materials are transported, handled and processed; the remaining areas will need to be surveyed at a much lower frequency.

The area monitoring strategy can be based upon a simple grid pattern or can focus on fixed work stations, high occupancy areas and any other areas where localized gamma radiation is known to occur.

The monitoring programme needs to be fully documented in the local operating instructions. The survey measurements need to be recorded and the results reviewed at a defined frequency. In addition, the monitoring programme and survey strategy need to be reviewed and revised at a specified frequency.

II.3.5. Selection criteria for portable gamma radiation instruments

Desirable criteria to consider when selecting the gamma radiation monitors used in uranium mining and milling facilities include the following:

- Ruggedness, reliability and serviceability;
- Waterproof and weatherproof;
- Operability across a wide range of temperatures and humidity;
- Portability (light weight);
- Switchable ratemeter and integrated measurement modes;
- Data logging capability;
- Sensitivity to the range of low and high energy gamma radiation found in uranium mines and mills;
- Energy independent response;
- Audible and visual overload protection;
- High speed of response to changing dose rates;
- Logarithmic/linear analogue/digital displays;
- Illuminated display and switchable audible output;
- Unaffected by radiofrequencies and magnetic fields;
- Battery availability and life expectancy;
- Easily decontaminated;

— Cost effective (initial cost, ongoing maintenance costs);
— Ready availability of spare parts and national service/repair centres;
— Intrinsic safety in explosive/flammable locations.

II.3.6. Calibration and daily check of portable gamma radiation monitors

The monitors need to be calibrated at an accredited national calibration facility (traceable to a national or international, primary standard) over a range of defined gamma emission energies [49]. Calibration is usually carried out every 12–18 months and after major repairs.

In addition, each gamma monitor is expected to undergo a series of checks prior to use to confirm its operability. The results of these checks are recorded and retained for internal and external audit purposes, and can include the following:

— Background gamma dose rate at a fixed position in the equipment store;
— Contact dose rate against a known check source;
— High voltage reading;
— Integrity of cables joining the probe to the scaler/ratemeter for good contact;
— Battery level.

II.3.7. Personal monitoring and dose assessment

Personal monitoring of individual workers is necessary for dose tracking, optimization purposes and the official annual dose record. In a large facility with many thousands of workers, who needs to be individually monitored depends on the facility. For example, high grade ore mines, with corresponding high gamma radiation levels need extensive individual monitoring for annual gamma doses in the mine and plant. Where gamma radiation comprises a small fraction of the annual dose limit the need for individual monitoring in the mine is significantly less. Some operators may decide to implement individual gamma monitoring for all workers in supervised and controlled areas regardless of the cost, as a form of insurance against the possibility of occupational exposure lawsuits.

Since the gamma radiation levels and annual doses can vary widely through the uranium mining and processing operation, comprehensive area surveys are required to determine the area classification of each part of the facility. The area classification scheme can be used as a guide to determine which workers need to be considered for personal monitoring to estimate their annual doses (see Table 5).

TABLE 5. PERSONAL MONITORING OPTIONS

Area classification	Total projected annual doses from all exposure pathways (mSv/a)	Personal monitoring options
Uncontrolled	<1	Not needed
Supervised	1–6	Dose assignment by area surveys and occupancy factors or selective personal monitoring of representative individuals
Controlled	>6–20	Workers need more intensive personal monitoring

II.3.8. Assessing occupational exposures

Occupational gamma doses can be assessed by a variety of methods, including: (i) prospective assessments based on modelling and calculation; (ii) individual monitoring of each worker or representative workers from a larger group of workers; and (iii) using the results of area monitoring and occupancy factors to estimate annual gamma doses. During the design process for a new uranium mine and processing plant, prospective hazard assessments are carried out to provide estimates of the radiation hazards prevailing in the future workplace. The gamma dose rates in the workplace and the projected annual occupational doses are estimated by modelling, calculation and experience. These estimates are then used to optimize the design of the plant to keep gamma doses ALARA.

A wide range of technologies can be used to assess individual doses, and common dosimetric methods used include [11]:

(a) Film badges can be used to assess skin dose and deep dose. This method is rarely used in modern uranium mines.
(b) TLDs are currently the most popular method of assessment.
(c) OSLDs are a new dosimetry technique.
(d) EPDs provide dose rate readings and total dose tracking capability.

TLDs and OSLDs are small, inexpensive, robust and easy to use, and are accepted by regulatory bodies as the standard for personal gamma measurement. They have wide acceptance in the workforce and are available worldwide. However, the major disadvantage is that they are generally only effective for recording dose and showing compliance, and have limited applicability for dose optimization. The dosimeters are exposed for a period of one to three months and the results indicate the total dose over that period. This makes the investigation of high doses difficult, as the dosimeter provides no timeline for when the exposure occurred.

The development of modern electronic dosimetry over the last thirty years has enabled the development of advanced EPDs which can accurately and reliably record both the accumulated dose and the prevailing doses rates and provide a visual readout. These EPDs also incorporate dose and dose rate alarm levels, providing workers with direct feedback in real time so that corrective actions can be implemented. Many types of active personal dosimeter are commercially available. They are usually based on an energy compensated Geiger–Müller counter or a silicon detector. These dosimeters are useful as alarm dosimeters for use in controlled areas and for short term radiation control of workers' exposures (see Refs [50–54] for further information).

Active personal dosimeters have been accepted as legal dosimeters for routine dosimetry in some countries (e.g. United Kingdom [51]). Based on the findings of these investigations, it is evident that the energy and directional response characteristics of recently developed active personal dosimeters are in most cases as good as those of passive dosimeters.

II.3.9. Natural background correction

Natural background radiation sources (terrestrial and cosmic radiation sources) can contribute up to 1 mSv/a to the dose indicated on personal dosimeters and this needs to be corrected. Prior to the plant startup, a background baseline survey needs to be carried out to determine the prevailing gamma dose rates and annual background exposures. These values can be used to provide a background value to subtract from the TLD or OSLD results.

II.3.10. Interpretation of monitoring results

The most important part of any monitoring programme is the interpretation of results [11, 55]. The area monitoring results need to be evaluated and reviewed by managers on a regular basis (e.g. quarterly) to determine whether there are any significant changes or trends in the gamma radiation levels. Increasing gamma radiation levels might indicate the buildup of gamma emitters in the mine process or degradation in the engineered controls.

A more detailed and robust technical review process is required for the results of the personal dosimetry programme. The monthly results for each individual need to be checked for anomalous results, and the overall results need to be reviewed on a quarterly and annual basis by management. The results of all monitoring programmes are to be stored in both paper and electronic formats and summarized in a database linked to a geographic information system.

Appendix III

RADON AND RADON PROGENY

III.1. INTRODUCTION

The major isotopes of radon are ^{222}Rn, with a half-life of 3.82 days, and ^{220}Rn (also known as thoron), with a half-life of 55.6 seconds. They are present in ambient air and originate from the ^{238}U and ^{232}Th decay chain series. The parent isotopes of these two gases are ^{226}Ra and ^{224}Ra, respectively. The isotopes and their short lived progeny represent a radiological hazard to humans when present in significant concentrations. As a gas, radon is emitted from uranium and thorium bearing ores into the working environment of operational mines and mills. Radon alone does not generally present the main radiological risk, as inhalation of this inert gas results in it being exhaled within a much shorter time than the isotopes' respective half-lives. It is the relatively short lived decay products of these isotopes, which are emitted as free metallic ions, that present the main radiological inhalation risk from the presence of radon and thoron. The inhalation of significant activities of radon and its progenies has long been related to elevated incidences of lung cancer and other diseases in uranium industry workers (see Refs [3, 33, 56–58]).

The majority of radon progeny, depending upon the aerosol concentrations, attaches to submicron particles. Because of their particulate properties, the attached and unattached progeny can become lodged in the respiratory tract when inhaled. Their relatively short half-lives mean that they generally decay, causing exposure to the respiratory tract prior to their removal by respiratory system clearance mechanisms.

During the mining and milling of uranium and thorium ores, ^{222}Rn or ^{220}Rn and their progeny can present a significant radiological hazard. The level of risk is primarily dependent on the type of mining activity and ore grade, with underground mining activities having the highest exposure risk. In general, most uranium deposits contain very low thorium (^{232}Th) concentrations, and ^{222}Rn and its progeny are the predominant risk in uranium mines. At operations that mine thorium based ores, such as monazite, ^{220}Rn and its progeny can be of greater exposure significance. The rates of radon release are complex and depend on many factors, such as rock mineralogy and structure, mineral grain size, emanation coefficient, alpha recoil, the distribution of parent radionuclides (e.g. ^{238}U, ^{226}Ra), atmospheric pressure, temperature and moisture content [59–65]. The transport of radon from cracks and fissures in the rock to the mine atmosphere takes place through diffusion, advection and convection. The different mining activities such as blasting and mucking also trigger the release of radon and its short lived progeny into the mine air. In order to assess and minimize the dose to the miners and to understand the adequacy of ventilation at different workings in the underground uranium mine, regular monitoring of radon or radon progeny concentrations at different working areas usually forms part of the radiation protection programme.

The radon sources in mining operations can occur in ore body and stockpiles, waste rock stockpiles, mine water containing dissolved radon and radium, tailings, and process material stockpiles, containers and vessels. Factors that affect the radon concentration in a mining operation include:

— Radium concentrations;
— Porosity;
— Exposed surface area;
— Emanation rate;
— Moisture content;
— Ventilation;
— Temperature;
— Pressure.

At some operations, it can be simpler to measure the radon concentration rather than the progeny concentration. If the equilibrium factor F is known, then the radon progeny concentration in terms of the equilibrium equivalent radon concentration can be estimated. The equilibrium factor is defined as the ratio of equilibrium equivalent concentration to the activity concentration of the parent nuclide, radon, in air:

$$F = \frac{\mathrm{EEC}}{C_{\mathrm{Rn}}}$$

where EEC is equilibrium equivalent concentration and C_{Rn} is the radon concentration.

In underground operations where work areas are kept ventilated by using fresh air to control radon and its progeny concentrations, the radon and short lived progeny will not be in equilibrium. For dose assessments, the progeny concentrations need to be known. From a measured radon concentration and known equilibrium factor, the progeny concentration can be estimated. The default equilibrium factor of 0.4 as per the ICRP recommendation for mines where the equilibrium factor has not been established can be used in the absence of measured data [3].

III.2. CONTROL MEASURES

As an atmospheric contaminant, radon and its progeny are best controlled through adequate ventilation. In general, this means that radon and its progeny are usually only a significant risk in underground operations. In surface operations, exploration, open cut mines, heap mines, ISL mines and processing facilities, atmospheric dispersion and mixing are generally enough to control concentrations of radon and its progeny to acceptable levels. There can be situations or locations that warrant assessment and monitoring based on the potential risk of accumulation of radon and its progeny, such as inside process vessels, where pressurized groundwater or lixiviant enters the atmosphere (e.g. ISL) or in deep open cut pits or enclosed areas containing significant amounts of radioactive wastes or products. These situations are usually assessed on a case by case basis.

In underground operations, the establishment of effective ventilation systems is the primary control mechanism to reduce exposure to radon and its progeny. Administrative controls include the establishment of action limits, which, when exceeded, trigger escalation or restriction of work areas. Monitoring programmes for standard underground air contaminants need to incorporate radon or radon progeny measurements into their programme and align them with operational ventilation controls (see Refs [66–71]).

The implementation of controls needs to follow the hierarchy of control, with elimination of the hazard being the preferred option. As radon gas is the source of radon progeny, efforts need to focus on eliminating radon gas before it can decay into significant concentrations of radon progeny. The time taken for the decay of radon into its progeny isotopes can be used effectively to eliminate it from the working environment before it builds up into significant concentrations. Examples of control measures that can be used to minimize radon and radon progeny concentrations in exploration, mining, processing and closure include:

(a) Rapid removal of broken ore from the stopes and other work areas (the broken ore presents a greater surface area from which radon gas can exhale).
(b) Adequate control of mine water, which can release dissolved radon into the mine atmosphere. Control can be achieved by removing water from underground work areas and placing mine water ponds in well ventilated low occupancy areas on the surface.
(c) Establishment of a proper ventilation circuit in underground mines and locations where radon and its progeny can accumulate to provide adequate fresh air to the mine workings or work area.
(d) Sealing off and isolation of abandoned underground workings to reduce leakage of radon gas and its progeny into the active work areas.

(e) Establishment of action limits for monitoring programmes with specific control measures implemented when they are exceeded, such as the removal of personnel, closure of work areas and the use of PPE.
(f) Location of meal rooms and offices away from radon sources (e.g. ore stockpiles or open process vessels) in well ventilated areas.
(g) Provision of enclosed cabin equipment with appropriate filtration to remove radon progeny from cabin environments (e.g. refuges, control rooms, driving cabs).
(h) Covering of the tailings (e.g. with water or soil and rock) during operations and capping and sealing of the tailings at the end of the mine's life.
(i) Use of appropriate respiratory protection when necessary to re-establish controls, or in sealed off areas or for critical operational activities.

As with any control programme, inspections, maintenance programmes, monitoring, reviews and audits need to be established to confirm the effectiveness of the controls. These assurances need to allow for corrective actions to be put in place if a deficiency is identified in the controls. Appropriate resources need to be committed to the development and maintenance of these controls in the long term. Specific control measures for radon and its progeny have been covered in the relevant sections for the types of mining (see Table 6 for a summary).

III.3. RADON MONITORING AND DOSIMETRY

A range of different methodologies are available for the detection of radon and its progeny (see Refs [72–78]). The monitoring programme developed for the operation will include the locations, frequency and type of monitoring that will be performed for control or dosimetric purposes.

In the planning stage of the operation, a decision needs to be made as to whether radon, radon progeny or both will be measured during the operational stage. In India and South Africa, uranium mines typically measure radon and use appropriate calculations with an equilibrium factor to estimate the radon progeny. Australian and Canadian uranium mining operations monitor radon progeny directly. The following methods have been successfully utilized at operations and incorporated into their monitoring programmes for control and dose assessment purposes.

III.3.1. Scintillation cell technique (^{222}Ra concentrations)

The scintillation cell technique is one of the simplest methods for the collection of many air samples. This grab sampling method is applicable in

TABLE 6. SPECIFIC CONTROL MEASURES

Process type	Radon and radon progeny risk	Controls
Exploration	Low	Natural ventilation is generally adequate. Usually only a potential risk in indoor locations.
Underground mining	Critical	Adequate and monitored mine ventilation system with associated administrative controls to react to high monitoring results. Use of appropriate respiratory protection if necessary.
Surface mining	Low	Natural ventilation is generally adequate. For deep pits or areas with significant inversions access restrictions or vehicle air filtration may be necessary.
In situ leaching	Low (some areas high)	Natural ventilation is generally adequate. Areas where lixiviant returns to surface and enters normal temperature and pressure conditions need to be low occupancy areas. First stage processing vessels may need extraction ventilation and entry checks may be necessary for access to vessels.
Heap leach	Very low	Natural ventilation is usually adequate.
Processing	Low	Natural ventilation is usually adequate. Only a potential risk in indoor locations.
High grade operations	Critical	Adequate and monitored mine ventilation system with associated administrative controls to react to high monitoring results. Use of appropriate respiratory protection if necessary.
Non-conventional operations	Usually low	Natural ventilation is generally adequate except in the case of underground mining.

uranium mines and mills and has been used since the inception of industrial scale uranium mining activities [79–81]. The method uses a cylindrical (100–200 ml) Plexiglas or metal cell internally coated with silver activated zinc sulphide (ZnS(Ag)) scintillation material. These cells are better known as Lucas or Van Dilla cells.

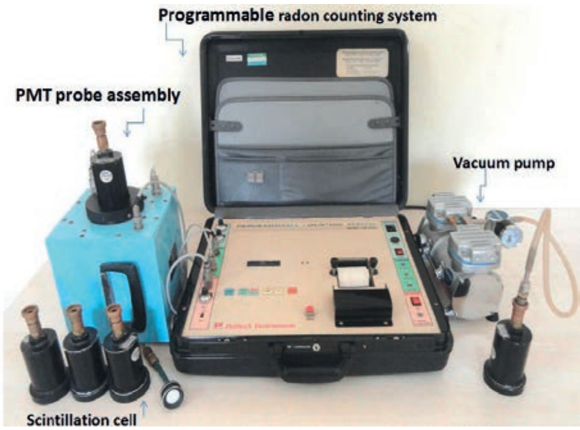

FIG. 41. Programmable radon counting system for the measurement of radon in mine air.

To prepare for sampling, the cells are evacuated and sealed (using a valve assembly) and then opened at the sampling location to allow filtered air (filtered through a membrane filter head) into them, and they are then sealed again until they can be analysed. The cells contain a transparent glass window (on the base) and can be optically coupled to a photomultiplier tube and counting system (see Fig. 41). The alpha activity in the cell is counted over a known period, typically for about 600 s, approximately 180 min post-sampling, when the short-lived progeny attain equilibrium with the parent radon in the cell. Counting times can be increased to obtain lower limits of detection.

The interaction of an alpha particle with ZnS(Ag) on the cell wall generates a flash of light, which is detected by the photomultiplier tube and converted into an electrical signal. The efficiency of the cells varies from 70% to 80%. The radon concentration is calculated using:

$$C_{\mathrm{Rn}} = \frac{6.697 \times 10^{-2} \cdot C}{E \cdot V \cdot e^{-\lambda t}\left(1 - e^{-\lambda T}\right)}$$

where

C_{Rn} is the radon concentration (Bq/m^3);
C is the net counts in T seconds (counting time);
λ is the decay constant of ^{222}Rn (s^{-1});
E is the efficiency of the cell (%);
V is the volume of the scintillation cell (L);
T is the counting time (s);

and t is the delay (>180 min) between the sampling and counting time(s).

III.3.2. Low level radon detection system

The low level radon detection system (LLRDS) is used for the estimation of radon concentrations in the environment and mainly works based on the electrode position of freshly formed positively charged (~90%) ^{218}Po atoms on a negatively charged plate for a predetermined collection and alpha counting period [82]. Ashok et al. [83] report (see Fig. 42):

> "It is provided with a swage lock connector for an air inlet and outlet. It has an inner arrangement for exposing metallic disc to the ^{222}Rn gas. In this method, the LLRDS chamber was evacuated and the air was allowed inside, until it attains the pressure equilibrium with the atmosphere (2–3 min). A delay of 10 min was allowed for the complete decay of thoron, which may be present in the chamber."

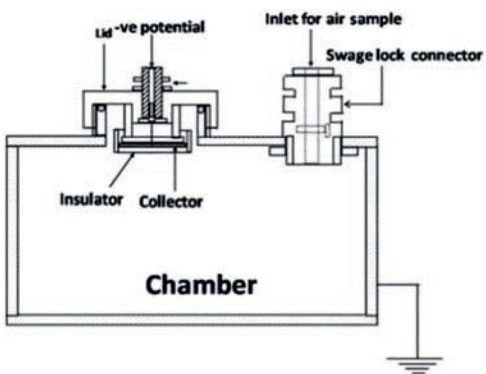

FIG. 42. Low level radon detection system (fig. 1 of Ref. [83]).

Khan and Puranik [84] describe:

> "The system consists of a 5 liter cylindrical aluminum chamber with a ~5 cm dia Al disk on the top lid.... A negative voltage of −800 V supplied to the metallic disc for a period of about 90 min and the alpha activity deposited on the plate is counted ideally from 1 to 75 min post collection. The radon concentration is estimated from the relation,

$$C_{\mathrm{Rn}} = \frac{C}{E \cdot V \cdot Z \cdot 0.9\left(1 - e^{(0.042H - 4.31)}\right)}$$

"where

C — net counts observed
E — efficiency of the counter
V — volume of the chamber (m^3)
H — relative humidity in the sample (%)
Z — alpha emission factor

$$Z = \sum_{i=1}^{3} K_i \left(1 - e^{-\lambda_i t}\right)\left(e^{-\lambda_i T_1} - e^{-\lambda_i T_2}\right)$$

$K_1 = 277$ s, $K_2 = 982$ s, $K_3 = -5599$ s
λ_i — decay constant of the radon daughters (s^{-1})."

III.3.3. Solid state nuclear track detector

The solid state nuclear track detector (SSNTD) was developed for the evaluation of very low levels of radon in the environment and dwellings and for dosimetry for mine workers [84]. A simple dosimetry system is shown in Fig. 43 (see also Refs [85–89]).

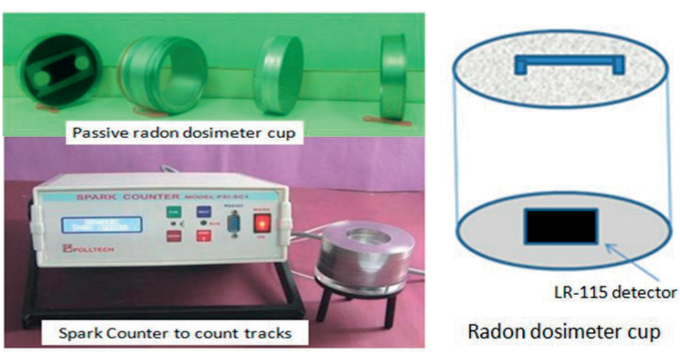

FIG. 43. SSNTD based passive radon dosimeter.

Khan and Puranik [84] describe:

“The device comprises of a 60 ml cylindrical aluminum chamber covered with a permeable membrane which allows only radon to diffuse in, due to its relatively longer half life, and serves as a barrier for Rn-219, Rn-220 and aerosols. A 1.8 cm × 3 cm SSNTD film is placed between two TLD chips mounted on a disc at the base of the chamber. The SSNTD film and the TLD in the chamber are replaced every two months [this method provides a long term average radon gas concentration value over periods ranging up to several months]. ...The SSNTD film is etched with 10% sodium hydroxide solution at a temperature of 60°C for 90 min. The tracks are electronically counted which are correlated to radon exposure using a calibration system.... The cumulative radon exposure is obtained from the track density as,

$$E\ (Bq{\cdot}h{\cdot}l^{-1}) = 0.554\ T,$$

“where E is the cumulative exposure, T is track density per cm^2, h is the exposure period in hours and 0.554 is the calibration factor between the track density and radon concentration ($Bq{\cdot}l^{-1}$).

“Average radon concentration for the exposure period can be obtained from the relation,

$$C\ (Bq{\cdot}l^{-1}) = 0.554\ T/h.\text{”}$$

III.3.4. Diffusion based exchange-twin cup dosimeter

A twin cup dosimeter for the measurement of radon and thoron gas concentrations simultaneously present in the air over extended periods of up to three months was designed and developed by the Bhabha Atomic Research Centre [90]. The LR-115 type II cellulose nitrate based SSNTD manufactured by Kodak Pathe, France has been used as the passive detector. Three detectors are used in this device [90]:

“Each chamber [cup] has a length of 4.5 cm and a radius of 3.1 cm.

....

“The SSNTD1 placed in compartment 1 measures radon alone which diffuses into it from the ambient air through a semi-permeable membrane.... These

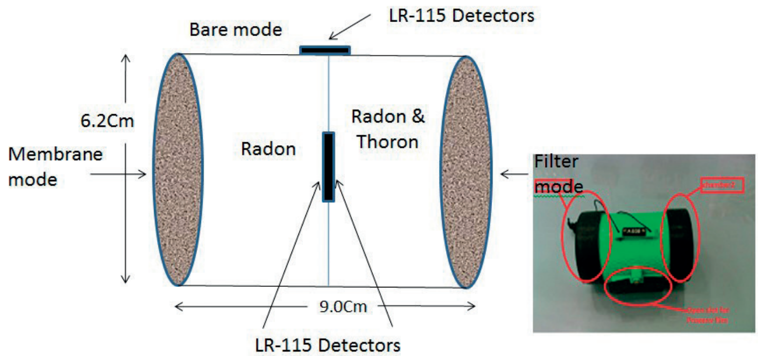

FIG. 44. Twin cup radon–thoron dosimeter.

membranes...allow more than 95% of the radon gas to diffuse and suppress thoron gas to less than 1%. (The mean time for radon to reach steady state in the cup will be in the range of 4 to 5 h.) On the other hand, the glass fibre filter paper in compartment 2 allows both radon and thoron gases to diffuse in and hence the tracks on SSNTD2 are related to the concentrations of both gases. The SSNTD3 exposed in the bare mode (placed on the outer surface of the dosemeter) registers alpha tracks attributable to the airborne concentrations of both the gases and their alpha emitting progeny, namely ^{218}Po, ^{214}Po and ^{216}Po, ^{212}Po."

By deploying the twin cup dosimeter at a selected location, radon and thoron concentration in the air can be measured (see Fig. 44).

III.3.5. Alpha spectrometry with silicon PIN diodes, surface barriers and diffused junction detectors

The spectrometric capability and very good energy resolution of PIN diodes, surface barrier detectors and passivated ion implanted semiconductor detectors fabricated from silicon semiconductor materials can be utilized to distinguish between various energy peaks produced by alpha particles emitted from radon and thoron decay products [91]. It is possible to obtain the radon progeny concentrations by distinguishing between the 6.00 MeV alpha particles from ^{218}Po and the 7.69 MeV alpha particle from ^{214}Po by discriminating the two energy peaks separately during the counting interval. Similarly, the thoron concentration can also be measured independently using the 8.785 MeV alpha energy peak from ^{212}Po atoms. Alpha spectrometry is a very useful tool for the measurement of individual radon progeny concentrations. In this method, the sample is usually collected on a membrane filter with a pore size of less than 1 µm at a known flow rate for a specified time. Then, the sample is counted twice at different intervals using an alpha spectrometer to obtain separate activities of ^{218}Po and ^{214}Po. Various RDP and radon–thoron measurement equipment, which works on the principle of alpha spectrometry, is currently commercially available. For example, the RAD7 is used extensively in the field of radon measurements and applies the alpha energy discrimination technique for electrostatically deposited polonium atoms.

III.3.5.1. Activated charcoal monitoring

Radon diffuses passively into activated charcoal, where it decays, and the decay products remain attached to the charcoal. Charcoal canisters for radon monitoring are a cheap and effective integrated sampling technique that is commonly used for sampling in low level radon environments, such as homes. After exposure to the atmosphere for a period, usually days to weeks, the canister is sealed and analysed via gamma spectrometry. The concentration of radon is determined by an analysis of the spectrum produced from the decay of the radon progeny.

III.3.5.2. Ionization chambers

Radon gas was first discovered using an ionization chamber device. Due to less costly options, this technique is not commonly used, but many devices have been developed using ionization chambers. Equipment based on this technique is either sealed or flowthrough, with sealed equipment typically limited to laboratories. Flow through equipment is suitable for field analysis, but has been superseded by scintillation cells. A larger chamber provides lower detection levels, but limits the effectiveness of the technique for field analysis.

Air is filtered to remove dust and radon progeny prior to being drawn into the ionization chamber. The decay of radon ionizes the chamber gas and this is recorded as a pulse by the detector. Radon concentrations are calculated from the volume, sampling times and count rate relationships.

III.3.5.3. Two filter sampling

The two filter method can be used to measure radon and its progeny and radon/thoron gas [92, 93]. Air is drawn through the first filter, where radon progeny are collected, and radon gas passes through into a chamber. The air passes through the chamber for a known period to allow the ingrowth of radon progeny before being passed through another filter. The radon progeny concentration can be determined from gross alpha counting of the first filter. The radon progeny that are measured on the second filter comprise a measurement of the radon concentration in the air. This method has been incorporated into a number of commercially available active detector systems.

III.3.5.4. Other equipment

There is a large range of commercially available radon monitors for instantaneous, integrated or continuous monitoring of radon concentrations. A search for commercial products and providers will yield a reasonable number of results for equipment that is based on one of the techniques described.

Measurement of radon is far easier than measurement of radon progeny. In ambient situations where the equilibrium factor F can be accurately assumed (e.g. 0.4 indoors and 0.6 outdoors), it is much easier to monitor for radon than its progeny. Dose assessments for exposure to radon progeny can then be made based on the assumed equilibrium factor with reasonable accuracy.

III.4. RADON PROGENY MONITORING

III.4.1. Filter sampling and counting methods

A range of methods exist for the monitoring of radon progeny concentrations using air filters. They all follow the approach of collecting a sample from a known volume of air through a filter followed by single or multiple alpha particle counting of the sampled filter. The concentration is calculated based on the counts/count rates, decay rates, sample, delay and count time. The methods then provide a result for either the potential alpha energy concentration (PAEC) in $\mu J/m^3$ or in the WL for use in dosimetric calculations (where 1 WL = 20.8 $\mu J/m^3$).

Standard air sampling procedures are to be adhered to for the collection of samples. This includes the use of calibrated sampling pumps, appropriate filter media, sampling heads and tubing.

III.4.1.1. Kusnetz method

This procedure involves sampling air through a high efficiency filter paper for a period of typically 5 min to collect a known volume of air of between 100 L and 250 L [94]. The filter is then safely stored for a minimum of 40 min but not greater than 90 min prior to alpha counting in an appropriate detector. The minimum counting period is 1 min, but the sample can be counted for longer periods, up to 10 min, to improve accuracy. Typically, 5 min is used. This sampling method is convenient and provides a result within a suitable time frame for operational purposes. The method, however, is not suitable for atmospheres containing detectable concentrations of ^{220}Rn, as the ingrowth of its progeny will contribute to the alpha counts. The ^{222}Rn progeny concentrations can be determined from the following expression:

$$\mathrm{WL} = \frac{(C_\mathrm{S} - C_\mathrm{B})}{V t_\mathrm{c} K E}$$

where

WL is the concentration in working levels;
C_S is the gross alpha count;
C_B is the background alpha count;
V is the volume of air sampled (L);
t_c is the counting time (min);
K is Kusnetz conversion factor (dpm) relating to the delay time t_k with $K = 203 - 2t_\mathrm{k}$ when $40 < t_\mathrm{k} < 70$ and $K = 195 - 1.5t_\mathrm{k}$ when $70 < t_\mathrm{k} < 90$;

and E is the efficiency factor of the alpha counter.

The Canadian Nuclear Safety Commission (CNSC) relies on a modified Kusnetz method for the sampling of radon progeny concentrations at underground mines and they have published guidelines detailing this variation [72]. This method involves a lower volume of air (10–50 L), which is more easily obtained using battery powered sampling pumps.

III.4.1.2. Rolle method

The Rolle method has also found popularity in the operational environment because of its quick sampling and analysis times [95, 96]. Unlike the Kusnetz method, the Rolle method is quite insensitive to the presence of ^{220}Rn and its progeny, which makes the method more applicable to situations where ^{220}Rn can be present in significant concentrations. The Rolle method involves the sampling of air at flow rates between 2 to 10 L/min typically for a period of 10 min. This is followed by a delay time of 5–10 min prior to gross alpha counting for a period of typically 5 min. The shorter delay time means that samples can be analysed at the sampling location in the short term using a portable scaler/ratemeter. The WL concentration of radon progeny is calculated in the same way as in the Kusnetz method, with the exception that the conversion factor K is determined from Table 7. The error associated with the conversion factor for this method is in the order of 10–15% and can be minimized through appropriate selection of the sampling, delay and count times (see Table 8).

III.4.1.3. Borak method

This is the quickest method for the determination of radon progeny concentrations and is commonly used for operational control [97]. This method allows for the complete sampling and analysis process to be performed in less than 10 min, but uncertainties can be up to approximately 20% at a concentration

TABLE 7. CONVERSION FACTORS

Time after sampling (h)	Conversion factor
5	13.2
7	11.3
9	9.8
11	8.6
13	7.5
15	6.7
16	6.3

TABLE 8. SELECTING PARAMETERS

Sampling time (min)	Delay time (min)	Counting time (min)	Conversion factor	Error (±%)
4	6.46	5	213	12
5	6.06	5	213	11
10	4.35	5	213	11
15	1.36	10	212	10
20	2.12	5	210	10

of 0.1 WL. The method involves taking a 3 min air sample through a 25 mm 0.8 μm glass fibre filter using a sampling pump operating at 3.5 L/min. A delay period of 3 min is then applied prior to a counting time of 3 min (commonly referred to as the 333 sampling method). The radon progeny concentration in μJ/m^3 is then determined by:

$$\mathrm{RDP} = \frac{C \times 0.2237}{E}$$

where C is the counts recorded and E is the counter efficiency (%).

III.4.1.4. Hill method

This method involves the sampling of air for a period of 2 min at a suggested flow rate of 2 L/min. The sample is then dual counted for activity over two periods of 2 min starting at 0.5 and 3.5 min after the end of sampling [98]. The PAEC is then determined from:

$$\mathrm{PAEC} = \frac{I_0}{\gamma E}$$

where

E is the detector efficiency (%);
I_0 is the integrated counts from the first sampling period;

and γ is a factor determined from the ratio I_1/I_0 with I_1 the integrated counts from the second sampling period. Due to the short counting periods, the statistical uncertainty is greater than that for other counting methods.

III.4.1.5. James–Strong method

This method is similar to the Hill method, but involves counting while sampling to determine the first integrated counts I_0. The sampling/count duration is typically 2, 5 or 10 min and is then followed by a second count 1 min after the end of the first count to determine I_1. The second count is performed for the same duration as the first count. This method involves the use of equipment that is capable of sampling air and counting at the same time [99].

III.4.1.6. Markov method

This is another two count method from a typically 5 min sampling period [100]. The filter is counted from 1 to 3 min and again from 7 to 10 min at the end of sampling to obtain the total alpha counts I_1 and I_2. The PAEC and ^{218}Po concentration can be determined from the following expressions:

$$\mathrm{PAEC} = KI_2(TE\mu)$$

$$^{218}\mathrm{Po} = \frac{h(I_1 - I_2)}{(TE\mu)}$$

where

T is the filter trapping efficiency;
E is the counting efficiency;
K is a constant;
I_1, I_2 are the total alpha counts for counting periods 1 and 2;

and μ is the sampling flow rate.

III.4.1.7. Modified Tsivoglou method

The modified Tsivoglou method yields information relating to the concentrations of individual ^{222}Rn progeny [101–104]. The method is more complicated and involves larger sampling and counting times than the Kusnetz method. In order to obtain individual progeny concentrations, three counts of the sample are performed after different delay times. The total sampling and analysis time is approximately 45 min if the lower sampling times are used.

Sampling occurs over time periods of 5, 10 or 30 min at flow rates of 5–10 L/min using a membrane or glass fibre filter appropriate for the sampling. Counting of the sample occurs over periods of 2–5, 6–20 and 21–30 min at the end of sampling. The concentrations of the ^{222}Rn progeny from a 5 min sample can be calculated from the following expressions:

$$C_1\left({}^{218}\mathrm{Po}\right)=\frac{6.247N_t(2-5)-3.028N_t(6-20)+2.857N_t(21-30)}{EQ}$$

$$C_2\left({}^{214}\mathrm{Pb}\right)=\frac{0.056N_t(2-5)-0.776N_t(6-20)+1.836N_t(21-30)}{EQ}$$

$$C_3\left({}^{214}\mathrm{Bi}\right)=\frac{-0.8327N_t(2-5)+1.224N_t(6-20)-1.389N_t(21-30)}{EQ}$$

$$C_P\left(\mathrm{PAEC}\left\{\mathrm{nJ/m}^3\right\}\right)=\frac{2.011N_t(2-5)-1.372N_t(6-20)+3.954N_t(21-30)}{EQ}$$

where

C_1, C_2 and C_3	are the concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi, respectively (Bq/m^3);
$N_t(\ldots.)$	is the net counts for the respective intervals;
E	is the counter efficiency (%);

and Q is the sampling airflow rate (L/min). The main advantages of this method are the reduction in error and the improved limit of detection.

III.4.1.8. Rock method

This method is for the determination of ^{220}Rn progeny concentrations and similar to the Kusnetz method for sampling [105]. A long delay period of 5–17 h allows for the ingrowth of ^{220}Rn. This method can be used after analysis by the Kusnetz method for determination of the concentrations of ^{222}Rn and ^{220}Rn progeny. Calculation of the concentration in WL is determined using the same equation as the Kusnetz method, but the conversion factor is selected from Table 7 based on the delay time chosen.

III.4.1.9. Coté method

This method allows for the determination of ^{222}Rn and ^{220}Rn progeny concentrations from a single sample and is therefore useful where the concentrations of the two isotopes are mixed [106]. On account of the short delay period from the completion of sampling, this method generally has to be started at the sampling location. The method involves the collection of a sample for a period of 10 min followed by three 15 min counting periods, the first of which starts 1–2 min after the end of sampling. The second counting period occurs from 155–170 min after sampling and the third occurs from 225–240 min after sampling. The first count provides the concentration of ^{222}Rn progeny, the second count provides the concentrations of ^{222}Rn and ^{220}Rn progeny and the third count provides the concentration of ^{220}Rn progeny.

The concentrations are calculated using the same equation as the Kusnetz method, with conversion factors (K) of 218, 14.1 and 14.2 being used for the first, second and third count calculations, respectively.

III.4.1.10. Other methods

The methods described in this section so far describe techniques that involve air sampling and analysis through gross alpha counting of the sample using a scaler/ratemeter. Other techniques have been developed which utilize alpha/beta or alpha spectrometry sampling, including the Shreve method and the 3R/WL method. These methods are appropriate to determine radon progeny concentrations, but will not be covered in this review.

III.4.2. Integrated monitoring

Integrated sampling provides an average concentration over the period of time that the monitor was deployed. Integrated sampling is suitable for determining the average concentration over periods of days, weeks or months. Active integrated sampling provides the basis for the personal radon progeny monitors that have been developed to assess occupational exposures in uranium mining. Passive systems are mainly designed for the measurement of radon concentrations, as described in Section III.3.

III.4.2.1. Thermoluminescent dosimeter

In an active system, the air filter is typically coupled closely to a TLD material such as calcium fluoride dysprosium or lithium fluoride. A second TLD material is incorporated into the system to account for the background gamma radiation present at that sampling location. TLDs are well suited for sampling for a period of days to weeks, but care has to be taken to ensure that any active equipment remains operational and that filters do not block.

Radon progeny alpha particles emitted from the filter impact the TLD, which captures the energy transmission. The TLD can be read by heating it in a system that is coupled to a photomultiplier tube. Background gamma corrections can be made by reading the second TLD in the monitor. The radon progeny concentrations are calculated from the net TLD reading.

III.4.2.2. Alpha track detectors

These are either active or passive systems, with the active systems being similar to the TLD system described above (alpha track material is used in place of a TLD). At the end of the sampling period, the material is etched and read under a microscope to determine the alpha tracks, which relate to the PAEC of the radon progeny. The passive version of such a system involves using a screen or filter for a second track detector that is used to detect radon gas only. Analysis of this detector provides the radon gas result, which is subtracted from the result from the detector that has monitored the radon and progeny.

III.4.2.3. Electret detector

An electret is a dielectric material that loses charge when alpha particles interact with it. This loss of charge is proportional to the concentration of the alpha source and can therefore also be used in a system similar to those utilizing a TLD. Reading the electret is a simple matter of measuring the remaining charge after the end of the exposure period. Both passive and active electret systems are commercially available. The passive systems are the simplest to operate and maintain and comprise a variety of different sized chambers, an electret device that screws into the chamber and a simple readout device. The exposure period can range from a few days to several months [107–110].

An active electret system similar to that described using TLDs draws air through a filter and couples the electret to the filter so the radon progeny is measured. Commercial units that can monitor radon progeny for up to several days are available.

III.4.3. Continuous monitoring

Continuous monitors are designed to collect samples and analyse them at the same time. A number of radon progeny monitors have been developed that incorporate an air sampling system to deposit radon progeny onto a filter which is closely coupled to an alpha or alpha/beta detector. These systems are integrated monitoring systems that analyse the sample over periods of several minutes to a few hours and provide either direct feedback or a downloadable result.

Commercial systems are available, with the alpha nuclear prism being in commonly use in Canadian uranium mines. A similar RDP monitor made by Radiation Detection Systems in Australia is in use in many Australian uranium mines.

III.5. DOSIMETRY APPROACH

Two different approaches, ambient dosimetry or personal dosimetry, can be adopted for the assessment of dose to uranium mine workers. A comparison of internal doses due to radon progeny evaluated using the two techniques has been performed at uranium mines in India for different categories of workers. The study showed that both techniques are in reasonably good agreement, with variations being within about 20% [111].

III.5.1. Dose evaluation of mine workers by ambient dosimetry

Dose estimations based on area monitoring for radon or radon progeny and the annual occupancy period is referred to as ambient dosimetry. Regular radon or radon progeny concentration measurements are made at different mine work areas throughout a monitoring period, depending on the mine operations and the radiation monitoring plans. Where radon concentration measurements are made, the equilibrium factor F for different locations needs to be determined in order to calculate the radon progeny concentration. Doses can be calculated from a combination of the estimated or measured average progeny concentrations and the occupancy of workers at different locations in the mine:

$$H = \frac{KA\sum_{i}^{n} \mathrm{WL}_i T_i}{170}$$

where

H is the effective dose (mSv);
K is the conversion factor (1 WLM = 5 mSv);
WL_i is the radon progeny concentration at the ith location (WL);
T_i is the time spent by the mine worker at the ith location (h);
n is the number of locations;

and A is the annual attendance (days/years) of the worker. The WLM obtained from radon progeny concentrations is further converted into effective dose using a DCF of 5 mSv/WLM based on the recommended value by the ICRP [3].

III.5.2. Personal dosimetry approach

Many personal dosimeters have been developed for the measurement of radon or its progeny. In some cases, the dosimeters can measure all exposure pathways (e.g. radon and thoron progeny, gamma radiation, LLRD). Personal dosimetry allows the doses to be directly attributed to individuals who have worn a monitor for the sampling period. Personal monitors generally need a background correction to account for the exposure received while the individual was not at work.

Appendix IV

INHALATION OF LONG LIVED RADIONUCLIDES IN AIRBORNE DUST

IV.1. INTRODUCTION

Uranium ore contains all elements of the ^{238}U and ^{235}U decay chains. From the perspective of internal exposure to LLRD, ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra and ^{210}Po are the most significant radionuclides. Mining operations involving, for example, drilling, blasting and mucking, produce airborne dusts containing these nuclides, which are in most cases close to radioactive equilibrium with each other. In milling processes, airborne LLRD is potentially generated during ore grinding and crushing at the initial stages of processing, and during drying and packaging at the final stages of processing. Before the ore is leached, the long lived decay products of uranium remain close to radioactive equilibrium; after chemical leaching of the uranium has occurred, most of the radionuclides remain with the waste materials such as tailings (or, in the case of ISL operations, calcite/gypsum and other waste by-products). In both conventional mills and ISL mines, the radiological hazards associated with precipitation, drying and packaging operations are associated with uranium in dusts, which has been chemically separated from its decay products.

Airborne LLRDs are an inhalation hazard in uranium mines, mills and in the yellowcake production areas of ISL. The degree of hazard is determined primarily by the airborne activity, radionuclide distribution, chemical composition and particle size of the material. Chemical composition (molecular species) is a determinant of solubility and absorption characteristics. Particle sizes less than 20 μm are respirable, with particles less than 5 μm reaching the lower respiratory tract. The degree of solubility and therefore absorption, specific activity and particle size of the dusts inhaled will determine the resultant radiation dose.

Miners encounter inhalation hazards from LLRD primarily in drilling and blasting operations, where fine particles may become airborne. Potential hazards also exist for LLRD exposure wherever ore material is handled, such as during haulage and stockpile operations. In milling, operators have the highest potential to encounter LLRD as ore enters the milling process through crushing and grinding facilities and as uranium exits the mill when concentrates are produced, dried and packaged. As chemical separation processes at mills and ISL mines are typically aqueous and contained, exposure to airborne LLRD is minimal through chemical processing circuits, except for spillage to work areas as a result of a process upset.

In both mine and mill (including ISL) atmospheres, LLRD concentrations in air are monitored using both workplace air monitoring and personal monitoring techniques, including continuous and grab sampling methods. As warranted by the degree of hazard, bioassay monitoring for radionuclides in excreta can also be performed to estimate intakes. Once intakes have been estimated, the dose can be calculated with the use of dose conversion coefficients developed from biokinetic and dosimetric models.

Containment of radioactive materials supplemented by formal procedural and administrative controls is always the primary means of controlling exposures to LLRD. Processing facilities and tasks are to be designed to minimize the need for the use of protective respiratory equipment. Where practicable, radon, RDP and LLRD need to be controlled so that protective respiratory equipment is not necessary for routine tasks. Respiratory equipment may nevertheless be needed in emergencies, for certain repair and maintenance activities, and in special short term circumstances under the control of procedures prepared specifically to address and control the hazards for the task (e.g. using a radiation work permit). In some circumstances, protective respiratory equipment may be worn routinely to provide an additional layer of defence as part of an ALARA practice, if the potential for elevated concentrations of LLRD exist, but potential negative impacts on worker performance, safety and comfort need to be considered.

IV.2. TYPES AND OBJECTIVES OF LLRD SAMPLING IN URANIUM MINING AND PROCESSING

With regard to workplace and personnel sampling, the Australian Radiation Protection and Nuclear Safety Agency reports that [112]:

> "Both types of sampling involve drawing air through a filter paper at a known rate for a known period and subsequently counting the activity collected on the filter. Personal samplers operate at low flow rates — typically about 2 litres per minute, which would draw a volume of about 1 m^3 if worn for a full 8-hour shift. Area samplers operate at much higher flow rates and can collect a greater quantity of dust. This can make it easier to quantify the radioactive material on the filter, but it may also introduce technical difficulties related to the larger filter diameter and the possibility of self-absorption of alpha particles by the dust when counting. The design of the sampling head that holds the filter paper may have an effect on the

efficiency of collection of the dust, and may cause the efficiency to vary significantly with the size of the dust particles."

These factors have to be considered when converting raw counts as measured on the filter paper to air concentrations.

IV.2.1. Workplace monitoring

Samplers are located within the workplace and the employee's occupancy of the area is recorded. Fixed or variable locations using either grab or continuous methods are used, depending on the exposure conditions. Area sampling at fixed locations using higher flow rates (with associated greater volumes of air sampled) results in lower detection limits with higher statistical confidence than the low flow rate personnel (i.e. lapel samplers) monitoring results. However, area monitoring can result in uncertainties due to the location of workers, the time of exposure at each specific location and the LLRD concentrations in the worker's breathing zone. In many situations personal monitoring is necessary to assess the worker inhalation of LLRD more accurately.

IV.2.2. Considerations of self-absorption effects[6]

Self-absorption of the alpha activity can have significant effects on results when air filter samples have large dust loadings. Alpha particles have a very short range in air (about 40 mm for an alpha energy of about 5 MeV) and shorter ranges through denser matter. In some cases, penetration of the dust into the filter paper matrix itself will increase this effect (i.e. loss of counts due to self-absorption within the sample or filter paper). To limit this effect, filter papers with a pore size that will ensure that the deposit is collected on the surface are chosen. For example, glass fibre filters are usually selected for alpha sampling in high dust environments, since their pore size is typically about 5 µm, compared to membrane type filters with much smaller pore sizes. This will minimize loss due to self-absorption and dust particles falling off the filter between sampling and counting. Self-absorption can be estimated as follows:

$$\%\mathrm{SA} = \frac{C_2 - C_1}{C_1 + C_2 + C_3} \times 100$$

where

[6] This section is based on Ref. [113], which contains further information on gross alpha counting of filters.

%SA is the percentage of self-absorption;
C_1 is the sample count (above background);
C_2 is the count obtained by turning the sample filter upside down;

and C_3 is the count obtained by covering the sample filter (sample side up) with an unused filter paper.

IV.2.3. Effects of particle size on choice of air sampling equipment and techniques for the assessment of LLRD

Paragraph V.38 of GSG-7 [11] states:

"(a) The inhalable dust fraction is the fraction of total airborne particles that enters the body through the nose or the mouth during breathing. ...
(b) The thoracic dust fraction is the subfraction of the inhalable fraction that can penetrate into the tracheo-alveolar region of the lung. ...
(c) The respirable dust fraction is the subfraction of the inhalable fraction that penetrates into the alveolar region of the lung".

With regard to the activity median aerodynamic diameter (AMAD), para. V.39 of GSG-7 [11] states:

"(a) Air samplers typically underestimate the airborne activity concentration and thus the activity inhaled. The degree of underestimation depends on the AMAD and geometric standard deviation of the ambient aerosol, on the dust load in the air and on the type of sampler used [(see Ref. [114])]. A correction factor can be applied to minimize the degree of underestimation. For an AMAD of 5 μm and a geometric standard deviation of 2.5 (the default values recommended in Ref. [[20]] for workplaces in which the actual values are unknown), this correction factor is 1.18 for inhalable samplers, 1.41 for thoracic samplers and 2.5 for respirable samplers [(see Ref. [114])]. The use of the appropriate correction factor does not remove all of the uncertainty, however. This is because the AMAD and geometric standard deviation vary with the location, time and circumstances of dust production, and can therefore never be precisely known.
(b) The size distribution of aerosol particles also has a significant effect on the dose coefficient, leading to an additional source of uncertainty when assessing the effective dose due to the inhalation of particles. The dependence of the dose coefficient on the AMAD is particularly strong for particles of lung absorption type S. When assessing the

effective dose, a sampler should be selected with a sampling efficiency that follows as closely as possible the dependency on the AMAD of the relevant dose coefficients [(see Ref. [114])]."

IV.3. DOSE ASSESSMENT

IV.3.1. Dose assessment for intakes of uranium ore

Using the dose coefficients listed in Ref. [112], the doses per unit intake are determined by summing the contribution of each nuclide in the ^{238}U (uranium) and ^{235}U (actinium) decay chains. By applying the values of total alpha activity and total committed effective dose, the committed effective dose per unit intake of alpha activity is calculated to be 0.003 5 mSv/Bq.

IV.3.2. Importance of uranium mill compound characteristics for dose assessment and assignment

Historically, uranium mills have [35]:

"produced a uranium concentrate generically referred to as 'yellowcake', although these products have demonstrated a wide range of color variation including yellow, green, brown, and black. This color variation has been attributed to the range of uranium oxide species produced by these facilities. The variability of molecular speciation in these products has been shown to have significant implications for radiation and worker health protection programs as related to both the potential radiotoxicity (radiation dose) and chemotoxicity (renal system impact as a heavy metal) resulting from internal exposure (via inhalation or ingestion) to these products.

....

"Over the years, studies have shown that industrial uranium compounds (e.g., as used and produced in uranium fuel cycle facilities) have demonstrated a range of solubility characteristics....

"…Differences between individual mill products were attributed to differences in details of precipitation chemistry and thermal exposure; i.e., feed rate and temperature of the calciner" (see Refs [37, 115, 116]).

Accordingly, establishing appropriate exposure limits (e.g. annual limits on intake, derived air concentration) needs to consider the specific uranium compounds being produced [35, 117]. For example, Table 9 provides traditional assignments of solubility classifications and absorption types (ICRP recommendations [36, 121]) for a number of industrial uranium compounds, including those typically being produced at modern uranium leaching facilities (e.g. UO_2, UO_3, UO_4, U_3O_8).

Brown and Chambers report [35] (see also Refs [34, 122, 124]):

> "Annex D of ICRP 71 [36] provides instructions on how to assign material to absorption types based on experimental data (e.g., lung fluid simulation studies) using absorption rates at different times rather than overall retention or clearance rates. Specifically, for an in vitro dissolution experiment, classification depends on the amount of undissolved material or percent retained in the sample at specified time intervals."

Excluding particle transport, which is small for uranium, the classification criteria for absorption types F, M and S are shown in Table 10 [35].

Brown and Chambers report [35]:

> "The chemical toxicity of uranium as a heavy metal has been considered generally a greater concern for human health than its radiological toxicity (for natural or low enriched uranium). Given that natural uranium is a weakly radioactive element, its potential chemical toxicity is often of greater concern than its radiotoxicity — low specific activity of approximately 2.5×10^4 Bq g^{-1} (see US NRC 10 CFR 20, Appendix B [125]). The chemical toxicity of uranium is associated primarily with potential damage to the kidney. There is no conclusive evidence that uranium produces cancer in humans (ATSDR 2011 [126]). Uranium (and other heavy metals such as lead, mercury, and cadmium) can damage the kidneys by chemical action in the renal proximal tubules. Although there are no unique biomarkers for uranium exposure, urinary levels of glucose, lactate dehydrogenase (LDH), and protein albumen are common indicators of exposure (often by ratio to creatinine).
>
> "However, there is no documented evidence in the literature of permanent renal injury among uranium mine and mill workers exposed to soluble and insoluble uranium compounds (Johnson et al., 2009 [127]), and there have been no reports of death in humans following an acute intake of uranium by any route of entry (Kathren and Burklin 2008 [128])."

TABLE 9. INHALATION CLASSIFICATION AND ABSORPTION TYPES FOR SOME URANIUM COMPOUNDS *(table 2-11 of Ref. [118])*

Uranium compound	Chemical formula	Material clearance type
Uranium hexafluoride	UF_6	F
Uranyl fluoride	UO_2F_2	F
Uranyl nitrate	$UO_2(NO_3)_2$	F
Uranyl acetate	$UO_2(CH_3COO)_2$	F
Uranyl chloride	UO_2Cl_2	F
Uranyl sulphate	UO_2SO_4	F
Uranium trioxide[a]	UO_3	M
Uranium tetrafluoride	UF_4	M
Triuranium octoxide[a]	U_3O_8	S[b]
Uranium dioxide[a]	UO_2	S[b]
Uranium peroxide[a]	UO_4	M
Ammonium diuranate	$(NH_4)_2U_2O_7$	M[c]
Uranium aluminide	UAlx	S
Uranium carbide	UC_2	S
Uranium–zirconium alloy	U–Zr	S
Ore dust	Various	S[d]

[a] Final products historically produced by uranium mills and ISL facilities (can be in combination, see Refs [35, 119, 120]).

[b] The solubility of uranium oxides is very dependent on heat treatment. The rate of oxidation may also affect the solubility. Solubility studies (lung fluid simulation studies) may need to be performed to characterize the actual materials present.

[c] Ammonium diuranate is known to contain uranium as UO_3; therefore, it is not assigned to a single inhalation class.

[d] Unless solubility studies indicate otherwise, assume absorption type S (ICRP recommendations [36, 121], considered “essentially equivalent” to solubility class Y (ICRP recommendation [122]; see also Ref. [123]).

TABLE 10. ICRP 71 ABSORPTION TYPES *(based on table 1 of Ref. [35])*

Type	Absorption rate
F	<13% remains @ 30 d
M	>13% @ 30 d and <87% at 180 d
S	>87% remains @ 180 d

Intakes of absorption types F and M of natural uranium will always be limited by chemical toxicity. Intakes of absorption type S will be limited by radiotoxicity [129].

IV.3.3. Bioassay programmes

The primary purpose of a bioassay programme is to assess and verify the adequacy of air sampling programmes and to detect uranium intake by employees potentially exposed to LLRD during work (or via ingestion due to poor housekeeping or via wounds; see Appendix VI). The Nuclear Regulatory Commission [130] report:

> "There are two important areas in uranium mill operations where workers could be exposed to uranium. Uranium is radiologically and chemically toxic. Bioassay may be needed due to the primary risks associated with the radiological and chemical exposures, as follows:
>
> a. **Ore-dust areas**: These are the areas beginning with the transfer of ore from the ore pad to the crusher through the final thickening stage. Dust created by uranium extraction and milling activities, or blown by the wind from ore stockpiles, is a potential source of inhalation and contamination.
> b. **Yellowcake areas**: These are the areas that contain uranium extracted from the ore [as a concentrated precipitate in varying concentrations of aqueous forms] from the ion exchange or solvent extraction stage through the final packaging [of dry product]".

Ore dust areas and yellowcake areas are the most likely areas for employees to experience such exposures. The bioassay programme needs to include pre-employment samples to establish baselines and exit samples upon termination. In addition, there is a need for routine sample collection and analysis to verify the adequacy of air sampling and engineered controls, as well as special sampling based on air sampling results, and radiation work permit conditions for special or ad hoc tasks or incidents potentially involving intakes.

Bioassay programmes at uranium leaching facilities (usually only urinalysis is necessary) need to be appropriate for the specific characteristics of the uranium products to which employees are potentially exposed. Product specific solubility characteristics have metabolic implications for bioassays that help to define appropriate sampling frequencies, action levels requiring follow-up, and the interpretation and dose implications of bioassay results [35, 118, 130–132].

IV.3.4. Bioassay programme elements

Uranium mine and mill bioassay programmes include the following elements:

(a) Prior to assignment to work in ore handling or yellowcake areas, all new employees need to submit a baseline urinalysis sample. Upon termination, an exit bioassay is needed from all employees who may have been exposed to LLRD.
(b) During operations, employees who could be exposed to ore dust, intermediate uranium concentrates or dried yellowcake submit bioassay samples on at least a monthly basis or more frequently, as determined by product absorption/solubility characteristics. For the most soluble products (absorption type F), weekly urinalysis is undertaken. Samples are analysed for uranium content by analytical laboratories meeting appropriate performance criteria (e.g. see Ref. [133]),
(c) Special samples may be necessary in response to incidents or other circumstances indicative of a higher potential for intake. These circumstances could include contamination detected on the face, eating or drinking with contaminated hands, a respirator internally contaminated following use, process upsets or spills creating the potential for elevated airborne uranium levels, or any other employee exposures which may have resulted in intakes in excess of 10% of annual limits on intake (ALI).
(d) Action (reference) levels for urinalysis are established that define results above which follow-up sampling, investigations and formal dose assessment are necessary (see Ref. [130] for detailed information on the actions following elevated uranium bioassay results). Paragraph 3.131 of GSG-7 [11] presents methods for calculating derived investigation levels and derived recording levels “specific to the physical and chemical form of

> the radionuclide in the workplace, and are a function of the period of time between the time of intake and the time of measurement."

Workers potentially exposed to very soluble yellowcake concentrates (e.g. absorption type F; see Section IV.3.2) have urine specimens submitted for uranium analysis on an approximately weekly basis, including follow-up (for any positive results) for the biomarkers associated with potential renal injury (e.g. glucose, lactate dehydrogenase, protein albumen) [35]. Additional information and guidance on establishing uranium bioassay programmes, including recommendations on quality assurance, are provided in Refs [11, 20, 21, 35, 130, 133, 134].

IV.3.5. Methods of uranium bioassay

In choosing the method or combination of methods appropriate for bioassay, the purpose of the monitoring (i.e. routine or special), the working environment, the physical and chemical forms of the uranium species, and the practicability of measurement are to be considered. In general [38]:

> "Bioassay monitoring techniques fall into two broad categories: direct measurement of radioactive materials in the body (in vivo counting) and analysis of material removed from the body for laboratory (in vitro analysis). In vivo counting includes measurements of the chest, lung, skeleton, liver, and wounds. In vitro measurements include urinalysis, fecal analysis, and occasionally analysis of tissue, sputum, or blood samples. Methods for in vitro analysis include liquid scintillation counting, fluorescence measurements, gamma spectrometry, chemical separation followed by electrodeposition, and counting with radiation detectors. ...
>
> "In addition, to ensure that adverse chemical toxicity effects are unlikely, bioassays for uranium should be performed when intakes of 1 mg or more of soluble uranium are likely to occur in any one work day" [133] or 10 mg per week [130].

In vivo lung counting may be applicable to detect possible inhalation and retention in the lung of uranium in chemical forms of low solubility (e.g. absorption type S; see appendix B to 10 CFR 20 [125]). However, lung counting typically needs to be performed at off-site locations possessing specialized equipment and highly trained personnel, and only needs to be considered for special monitoring (e.g. see the guidance in tables 1 and 2 of Ref. [130]). For more soluble uranium species (absorption types F and M), any residual lung deposition remaining a month or two following intake would probably be below the minimum detection limit of natural uranium with state of art in vivo lung counting systems (see section A.10 of Ref. [129]).

IV.3.6. General guidance for prevention of specimen contamination

With regard to the collection of specimens, the Nuclear Regulatory Commission [130] recommends:

“i. All bioassay sample or specimen should be collected in an area free of uranium before the worker enters to the work area. The collection may occur at an area inside or outside the mill that is designated specifically to be maintained free of uranium contamination. Use of disposable collection containers is highly recommended.

ii. Under any circumstances workers should either shower or wash their hands thoroughly before providing the specimen sample. When a shower is not possible, disposable plastic or rubber gloves should be worn during voiding.”

Specimen samples are also often produced away from the mill (e.g. at home) during brief off periods, provided that the time following the last potential exposure on-site (at work within ore or yellowcake areas) is no more than a few days prior to voiding.

IV.3.7. Estimates of intake and assignment of dose from air sampling and/or bioassay results

Table 11, based on data from table 3.2 of Ref. [126] and GSG-7 [11], presents dose coefficients and ALIs for uranium which are the averages of the dose coefficients for the individual component nuclides (^{238}U, ^{234}U, ^{235}U) weighted according to the nuclide activity concentration of naturally occurring uranium. The overall dose coefficients calculated based on these assumptions are shown for lung absorption types F, M and S and an AMAD of 5 μm.

In circumstances where multiple locations with differing exposure conditions (air concentrations, times of exposure) are involved, a simple sum can be used where $I_{inh,\ total}$ represents the sum of intakes at each location using the airborne concentration and exposure time specific to that location. For individual personnel monitoring using breathing zone samplers, only the average concentrations during the sampling period as measured with the breathing zone samplers need to be considered by summing calculations of I_{inh} over multiple sampling time periods if necessary. It is recognized that more complex situations

TABLE 11. ANNUAL LIMITS ON INTAKE AND DOSE COEFFICIENTS FOR NATURAL URANIUM (5 μm AMAD)

	ICRP absorption type F compound	ICRP absorption type M compound	ICRP absorption type S compound
Dose coefficient (μSv/Bq)	0.61	1.85	6.25
ALI (kBq)	32.8	10.8	3.20
ALI (mg U_{nat})	1300	430	127

are possible, for example in which the worker is exposed to more than one chemical species of different absorption types during the same assessment period (e.g. both ore dust and a relatively soluble yellow cake product). Although these circumstances may be unusual, considerations would need to be made for the differing dose coefficients as applicable.

Using the dose coefficients provides an estimate of dose for the total intake $I_{\text{inh, total}}$ during the monitoring period (interval) of interest. Note that the dose per unit intake, calculated for an AMAD of 5 μm, varies by an order of magnitude between the lung absorption types F and S. The composition of uranium concentrates (e.g. yellowcake) depends strongly on the specific extraction and post-extraction conditions. In particular, the use of high calcining temperatures during product drying results in an increase in the fraction of uranium compounds that dissolve relatively slowly (type S) in the lung, while the use of much lower temperature dryers is likely to produce a relatively soluble (type F) product [35, 116, 129, 130].

IV.3.8. Calculating dose from bioassay results

To provide guidance on the interpretation of bioassay data, two simplifying assumptions are often used. The first considers that exposure occurred at a continuous and constant rate [21, 55]. While this can be used for formulating general guidance and drawing generalized conclusions on the implications of exposure, it is usually unrealistic in terms of occupational exposure. The second assumes that all patterns of intake could be represented by an acute intake at the midpoint of the monitoring interval. This proposal was recommended by the ICRP initially in Ref. [55] and promulgated subsequently in Ref. [135]. ICRP recommendations [21] include an additional provision that any underestimate of the intake does not exceed a factor of three.

In principle, the concept of a midpoint intake has the advantage that the optimum monitoring interval for an unknown exposure pattern can be addressed, and the uncertainty in the assessment of intake or dose can be calculated. In practice, this is achieved by consideration of the extremes of intake pattern (i.e. the intake may have occurred soon after the date of the last measurement or shortly before the current one). This procedure also allows for previous intakes or effective dose to be related to intakes within the current monitoring interval by subtraction of the amount predicted to result from the previous one.

Appendix V

SURFACE CONTAMINATION

V.1. INTRODUCTION

The mining and milling of uranium ores involves the handling and processing of large amounts of ores, process materials and product in both wet and dry forms. These materials contain various mixtures of the alpha, beta and gamma emitting radionuclides of the uranium decay chain. The mining, milling and processing of uranium ores results in the release of materials from the process stream and the deposition of radioactive scales inside the process. The IAEA Safety Glossary [136] defines contamination as:

> "*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."

It is also used less formally to refer to a quantity, namely the activity on a surface (or on a unit area of a surface), and it does not include residual radioactive material remaining at a site after the completion of decommissioning. According to SSR-6 (Rev. 1) [40]:

> "214. *Contamination* shall mean the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm^2 for beta and gamma emitters and *low toxicity alpha emitters*, or 0.04 Bq/cm^2 for all other alpha emitters.
>
> "215. *Non-fixed contamination* shall mean *contamination* that can be removed from a surface during routine conditions of transport.
>
> "216. *Fixed contamination* shall mean *contamination* other than *non-fixed contamination*."

Surface contamination monitoring programmes are site specific and dependent on factors such as:

— Ore grade;
— Type of mining and processing methods;
— Plant design;

— Extent and effectiveness of the engineered controls to contain radioactive materials within the process;
— Maintenance activities;
— Age of the plant.

The extent of the surface contamination monitoring programme needs to be commensurate with the nature and extent of the potential for surface contamination in the workplace and is intended to complement the airborne and gamma monitoring programmes [11, 67].

V.2. CONTROL MEASURES

The main risk arising from surface contamination in a uranium processing facility is the possibility of inhaling or ingesting the loose material. These materials will contain the long lived radionuclides of the uranium decay chain which, if inhaled, can result in significant occupational exposures. Ingestion is usually a minor exposure pathway and is generally only of potential significance in the uranium product section of the mill. Wounds represent another route for radioactive materials to enter the body, particularly when the wound is caused by equipment contaminated with radioactive material.

Surface contamination can become a significant issue in those areas of the plant handling materials with a high concentration of uranium (e.g. high grade ores and in the uranium product section). For example, a 1 mg/cm^2 layer of uranium product dust would result in an alpha surface contamination level of approximately 15–20 Bq/cm^2; the resuspension of this material would result in an inhalation hazard.

Removable contamination can be resuspended from surfaces during a wide variety of work activities. Fixed contamination can be liberated into the air during abrasive activities such as during the decontamination of process equipment. Over a period of time, fixed contamination can build up on surfaces inside the process, resulting in significant localized gamma dose rates in the plant.

In both the mine and mill, the design of the facility needs to limit the spread of radioactive material with engineered controls. This includes measures such as physical barriers to limit and direct the spread of materials, such as floor grading and sumps. In addition, a formal system of contamination control is important. This involves administrative procedures such as housekeeping programmes, cleaning of equipment, designation of clean and dirty zones, control of the movement and monitoring of equipment and people between zones and use of appropriate PPE. In addition, appropriate cleaning of facilities, particularly high occupancy areas such as control rooms and eating areas, coupled with monitoring to ensure ongoing effectiveness, is important.

In addition, good housekeeping and working practices are required to keep spillages to a minimum when loose materials need to be handled (e.g. during ore haulage and maintenance activities). Routine surface contamination monitoring programmes are needed to confirm that the plant is operating within the design specifications. Fixed contamination inside the plant process resulting in high localized gamma dose rates can be controlled by replacing or decontaminating components (e.g. tanks, pipes, valves). Where there is a buildup of loose material on working surfaces, the materials can be washed into the plant sump. The use of PPE such as dust masks, respirators and disposable clothing can help to reduce exposures arising from surface contamination; however, in a clean plant with good housekeeping, these personal control mechanisms are normally only necessary during plant maintenance activities.

In the uranium product section, the contamination is likely to comprise 60–80% uranium; since the product is coloured (usually yellow or green) and uranium has a low specific radioactivity, surface contamination at levels high enough to be significant for health and safety is usually visible as surface dust, provided that the plant surfaces are painted in a contrasting colour.

V.3. MONITORING AND DOSIMETRY

Contamination monitoring is necessary for the following main purposes:

- To verify the efficiency of engineered controls in the plant and process;
- To confirm good housekeeping practice;
- To confirm area designations;
- To identify contaminated areas and the level of contamination;
- To identify the spread and buildup of contamination;
- To monitor items and people exiting designated areas.

Surface contamination monitoring activities need to be focused on the following areas and processes:

- Dry areas of the process;
- Uranium product section (e.g. product precipitation, filtration, drying, weighing, packaging);
- Milling and crushing areas;
- Areas with a potential for dust generation;
- Product storage areas;

— Scrapyards;
— Equipment maintenance workshops;
— Eating areas;
— Exit gates from the facility.

Other areas of the facility can be monitored at less frequent intervals, such as offices, laboratories and other facilities outside the designated areas. Contamination monitoring is usually required during the following situations and activities:

(a) Routine area monitoring of workplace surfaces (e.g. floors);
(b) Maintenance activities on the plant (e.g. prior to process entry);
(c) Monitoring items removed from designated areas (e.g. for repair or refurbishment);
(d) Monitoring items for the purpose of clearance from the authorized site;
(e) Monitoring items for the classification of contaminated items for disposal;
(f) Transport of uranium product by road, sea and air;
(g) Monitoring people exiting designated areas;
(h) Monitoring work clothing;
(i) Monitoring to help identify the source of any unexplained airborne radioactivity;
(j) Monitoring accident situations;
(k) Monitoring during demolition activities after plant shutdown.

V.3.1. Assessing total, fixed and removable contamination

Surface contamination can be assessed by direct methods (using an instrument to assess total contamination) [137] or indirect methods (e.g. using smear papers to assess removable contamination) [138]. Surface contamination can comprise fixed and removable contamination. Removable contamination is of particular radiological importance, as this material can become resuspended as particles during routine work activities. The particles can be inhaled, resulting in the intake of long lived alpha and beta emitting radionuclides and a committed effective dose to the individual. Derived surface contamination limits (DSCLs) are usually set in terms of removable contamination.

In the mining environment, the realistic assessment of surface contamination is limited to the assessment of alpha and beta emissions from dry surfaces and very thin layers of materials. The direct assessment of alpha surface contamination in the workplace is at best a semi-quantitative technique. The assessment of alpha surface contamination presents significant challenges due to the poor penetrating power of alpha particles in materials. Alpha particles can be easily absorbed by moisture in the material and self-absorption in the material itself. The direct assessment of alpha particles is therefore only realistic on very thin layers (e.g. a fraction of a millimetre) of dry materials or specific types of very thin scales found on certain types of high density polyethylene (HDPE) and stainless steel components used in some of the older uranium plants.

Beta emitters provide a more realistic operational tool to directly assess surface contamination in the mining and milling environment. In this monitoring context, a direct measurement involves placing the contamination probe on the material and recording the emissions (counts) over a set period, subtracting the background counts and converting the net counts to Bq/m^2 using the efficiency factors given in the instrument calibration certificate. In work locations with significant gamma fields, the beta background count rate will often be elevated due to gamma interference with the beta count channel, making it difficult to obtain a pure beta reading.

One possible solution to this problem is to cover the detector surface with a clip on plastic and aluminium shield of approximately 3 mm and record the gamma count rate and then take a beta–gamma reading with the open probe. Simple subtraction provides the approximate beta count rate. The readout from a contamination monitor can be in counts per second (cps) or the total counts over a set time period (e.g. 30 s). Removable alpha and beta contamination on a surface can be assessed quantitatively using a dry or wet smear paper or adhesive tape. The sample is taken over a fixed area of 100/300 cm^2 and the smear paper disc or tape is counted in a calibrated alpha–beta detector–scaler assembly. This method provides a quantitative estimate of the average removable contamination in Bq/cm^2. The collection efficiency or pick-up from the surface is variable and depends on the nature of surface and how the swab is taken.

The removal and resuspension of fixed contamination on surfaces involves the use of specialized abrasive techniques such as high-pressure water jetting or grinding with tools. The main radiological hazard arising from fixed contamination is the generation of localized areas of gamma radiation. These gamma dose rates can be particularly intense in those situations where the contaminated materials are enriched with the gamma emitters of the ^{226}Ra decay chain (e.g. scales deposited on the inside of pipes and vessels in the process). In these types of situations, the fixed contamination can be quantified by taking contact readings using a gamma dose rate meter.

V.3.2. Surface contamination monitoring strategies

Mining and processing operations often produce large quantities of scrap materials, such as metal items, wood, bricks, plastic and HDPE items. Many of these materials can be recycled and reused by local communities or other processors. Some of these items will be contaminated and will need to be retained on the site or sent off-site for scrap processing at sites authorized by the regulator to handle contaminated items. It is essential that the operator has a waste management plan which ensures the segregation of suspected contaminated items from the mine and plant from clean items from other areas. Separate storage areas are required for the two types of material. In order to release items to the public domain without any conditions, the regulator will need the operator to demonstrate that the items are not contaminated. Where thousands of suspect items are involved (e.g. redundant underground support packs), this presents a monitoring challenge, as not every item can be monitored. In these cases, the monitoring strategy is statistically based (i.e. a random number of items are monitored for contamination) and the number of measurements that are necessary for such a programme will usually depend upon the total number of items to be assessed and the statistical confidence level required (e.g. 95–99%) for the results.

A similar problem arises during the demolition of a processing plant and other surface structures, such as headgears, rail lines, offices, stores, electrical equipment and cabling. Much of the clean material can be recycled and reused, and a statistically based survey approach can be used.

Monitoring individuals for contamination when they exit controlled areas with potentially high levels of contamination is a part of the monitoring and control strategy. Possible approaches include periodic assessments, random monitoring of individuals on exit and monitoring of all individuals on exit. The preferred approach will depend upon the site specific circumstances and the contamination potential. Hand held contamination probes can be used; however, automated hand and foot monitors are preferred when significant numbers of individuals are involved. The use of automated monitors linked to a locked turnstile provides greater confidence in the exit monitoring process compared to ‘self-frisking’ on exit. The hands and feet are counted for a predetermined period and a reading is provided that indicates whether or not contamination has been detected. Both visual and auditory indicators of the presence or absence of contamination are provided. The alarm level indicating contamination can be a multiple of the background alpha–beta level or a set level of alpha–beta contamination above the background level. Similar types of automated monitors can be used to assess contamination levels on clothing.

The survey personnel need to be trained in the correct monitoring methods and the recording of results. The raw results need to be entered into a database and processed to provide readings in Bq/cm^2; the paper records need to be retained and the database backed up on a regular basis. The monitoring programme needs to be fully documented in the local operating instructions. The survey measurements and results need to be reviewed with a defined frequency. In addition, the monitoring programme and the survey strategy will need to be reviewed and revised with a specified frequency in case operating conditions change.

V.3.3. Selection criteria for contamination monitoring instruments

Desirable properties for contamination monitors used in uranium mining and milling facilities are listed in Section II.3.5. Surface contamination monitors are not usually used underground due to the following factors:

(a) High humidity levels and dampness of the working areas results in significant self-absorption of alpha and beta particles;
(b) Plate-out of airborne alpha and beta emitting radon progeny on the probe results in erroneously high readings.

V.3.4. Calibration and daily check of surface contamination monitors

The monitors need to be calibrated as described in Section II.3.6.

V.3.5. Interpretation of monitoring results

The most important part of any monitoring programme is the interpretation of results [11, 55]. The results need to be evaluated to determine whether there are any changes or trends in contamination levels within the various operational areas.

Increasing surface contamination levels are of concern, as they indicate a degradation in the engineered or good housekeeping control systems and the possibility of increased inhalation exposures of the workforce from resuspended dusts containing the long lived alpha and beta emitters of the uranium decay chain.

A range of DSCLs can be defined for each operational area. If these levels are exceeded, an investigation is automatically triggered to determine the cause of the increase. DSCL values are related to a fraction of the annual effective annual dose to the worker by a simple model using an assumed resuspension factor, the dose coefficient of the dust mixture (μSv/Bq), default breathing rates and the assumed annual occupational exposure value in hours (e.g. 2000 h). The DSCL values may vary from area to area according to the radionuclide mixture of the materials in the area [138, 139].

Appendix VI

INGESTION, WOUND CONTAMINATION AND ABSORPTION

VI.1. INTRODUCTION

In the presence of radioactive materials, particularly alpha emitting radionuclides, it is important to prevent these materials from entering the body. Facilities that are involved in the processing of natural uranium will handle significant volumes of radioactive material. A typical uranium mill produces between 500 000 kg and 5 000 000 kg of uranium per year and the feed grade of the ore can range from below 0.1% to more than 5%. The large volumes of material being handled present practical problems in the control of radioactive material and result in potential opportunities for radioactive materials to enter the body. The potential hazards and control of airborne radioactivity are well understood (see Appendix IV). Ingestion is another potential route of intake and there are many relatively simple and straightforward control measures that can be put in place. Wound contamination represents another route for radioactive materials to enter the body. Clearly, the prevention of all types of wound, whether involving radioactive materials or not, is the primary control mechanism; however, wounds involving potentially radioactive materials require some additional follow-up measures.

VI.2. CONTROL MEASURES

A key control for the prevention of inadvertent intake of radioactive materials is to limit direct contact with them as much as is practicable. In a mill, containment of materials within process vessels and pipes is important. In a conventional mine, however, the nature of the operations involves the open handling of ore, so containment is not possible. In a mill, there will also be some radioactive materials outside of the containment features of the processing circuit, even if only for a transitory period. The handling and processing equipment, from drill pipes to haul trucks to process vessels, becomes contaminated owing to the nature of the work, and workers need to handle and repair this equipment, which is another source of potential exposure.

As described in Appendix V, the design of the facility needs to limit the spread of radioactive material and systems for contamination control are an important control measure. Simple personal hygiene (e.g. washing hands before eating and smoking) is very important for the prevention of inadvertent ingestion, along with appropriate housekeeping measures, particularly in high occupancy areas such as control rooms and eating areas.

A wound caused by material or equipment that is contaminated has the potential to place radioactive material directly into the body. In this case, prompt and thorough cleaning of the wound is important to remove as much radioactive material as possible. While radiation monitoring of the wound is important to determine if any detectable radiation is present, on account of the varied nature of wounds, the absence of measurable radiation from the wound might not always indicate that all residual contamination has been removed. In addition, the need for urgent medical treatment may make it impractical to conduct detailed radiation monitoring of the wound. For this reason, follow-up bioassay measurements are important to assess the dosimetric implications of a wound involving radioactive contamination.

The medical treatment of a wound can be complicated by the potential presence of radioactive material. In the case of wounds with natural uranium present, the doses to any people involved in the medical treatment of the patient are almost certainly going to be trivial (i.e. much less than 1 mSv). Nonetheless, it can be expected that medical personnel, particularly if they have not had specific training related to the treatment of contaminated wounds, will have legitimate concerns about their own safety and that of other patients. For this reason, to the extent practical, good practice is to work with medical facilities to train staff and to establish treatment protocols that incorporate radiation protection measures. In addition, a senior radiation protection professional present at the medical facility when a contaminated injured worker is being admitted can answer any questions the medical staff may have.

VI.3. MONITORING AND DOSIMETRY

The National Council on Radiation Protection and Measurements (NCRP) [140] provides a comprehensive system for assessing the dosimetric implications from contaminated wounds. The dose from a wound depends upon a variety of factors, including the physical and chemical properties of the radionuclide, the nature of the wound and any subsequent treatment. These complexities and the unplanned nature of wounds means that they need to be assessed on an individual basis.

In the context of the handling and processing of natural uranium compounds, radiation monitoring of the wound may provide an indication of the amount of the radionuclide in the wound site, but follow-up bioassay measurements (i.e. urinalysis) will be needed. Because uranium mining and milling processes can involve a wide range of uranium compounds and physical forms, from insoluble uranium in ore to soluble uranium compounds in solution to a variety of uranium precipitates, all of the different NCRP biokinetic models need to be used in the case of an incident.

The urinary excretion curves for the different NCRP models for uranium wound intake per unit intake basis are provided in Fig. 45. While several of the curves look quite different and are well separated, in practice distinguishing between the different models is not as simple because the amount of the intake is usually unknown. In fact, the urine excretion data are used to determine the intake. The urinary excretion curves relative to the first day excretion rate are presented in Fig. 46. This figure illustrates that deciding which NCRP model to use solely from the urine excretion data is not straightforward. In practice it can take from weeks to months before the urine excretion data fit a model clearly, especially when one has to contend with the considerable scatter in real world bioassay data.

There are several considerations in calculating doses from wound intakes. First, uranium ore normally contains all the ^{238}U and ^{235}U decay products and all the appropriate radionuclides need to be included in the dose calculation. Attention needs to be given to ^{230}Th, as it can be the dominant radionuclide in terms of effective dose, but may not be detectable in the urine up to the dose limit, and its presence may have to inferred from the nature of the source material

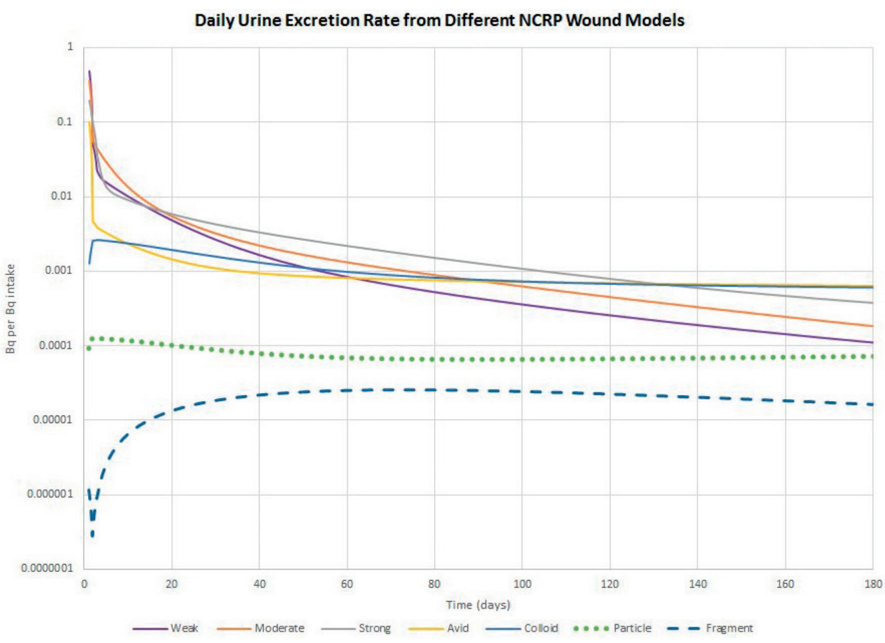

FIG. 45. Daily urine excretion rate from different NCRP wound models.

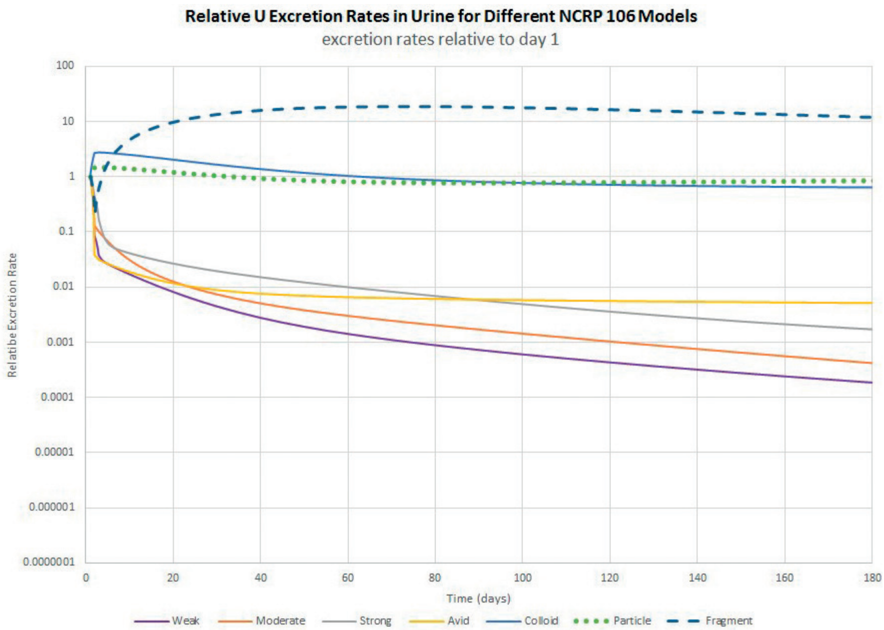

FIG. 46. Urinary excretion curves relative to the first day excretion rate for different NCRP models.

(i.e. ore versus refined uranium). Depending on the nature of the wound, the dose to the skin may also need to be considered. Finally, the amount of uranium in the urine for appreciable doses, particularly in the case of uranium ore and the dose due to ^{230}Th, can be quite modest (i.e. a few µg of uranium per litre), depending on the time from intake and the chemical and physical form of the uranium compound. This means that the worker's activities may need to be restricted to ensure that there are no subsequent workplace intakes that could complicate the dosimetric analysis.

In summary, wound dosimetry can be quite challenging and involves careful analysis of all available data. The use of modern dosimetry software is an important tool to help to analyse potential dose scenarios. Because the period of analysis can be protracted, it is important to remember the worker who was injured and ensure that they are kept well informed during this process. While a dose from a wound incident may be significant from a regulatory perspective, the worker will typically be more concerned from a health perspective and this aspect needs to be carefully addressed.

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Annex

IAEA QUESTIONNAIRE ON OCCUPATIONAL EXPOSURES IN URANIUM MINING AND PROCESSING

The questionnaire includes both basic questions such as the number of workers, the number of measurably exposed workers, the average effective dose and dose calculation methodology. Ideally, such data can be provided by subgroup (workgroups with anticipated like exposures but at all time respecting privacy issues).

There are also detailed questions on work with risk of internal exposure (inhalation of radon and its progeny and intakes of radionuclides), the contribution made by internal and external dose to the total effective dose and the factors used to convert exposure to effective dose for instance, radon (WLM) to dose (mSv), when appropriate. The questionnaire is intended to be completed with minimal effort. Information which is required is highlighted in the questionnaire purple; and optional information is highlighted in green. To assist, the majority of data may be entered using drop down boxes with supplementary information provided in adjacent cells).

A–1. BACKGROUND INFORMATION

This section requests the following (see Figs A–1 to A–6):

(a) Background information (e.g. location of facility, contact information);
(b) Operation information (e.g. type of operation, production, average grade, numbers of exposed workers);
(c) Monitoring approach (e.g. monitoring external gamma, radon decay products, airborne long lived alpha activity);
(d) Dose calculation (e.g. calculation methods, parameters and assumptions, factors used to convert exposure to effective dose — Bq to mSv);
(e) Radiation controls (e.g. ventilation, shielding, air-conditioned equipment);
(f) Auxiliary controls (e.g. radiation training, contamination control, quality assurance).

FIG. A–1. Background information.

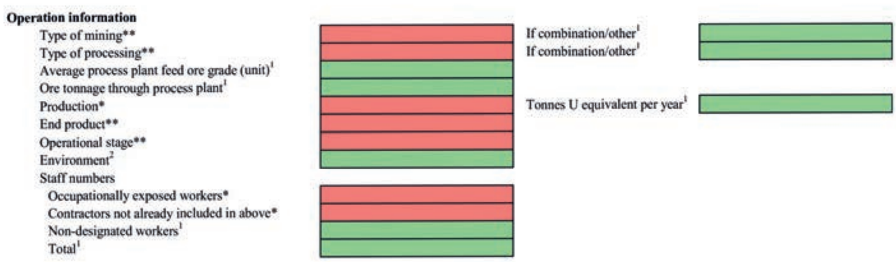

FIG. A–2. Operation information.

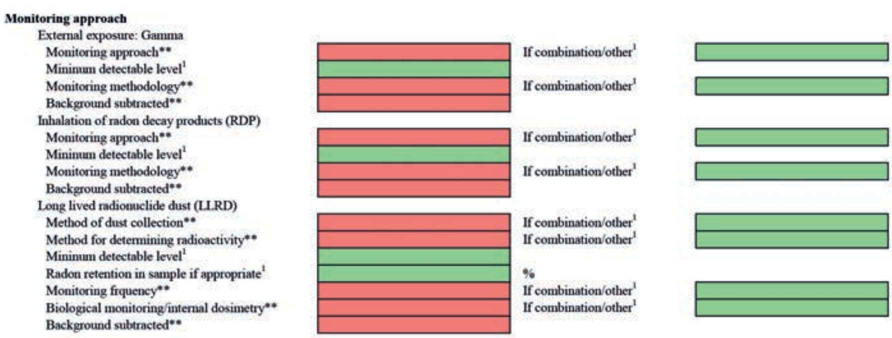

FIG. A–3. Monitoring approach.

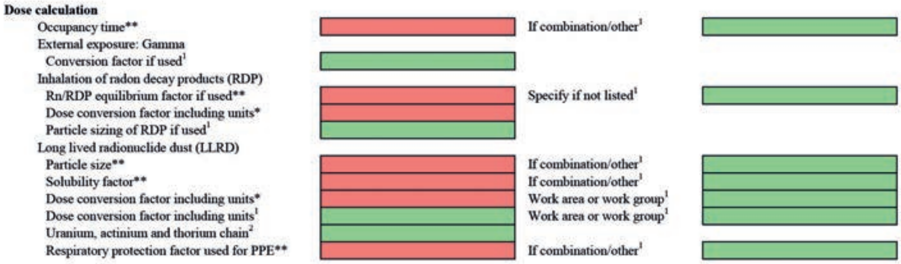

FIG. A–4. Dose calculation.

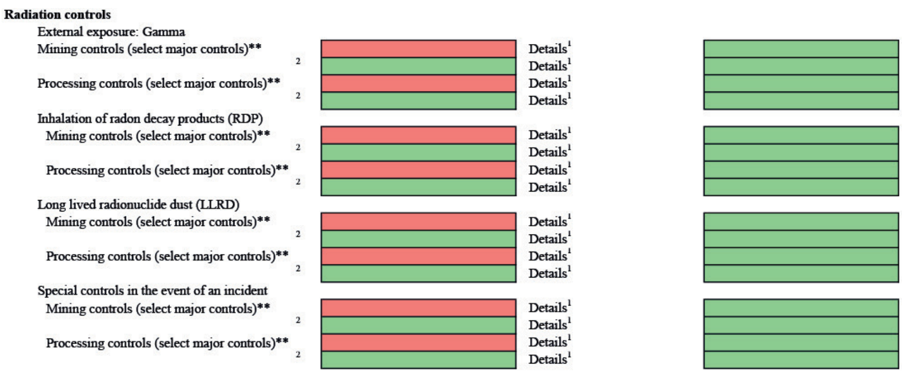

FIG. A–5. Radiation controls.

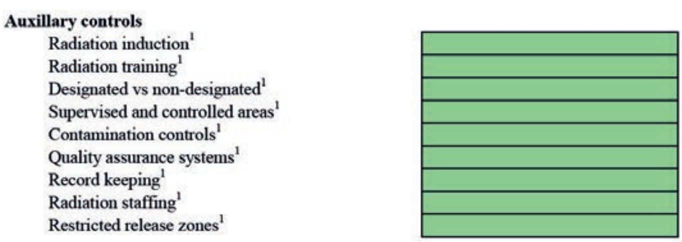

FIG. A–6. Auxiliary controls.

A–2. DOSE DATA

Ideally, this section can be completed by each operation/facility or a national dose registry and requires information on the dose contributions by exposure pathway (see Fig. A–7):

(a) Internal exposure by inhalation of radon and its decay products;
(b) Inhalation of long lived alpha activity and external gamma radiation;
(c) Contribution made by internal and external dose to the total effective dose.

A–3. DOSE HISTOGRAM

This section requires information on distribution of total effective dose by workgroup (see Fig. A–8). The basic data are the number of workers for each suggested dose interval. It is expected that States with a national database complete it automatically.

			Gamma					Inhaled LLRD					Inhaled RDP (+ ^{220}Rn contribution if appropriate)					Total			
Work group	Category	No.	Avg. dose	SD	Max	DCF	Basis of DCF	Avg. dose	SD	Max	DCF	Basis of DCF	Avg. dose	SD	Max	DCF	Basis of DCF	Avg. dose	SD	Max	Assumed distribution

FIG. A–7. Dose data (in mSv/a).

			No. of workers in dose range (total dose, mSv/a)											
Work group	Category	No.	0–0.5	0.5–1	1–1.5	...	...	...	9.5–10	10–10.5	...	...	...	20+

FIG. A–8. Dose histogram data.

ABBREVIATIONS

ALARA	as low as reasonably achievable
ALI	annual limits on intake
AMAD	activity median aerodynamic diameter
DCF	dose conversion factor
DSCL	derived surface contamination limit
EPD	electronic personal dosimeter
ICRP	International Commission on Radiological Protection
ISL	in situ leaching
ISR	in situ recovery
LLRD	long lived radionuclide dust
NORM	naturally occurring radioactive material
OSLD	optical stimulated luminescence dosimeter
PAEC	potential alpha energy concentration
PPE	personal protective equipment
RDP	radon decay products
SEG	similar exposure group
TLD	thermoluminescent dosimeter
UMEX	Information System on Uranium Mining Exposure
WL	working level
WLM	working level month

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