IAEA TECDOC SERIES

IAEA-TECDOC-1954

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Occupational Radiation Protection during the Decommissioning of Nuclear Installations

Main Aspects of Management, Planning and Conduct

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OCCUPATIONAL RADIATION PROTECTION DURING THE DECOMMISSIONING OF NUCLEAR INSTALLATIONS

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IAEA-TECDOC-1954

OCCUPATIONAL RADIATION PROTECTION DURING THE DECOMMISSIONING OF NUCLEAR INSTALLATIONS

MAIN ASPECTS OF MANAGEMENT, PLANNING AND CONDUCT

INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The decommissioning of a nuclear installation needs to be considered as early as the design stage of the installation. As part of an installation's initial authorization, a decommissioning plan is developed that demonstrates the feasibility of decommissioning, including activities such as planning for decommissioning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management.

When a nuclear installation ceases its operation, a final decommissioning plan is prepared, describing in detail the decommissioning strategy, how the facility will be safely dismantled, how radiation protection of workers and the public is ensured, how environmental impacts are addressed, how materials — radioactive and non-radioactive — are to be managed, and how the regulatory authorization for the facility and site is to be terminated.

Experiences in occupational radiation protection in the context of decommissioning activities exist, but many Member States do not yet have the necessary expertise in this specific area. The work activities during decommissioning will be different from those during the operational phase of a nuclear installation and will be conducted in a different work environment that is continuously changing. Decommissioning of a nuclear installation includes a range of different activities, mainly related to dismantling, decontamination and demolition of structures, systems and components, and the implementation of new ones.

The objective of the IAEA's programme on occupational radiation protection is to promote an internationally harmonized approach to occupational radiation protection through the development and application of standards and good practices for optimizing protection and safety, restricting exposures and implementing current radiation protection techniques in the workplace.

This publication, describing relevant practices and lessons learned, provides practical information on occupational radiation protection and examples from the nuclear industry on how to comply with the requirements for planned exposure situations established in IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, in the context of decommissioning activities.

The IAEA would like to express its gratitude for the supplementary funding from the European Commission and for the contributions of P. Hofvander (Sweden). The IAEA officers responsible for this publication were H.B. Okyar and J. Ma of the Division of Radiation, Transport and Waste Safety.

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1. INTRODUCTION

1.1.BACKGROUND

Decommissioning[1] of nuclear installations around the world is an increasing activity and will continue to be so in the coming years. Experiences in occupational radiation protection in the context of decommissioning activities exist but many Member States do not have the necessary expertise in this specific area yet. Compared to the operational phase of nuclear installations, the work activities during decommissioning will be different, and will be conducted in a different work environment that is continuously changing.

Decommissioning of a nuclear installation includes a range of different activities, mainly related to dismantling, decontamination and demolition of structures, systems and components (SSCs) in addition to the erection of new SSCs. Therefore, workers will also be subject to other types of risks and hazards, in addition to the radiation exposure.

IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [1], establishes requirements on occupational radiation protection, and IAEA Safety Standards Series No. GSG-7, Occupational Radiation Protection [2], provides recommendations on meeting these requirements. Additional information of a more practical nature can be found in Safety Reports Series No. 21, Optimization of Radiation Protection in the Control of Occupational Exposure [3].

In 2013, the IAEA decided to address these issues in a project on occupational radiation protection for the decommissioning of nuclear installations and to develop guidance material in a TECDOC. The project has been conducted with supplementary funding from the European Commission under the Instrument for Nuclear Safety Cooperation (INSC) with contract no. 2013-313-757, Project B4(1).

1.2.OBJECTIVE

This TECDOC provides practical information for the management, planning and conduct of occupational radiation protection in decommissioning of nuclear installations. It can be used in the planning of new decommissioning projects and for improvements in the implementation of existing decommissioning projects. This publication also provides useful input for licensing and supervision of decommissioning projects.

The target audience of this TECDOC includes managers, radiation protection officers, qualified experts, as well as other technical experts and professionals in nuclear installations, regulatory bodies and technical service providers.

1.3.SCOPE

This TECDOC describes practical aspects of management, planning, and conduct of occupational radiation protection for planned decommissioning projects at nuclear installations. The scope of

[1] The term 'decommissioning' is defined in IAEA Safety Standards Series No. GSR Part 6, Decommissioning of Facilities [4], para 1.1, as "the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility".

this TECDOC does neither include nuclear installations where accidents have occurred, nor facilities producing or using radiation sources for medical, industrial or research purposes.

1.4.STRUCTURE

Decommissioning is a process of continuous changes of SSCs of nuclear installations. Both the radiological and industrial hazards during decommissioning will differ from those in the operational phase. As a result, these differences ought to be addressed during planning for decommissioning. The organization, procedures, documentation and site ought to be adapted.

The impact of decommissioning on the protection of workers is discussed in Section 2 to provide the underlying basis for the remainder of the publication. This includes an overview of the impact of decommissioning on radiological and industrial hazards, on safety culture and on occupational radiation protection aspects of different decommissioning strategies.

Section 3 addresses the organization, procedures and documentation. It includes the establishment of the radiation protection programme for decommissioning activities, guidance on organizational issues, radiation protection training and qualification, information transfer and interaction strategies for radiation protection, optimization of protection and safety, planning of dismantling and waste management.

Section 4 addresses the radiological characterization and site preparation for decommissioning. It includes issues on monitoring of workplaces and individuals, and radiation protection systems and facilities.

Section 5 addresses the consideration of non-radiological hazards.

In each section, topics of interest from an occupational radiation protection perspective are discussed and supplemented by practical examples from different nuclear installations with relevant experience.

2. IMPACT OF DECOMMISSIONING ON THE PROTECTION OF WORKERS

2.1.HAZARDS

Radiological and industrial hazards arise during decommissioning activities. An understanding of these hazards is essential in order to be able to ensure the health and safety of workers. The focus on hazards during decommissioning needs to be adjusted compared to the operational phase. For example, buildings and systems that were disregarded or unutilized during operation will need to be accessed, modified or dismantled, and new structures may well need to be erected. Increased emphasis needs to be given on waste handling.

Prior to decommissioning, a thorough assessment of radiological and non-radiological hazards and consequent risks need to be conducted, including continuous re-assessment throughout the execution of decommissioning activities. Development of a new assessment process may not be necessary if an existing assessment process (from the operational phase) is adequate. During execution of decommissioning activities, there will be a continually changing environment as, for example, infrastructures are dismantled, engineering controls removed and temporary storage of raw or processed radioactive waste increases. Each workplace needs to be examined and the hazards need to be identified. In addition, the possibility for unexpected hazards, varying in both type and severity, needs to be considered.

All radiological hazards to which workers are exposed during decommissioning activities are to be considered and continuously evaluated. This will include assessment of external exposures and its internal exposures with special emphasis on alpha particles. The presence of alpha contamination and the control measures necessary to protect workers can be considered. A knowledge and understanding of the history of the operation of the nuclear installation, including any incidents (such as fuel failures in a nuclear power plant (NPP)) that may have occurred during its operation, is crucial for the evaluation of the potential radiological risks to workers. Failure of fuel containment may spread alpha contamination into plant systems (pipework/components). If this occurred early in the operational phase of an NPP, this layer of alpha contamination would be expected to have been covered by additional layers of corrosion products. As a result, it is difficult to measure the alpha contamination either from outside the pipework/components or via direct probe measurements inside the pipework/components. In such circumstances, a sample of the corrosion products (not merely a wipe test) is needed for detection of any alpha contamination.

In order to identify and address the hazards, operators of nuclear installations could use a variety of methods. Some decommissioned installations have found it informative to interview employees and retirees so as to understand any abnormal conditions that may have occurred during operation. In addition, radiation protection staff are expected to consider hazards that may result from the removal of engineering controls, e.g., removal of permanent or temporary shielding, and communicate these hazards to the workers. It may be necessary to construct shielding in areas adjacent to areas being dismantled. Similarly, additional ventilation units or the use of respiratory protection by workers may be needed during system and component breaches to minimize potential intakes of radioactive material. Also, flushing or segmentation of components may be necessary in order to remove or reduce the radiological hazard prior to dismantling, to ensure that workers' exposures are optimized.

In addition to radiological hazards, attention needs to be given to non-radiological (industrial) hazards, such as asbestos, electricity, oxygen-deficient environments (e.g. tanks), chemical hazards, falling debris, working at heights, noise, and fire (see Section 5).

In many cases, industrial safety considerations are consistent with radiation protection and safety considerations, but there might be occasions where there is a conflict between these safety aspects. For example, there are both industrial and radiation safety reasons to avoid injuries from cutting or to avoid techniques that are more susceptible to cause fire. On the other hand, using air supplied whole body suits, to protect workers against airborne radioactive contamination, creates an inherent industrial safety risk that needs to be assessed against the benefits the suits provide.

> An example where the various hazards were not properly balanced is described in Ref. [5] as so-called "ladder syndrome": A worker placed plastic bags around the rubber footplates of a ladder to avoid potential radiological contamination of the foot plates. The ladder was slipping while the worker was on the ladder, resulting in a serious personal injury of the worker. This example shows an inappropriate risk evaluation. The worker increased the industrial safety risk (and indeed suffered personal injury) to reduce the potential for a likely minor contamination of the rubber footplates of the ladder.

2.2.SAFETY ASSESSMENT

In the context of occupational health and safety, a risk assessment is a careful examination of what, in the workplace, could cause harm to people. It enables a weighing up of whether enough precautions are in place or whether more needs to be done to prevent harm to those at risk, including workers and members of the public. The International Labour Organization (ILO) guide on workplace risk assessment recommends a five steps method to conduct the risk assessment process [6]:

- **Step 1:** Identify the hazards;
- **Step 2:** Identify who might be harmed and how;
- **Step 3:** Evaluate the risk – Identify and decide on the safety and health risk control measures;
- **Step 4:** Record who is responsible for implementing which risk control measure, and the timeframe;
- **Step 5:** Record the findings, monitor and review the risk assessment, and update when necessary.

Paragraph 3.1 of IAEA Safety Standards Series No. WS-G-5.2, Safety Assessment for the Decommissioning of Facilities Using Radioactive Material [7], states:

"The range of decommissioning activities for which a safety assessment is required is broad, and the scope, extent and level of detail of safety assessments should be commensurate with the types of hazards and their potential consequences. A graded approach should therefore be applied to the development and review of safety assessments."

Further, para. 3.3 of WS-G-5.2 [7] states:

"In the application of the graded approach, account should be taken of:

(a) The purpose and scope of the safety assessment;
(b) The size and type of the facility (including its complexity);
(c) The physical and radiological state of the facility at the commencement of decommissioning activities;
(d) The complexity of the decommissioning activities and uncertainty issues;
(e) The radiological hazard (source term) and radiological characteristics;
(f) The chemical and physical state of the radioactive material;

(g) The likelihood of hazards and their potential unmitigated consequences;
(h) Presence and type of potential initiating events of incident/accident sequences;
(i) The nature and reliability of safety measures to protect against or to mitigate the consequences of accidents;
(j) The safety requirements and criteria against which the results will be assessed;
(k) The end state of the decommissioning of the facility;
(l) The availability of applicable safety assessments for this or other similar facilities and the novelty of the proposed decommissioning activities;
(m) The extent to which decommissioning could adversely affect ongoing operations with safety significance elsewhere at the facility or at nearby facilities."

Paragraph 3.6 of WS-G-5.2 [7] states:

"All relevant hazards (e.g. sources of harm) to workers, the public and the environment should be considered in the decommissioning safety assessment, including:

(a) Radiation exposures, for example, external exposure from direct radiation and other radiation sources (including criticality), internal exposure due to inhalation, ingestion or cuts and abrasions, and loss of containment leading to the uncontrolled release of radionuclides;
(b) Toxic and other dangerous materials, for example, asbestos, flammable materials, carcinogens, chemicals used for decontamination purposes, asphyxiants;
(c) Industrial hazards, for example, dropped loads, work at heights, fires, high temperatures, high pressures, noise, dust and asbestos."

2.3.SAFETY CULTURE

A strong safety culture is paramount for radiation and industrial safety during decommissioning. Paragraph 2.51 of GSR Part 3 [1] states that "The principal parties shall promote and maintain safety culture", and para. 3.4 of GSR Part 6 [4] states that "The responsibilities of the licensee shall include fostering a safety culture in order to encourage a questioning and learning attitude towards safety, and to discourage complacency."

Decommissioning of a nuclear installation will cause changes that may impact the prevailing safety culture. There can be a perception that, when moving from routine operations to decommissioning, the importance of radiation safety is reduced once the nuclear fuel has been removed from the reactor core or the site. This perception could adversely impact the safety culture and is deceptive since, despite removal of the fuel, the level of risk to workers is not necessarily reduced. The non-routine and sometimes hands-on nature of decommissioning activities implies that risks from radiation and industrial hazards are likely to be different compared to routine operations but continue to be important.

When the operation of a nuclear installation ceases, there is potential for an adverse impact on safety culture. This is especially because of the extent of changes occurring, and potential uncertainty in the future of staff and the facility itself when undergoing decommissioning. This may have negative effects on staff morale, particularly where staff is requested to decommission the same plant that it has put considerable effort into safely operating, maintaining and possibly upgrading it in the past. There is also a potential for impact on the performance of staff who may be requested to do work that will be putting them out of a job. The change in the status of a nuclear installation is one from operations, generating revenue, to decommissioning, which necessitates the expenditure of resources and is perceived as a "cost" burden. This is a transition that has the potential to adversely affect safety culture and the resources devoted to it. Furthermore, safety culture may be affected in a multi-unit plant, in which some units are being decommissioned while other units remain in operation, and in which staff is shared among these units.

Example from Danish Decommissioning (Denmark): An anonymous questionnaire among the employees identified that several responders would not confront a colleague after having witnessed the person to be breaking good safety practice. A "smiley arrangement" for providing safety observations (see Fig. 1) was started where employees fill in observations regarding safety issues. The arrangement is anchored in the quality management system which ensures that all issues from observations are addressed.

FIG. 1. A smiley arrangement emphasizes the need for a sound safety practice to workers (courtesy of Danish Decommissioning, Denmark).

Decommissioning projects are non-routine, and various groups of specialist contractors and itinerant workers may be used in addition to the operational staff. It can be challenging to get contractors to adopt the appropriate safety culture, particularly those who have not previously worked on a nuclear site. It is important to consider the content of safety communications and training for contractors, accounting for their own safety culture and how it might need to be changed to align with that of the site. Furthermore, different safety cultures of contractors from foreign countries with differing regulatory requirements need to be considered.

Example from Electricité de France (EDF) (France): EDF contractors for decommissioning are not always the same as those for plant operations. Potentially, a lack of safety culture could be observed. EDF sets the standards regarding radiation protection and industrial safety which are intended to be clearly understood by the contractors' workers and their management. These standards are referenced in all EDF contracts. The main radiation protection rules are included in a specification document which is already included in the tender. This document describes the ALARA process which will have to be implemented and the main rules about work in controlled areas.

Sometimes experienced workers think they know enough to ignore procedures and, therefore, adopt shortcuts. Empowering experienced staff to make suggestions for improvements to procedures may reduce non-compliance and improve procedures. While inexperienced people are likely to need detailed instructions regarding decommissioning work, experienced people are more likely to have adequate confidence with detailed instructions. It can be helpful to engage trade unions, as they understand the reasons for procedures and assist in enforcing them.

Workers are trained and reminded to stop work if something unexpected occurs or an unplanned condition is noticed (e.g. higher dose rates, contamination levels, work steps taking longer than expected, liquids in pipes thought to be drained, discovery of asbestos) during decommissioning work. The safety significance of an occurrence needs to be assessed, and if necessary, a new work plan needs to be developed.

It is challenging for both the regulatory body and the decommissioning management team to inspect safety culture, as it is primarily attitudes of the people involved. One way to show management's commitment to safety culture is by frequent visits to work areas to gain first-hand knowledge of the project status and any emerging issues. When performing such visits, the particular purpose is predefined, such as checking housekeeping, cleanliness, and workers' procedural compliance.

> Example from EDF (France): Cross visits by site management and contractors' management help each other to understand standards and share information. This enables reviews of previous experience and addresses future activities.

In addition, safety culture can be observed indirectly with help of indicators, such as individual and collective dose, contamination levels, radiation protection occurrences, housekeeping, information transfer in the plant, factors taking into account for decisions, interactions among the staff or between staff and inspectors. This could also include indicators of industrial hazards that need to be evaluated regularly and discussed with the plant management throughout decommissioning. If necessary, timely corrective actions are taken.

> Example from EDF (France): An indicator used by EDF is the ratio of the number of non-compliances to the number of observed situations. It helps the management to focus on specific areas or contractors, to anticipate problems and provide resolution before an event occur.

In June 2014, the International Radiation Protection Association (IRPA) published its "Guiding Principles for Establishing a Radiation Protection Culture" [8]. This publication contains an overall policy statement that could help the radiation protection organization in establishing practical guidelines and recommendations. In addition, documents that describe the essential traits and attributes of a healthy nuclear safety culture have been published in 2013 by the World Association of Nuclear Operators (WANO) [9] and by the Institute of Nuclear Power Operations (INPO) [10].

Safety culture can be established by various means, as indicated in para. 8.8 of GSG-7 [2]):

(a) Promoting the knowledge of relevant safety standards within the organization;
(b) Carrying out a risk analysis of the procedures applied;
(c) Establishing proper rules and procedures and observing regulatory requirements to keep risk at a minimum;
(d) Periodically evaluating the implementation and effectiveness of these rules and procedures;
(e) Engagement of relevant management and staff;
(f) Periodically training the staff in accordance with an established programme to follow the rules and procedures correctly;
(g) Discussion of the established programme among trained staff;
(h) Periodically updating the training programmes and coordinating them with the requirements of legal and regulatory bodies, which will check the effectiveness of these programmes;

(i) Dissemination and promotion of knowledge of actual incidents and accidents, to learn from their occurrence, and any reoccurrence, and to improve the safety culture;
(j) Soliciting safety related proposals from the staff through an incentive system.

2.4.OCCUPATIONAL RADIATION PROTECTION ASPECTS OF THE DECOMMISSIONING STRATEGY

Occupational radiation protection requirements need to be considered during the development of the decommissioning strategy because occupational radiation protection will be influenced by the chosen decommissioning strategy.

Important factors influencing the selection of the decommissioning strategy from the perspective of occupational radiation protection that are included in SSG-47 [11] are the following:

- Radiological situation within the facility;
- Local availability of decommissioning experiences and related technology;
- Availability of experienced radiation protection and other decommissioning personnel;
- Intended level of involvement of contractors for decommissioning work;
- Availability of radioactive waste processing and storage facilities.

The consideration of occupational radiation protection amongst other aspects will be an iterative process. In order to ensure that issues on worker safety are considered in the selection process of a strategy, it is recommended that experts in occupational radiation protection and occupational health hazards are involved as early as possible in developing the decommissioning plan.

The selection of decommissioning strategy is the responsibility of the licensee (see para 3.4 of GSR Part 6 [4]) and is a senior management decision. Therefore, responsible radiation protection personnel at an appropriate management level need to be involved. Good practical examples include the involvement of radiation protection committees with expertise in occupational radiation protection, and of high level radiation protection managers early in the decision-making on the decommissioning strategy and the development of the decommissioning plan.

In accordance with GSR Part 6 [4], the decommissioning strategy is either immediate dismantling or deferred dismantling or a combination of these strategies. There is no generically preferred decommissioning strategy from the viewpoint of occupational radiation protection. It can be advantageous to dismantle immediately after the permanent shutdown because knowledge of the operating history and equipment are accessible. Both can be beneficial for occupational radiation protection. On other hand, there exists some disadvantages considering radioactive decay and alpha build-up.

> Example from the Ignalina NPP site (Lithuania): The two NPP units were decommissioned immediately after permanent shutdown in 2004 and 2009, respectively. This decision was taken despite disadvantages involving early incurrence of cost and dealing with higher activities of radionuclides. There were also numerous advantages, including the retention of existing staff and infrastructure requiring less retraining, the early mitigation of a potential legacy problem and the better definition of decommissioning costs for the funding bodies.

Radiation and contamination levels within the nuclear installation and the related composition of radionuclides will influence occupational radiation protection and, therefore, need to be considered in the selection of a decommissioning strategy. In case of high radiation levels, deferred dismantling might be a more appropriate strategy because radioactive decay enables radiation levels to decrease over time. However, there are limitations with respect to radionuclide composition and dismantling techniques. For example, if radiologically relevant nuclides with long half-life are present (e.g. Am-241 or Sr-90), the decay of easily measurable gamma emitters with shorter half-lives (e.g. Co-60 and Cs-137) might lead to a nuclide composition which is difficult to measure and radiologically more challenging. Even the absolute amount of Am-241 can be elevated due to beta decay of Pu-241. Furthermore, the expected reduction of workers' dose may not be achieved when remote dismantling is replaced by manual dismantling. When no benefits from radioactive decay or even changes of radiological conditions towards unfavourable nuclide compositions are expected, immediate dismantling is the preferred decommissioning strategy.

A significant part of workers' exposures during decommissioning is caused by handling of radioactive wastes; therefore, the decommissioning strategy will also include the impact of radioactive waste management on occupational radiation protection. The availability of facilities for processing, storage and disposal of radioactive waste might influence workers' dose during the decommissioning process. This is further discussed in Section 3.5. In addition, before dismantling any existing building, a strategy for waste processing needs to be established. A lack of clarity in the related waste management strategy can cause unnecessary reiteration of waste characterization and processing and, consequently, additional exposure to workers. For example, the auxiliary buildings at an NPP are often decommissioned first. This can induce a lack of space to sort the wastes and often causes a strong "congestion" in the vicinity of the work areas with a resulting impact on occupational exposures.

> Example from Creys Malville (Fast Neutron Reactor, EDF, France): The sodium treatment factory has been installed in the secondary part of the plant to optimize the use of space (see Fig. 2).

FIG. 2. Sodium Treatment Facility at Creys Malville (courtesy of EDF, France).

The dismantling can be performed either from low contaminated areas and systems to high contaminated ones, or vice versa. From a perspective of occupational radiation protection, there is no general preference. Both strategies can be beneficial, depending on factors such as the availability of waste processing and storage facilities, access and transport paths, available space for dismantling work and local handling of dismantled components. An argument for dismantling highly activated or contaminated systems first could be the more significant reduction of dose rates for the further dismantling steps; on the other hand, availability of more space for transport and reduction of dose rate by decay could be arguments for dismantling starting in low contaminated areas. A potential benefit for working first in low contaminated areas could be learning decommissioning techniques in areas with less exposure to radiation.

For sites with more than one nuclear installation, further aspects can influence occupational radiation protection and need to be considered for strategy decisions. Amongst those are the following ones:

- Transferable learning from decommissioning for multi-unit sites;
- Sharing of personnel between several installations and central radiation protection organization;
- Sharing of radiation protection personnel between operating installations and installations in decommissioning;
- Sharing joint facilities for waste processing and storage;
- Sharing radiation protection equipment for measurements, dosimetry and protection.

In the case of an unexpected premature shutdown of the nuclear installation, an appropriate decommissioning strategy needs to be developed, as existing strategies may no longer be applicable. This could have implications for occupational radiation protection. For example, occupational radiation protection may be more challenging during dismantling work when the spent fuel is still in the reactor core than during preplanned decommissioning, which usually starts by removing the fuel from the core. Also, some equipment may not be available and, therefore, priorities for dismantling would need to be defined. This implies a modification of the decommissioning plan.

3. ESTABLISHMENT OF A RADIATION PROTECTION PROGRAMME FOR DECOMMISSIONING

3.1.GENERAL ASPECTS OF THE RADIATION PROTECTION PROGRAMME

Requirement 24 (Arrangements under the radiation protection programme) in GSR Part 3 [1] on arrangements under the radiation protection programme 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".

This requirement also applies to the decommissioning of nuclear installations. Recommendations on the radiation protection programme are provided in paras 3.49–3.158 of GSG-7 [2]. The Safety Guide introduces the general characteristics of a typical radiation protection programme, including the following elements: external and internal dosimetry arrangements, access control, permitting, workers' job coverage, instrumentation, respiratory protection, waste handling, environmental, and medical health surveillance.

When it is decided that a nuclear installation is to be decommissioned, an occupational radiation protection programme for the decommissioning stage needs to be established and maintained. Since there are many changes (e.g. radiological risks and hazards, sources of radiation, work procedures and tools) in the work environment, it is important that these changes be reflected in the radiation protection programme when decommissioning begins. As a consequence, there is a need for a clear adoption of procedures and documents in compliance with the integrated management system of the licensee. The organization will also need to be adjusted to ensure safe and optimized decommissioning activities. Implementation of the radiation protection programme necessitates a holistic approach, including industrial safety, occupational radiation protection, and radioactive waste management.

Usually all decommissioning activities are divided into decommissioning projects which can be executed either sequential or parallel. Decommissioning projects introduce new working methods, tools, and changes in radiological conditions. This needs to be considered in the radiation protection programme.

Requirement 2 of GSR Part 6 [4] stipulates:

"A graded approach shall be applied in all aspects of decommissioning in determining the scope and level of detail for any particular facility, consistent with the magnitude of the possible radiation risks arising from the decommissioning."

Assessment of decommissioning related risks and hazards will help to adequately allocate resources and revise the radiation protection programme. A systematic graded approach to all non-radiological hazards in the plant during decommissioning may be needed as well (see Section 5). The use of a graded approach in protection and safety is essential in planning and conducting the decommissioning activities.

Paragraph 3.4 of GSR Part 6 [4] states:

"The responsibilities of the licensee shall include … managing the decommissioning project and conducting decommissioning actions or ensuring oversight of the actions conducted by contractors."

Paragraph 4.3 of GSR Part 6 [4] states:

“The prime responsibility for safety shall remain with the licensee … The licensee can delegate the performance of specified tasks to contractors and the integrated management system shall make provisions to ensure that the work of contractors is appropriately specified and controlled and is conducted safely.”

During a decommissioning project, many different contractors can work in parallel. Therefore, coordination is necessary to avoid negative impacts on radiation protection; for example, contamination or exposure caused by parallel work. Exposure of workers employed by the licensee is normally well controlled. However, the control of exposure of itinerant workers, especially specialists, is more difficult if they work in different plants. The issue of itinerant workers is of specific concern and is addressed GSG-7 [2] and Safety Reports Series No. 84, Radiation Protection of Itinerant Workers [12].

In operating NPPs, it is common to use ‘ALARA committees’ or an equivalent approach in optimization of protection and safety. It is recognized that these committees provide added value for the management of safety and radiation protection during decommissioning projects. These may be comprised of representatives from various organizational levels, such as corporate, engineering, and plant personnel including radiation protection managers, qualified experts, management, operation and maintenance personnel. Implementing the ALARA approach will need to take into account human factors, organizational context, changes in workplace situations, safety culture, as well as a number of factors to be balanced bearing in mind both radiation protection as well as socio-economic issues.

> Example from NPPs (USA): One approach is to have a Radiological Safety Committee chaired by the radiation protection manager and with the station management represented. This Committee has functions including reviewing decommissioning dose goals and progress, approving/reviewing all major exposure jobs. The Committee is supported by a system of radiation work permits and Radiological Safety Reviews [13].

Performance indicators are typically used to assess the radiation protection performance in relation to the radiation protection programme. Examples include individual and collective dose (from external and internal exposure), personnel contamination, and surface contamination. In the decommissioning stage, the radiation protection indicators used during operation need to be adapted to the dismantling activities, and new radiation protection indicators need to be defined (e.g. airborne alpha activity).

The radiation protection programme needs to consider changes in potential radiological occurrences and the response thereto. Although the radioactive inventory of a nuclear installation decreases during decommissioning, there is a potential for an increasing trend in radiological occurrences such as high airborne radioactivity, spills of radioactive material, contaminated wounds, or unexpected high radiation levels caused by removal of shielding.

The licensee is responsible for making arrangements, not only for its own staff but also for the contractors it employs, to deal with radiological occurrences. Such occurrences may prompt action to prevent or mitigate hazards or adverse impacts on health and safety of workers. Workers, particularly contractors, will need to be trained on how to respond to all warning alarms (e.g. high activity in air).

As during routine operations, radiological occurrences (including incidents and reportable events) need to be investigated. The nature and thoroughness of the investigations will need to be commensurate with the actual or potential radiological consequences of the occurrence. The methodology includes apparent cause analysis, root cause analysis, and identification of trends.

The outcome of such investigations is formulated as recommendations to prevent reoccurrences, and such recommendations necessitate immediate action.

The record of occurrences (including near misses which have radiological consequences or the potential for such consequences) is one of the measures to indicate how well the decommissioning activities, and the associated occupational radiation exposure, are being managed.

> A salutary lesson of what can happen when the radiological situation is not properly controlled and an incident remains undetected for a period of time, is described in "Independent Review of the Exposure of Workers to Alpha Radiation at Bruce A Restart, Reactor Unit 1 Bruce Power, Ontario" [14]. The event was estimated to have cost the operating organization $330 million.

3.2.ORGANIZATION FOR RADIATION PROTECTION

3.2.1. Structure

A radiation protection organization is structured similarly to that of an operating nuclear installation. A qualified radiation protection manager will be designated as the person with the overall responsibility for implementing the radiation protection programme. Radiation protection personnel (e.g. supervisors, technical support personnel, technicians) need to be assigned to provide expertise in each of the areas that make up the radiation protection programme. The radiation protection organization is appropriately linked or integrated with the organization responsible for non-radiological hazards; an example is given in Fig. 3.

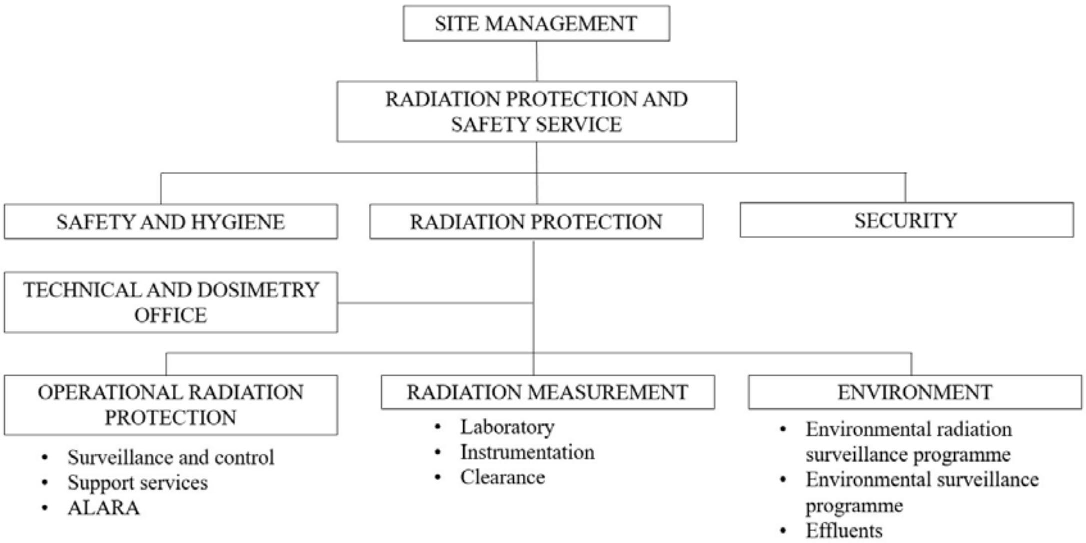

FIG. 3. Example of a Radiation Protection and Safety organization (courtesy of Vandellos NPP, Spain).

Roles for each area within the radiation protection programme need to be clearly defined and documented in the management system of the nuclear installation. The overall decommissioning organization is expected to understand the radiation protection organisation's responsibilities, especially if the responsibilities have changed from plant operations. Further recommendations on the management systems are provided in IAEA Safety Standards Series No. GS-G-3.5, The Management System for Nuclear Installations [15].

The person in charge of radiation protection during decommissioning is expected to have a position within the site management organization that allows participation in the high level decision-making process.

3.2.2. Resources

The radiation protection manager is in a position to identify the radiation protection resources needed as well as the skills and knowledge necessary to implement the radiation protection programme for decommissioning. Decommissioning is a non-routine activity involving unanticipated radiological and other occupational health conditions. This implies an increased flexibility in the number of the radiation protection personnel and their skills.

> Example from EDF (France): Some specific skills are needed during decommissioning. It is necessary to identify the necessary experts who may be from other companies. EDF uses AREVA as an external expert for alpha contamination management, because they have greater experience dealing with alpha contamination arising from reprocessing of spent fuel.

The availability of radiation protection resources to support decommissioning can be a significant issue that needs to be effectively planned and managed. Over time, the number and skills of radiation protection personnel varies depending on the stage of decommissioning. This is especially important in the case of deferred dismantling when a long time could elapse between decommissioning activities. Furthermore, planning may include a significant lead time to acquire the necessary radiation protection resources because of the need for both theoretical and practical training for decommissioning work. Managing resources also includes meeting the regulatory requirements for itinerant workers.

> Example from the Bradwell NPP site (United Kingdom): To enable the site to deliver its decommissioning programme, a larger monitoring workforce was required. Working together with a contract company over a two-year period, a large number of inexperienced members of the local community were task-qualified on radiological protection for decommissioning. As result suitably qualified radiation protection staff for decommissioning was available.

There may be pressure by the management to reduce staffing levels as an overall cost reduction of the decommissioning project. However, it is likely that additional resources for radiation protection, waste management, and occupational health will be needed for decommissioning in comparison to plant operations because of the increase in magnitude and change in the nature of hazards. Any change in the organizational structure, including staffing numbers, may be subject to regulatory review in accordance with the national legislation.

Regulatory bodies may also have to increase their own staff numbers to conduct licensing activities, approvals and inspections during decommissioning.

Furthermore, since the conduct of decommissioning activities necessitates specific knowledge in advanced technology and in radiation protection, it is important that both radiation protection personnel and regulatory bodies plan for a relevant level of corresponding expertise to ensure high quality radiation protection and regulatory oversight. Staff retention may be particularly challenging towards the end of a decommissioning project.

3.2.3. Training and qualification for decommissioning staff

From existing experiences in decommissioning, it is known that staff involved (e.g. managers, safety professionals, regulatory bodies) will need to have knowledge and skills that differ from those during the operating phase of an installation. Given that new techniques and equipment will be introduced during the decommissioning stage, previous qualifications and operational experience may be insufficient. Some account of decommissioning experience is likely to be needed. An overview of the related needs, opportunities and challenges is provided in Ref. [16]. It is important that the people involved in decommissioning are trained (and re-trained) commensurate with the risks to which they will be exposed, both radiological and industrial. The focus of training and qualification may change compared to the operational phase, and the respective programmes need to be revised accordingly. In most countries, regulatory requirements for qualified persons are in place; however, only a few have special focus on decommissioning.

When it is decided to start decommissioning, the existing radiation protection qualification and training programme are usually adapted for decommissioning purposes. The qualification and training programme are re-assessed and adjusted to suits needs of decommissioning. Paragraph 4.16 of SSG-47 [11] recommends that "all project personnel who will perform decommissioning tasks should receive basic training in radiation protection and safety or should prove they have such knowledge." This includes not only task related hazards but also those relating to the use of personal protective equipment (PPE), such as dressing and undressing routines (why, when and how). Training and mock-ups for specific tasks with specialized requirements are also considered; for example, remote handling techniques used by dismantling personnel, or operation of airborne aerosol monitors used by radiation protection personnel.

A good understanding of decommissioning activities and related hazards is needed in order to identify training needs for different workers including radiation protection staff, and to develop an adequate radiation protection training programme. Sometimes managers of the nuclear installation under decommissioning may think that radiological risks are significantly reduced or eliminated, so their decisions may negatively affect occupational radiation protection. Radiation protection technicians may be more familiar with routine surveillance in more stable radiological conditions; however, during decommissioning the working environment is less predictable.

Additional training on decommissioning aspects needs to be considered by the regulatory body as well. Understanding of decommissioning activities and related hazards by the regulatory body is necessary during the licensing process and enables it to perform a comprehensive assessment of decommissioning planning and execution.

One example of a training programme for workers involved in nuclear activities in Canada is provided in [17].

Some dismantling and decontamination equipment may necessitate specific skills and may affect occupational radiation protection, therefore training on application of this equipment are considered. Use of mock-ups or training in a non-classified area simulating the hazardous workplace will help optimize occupational radiation protection while conducting decommissioning activities. These can range from extensive installations to a simple pipe. Uses of mock-ups have also been demonstrated as useful for testing of existing equipment or development of new tools and techniques. An example is shown in Fig. 4.

FIG. 4. Example of mock-up training for glove bags and containments (courtesy of Humboldt Bay, USA).

Contractors or itinerant workers used in decommissioning projects often may not have worked on a nuclear site before and may need training in radiation protection and training on application of safety measures during their work. Decommissioning contractors with little or no experience in the nuclear field may not necessarily be aware of dose reducing techniques or equipment. Therefore, they may need specific advice and training; for example, use of ventilated tents to prevent the spread of contamination. Further recommendations on training for decommissioning purposes is provided in SSG-47 [11], and additional information can be found in IAEA Nuclear Energy Series No. NG-T-2.3, Decommissioning of Nuclear Facilities: Training and Human Resource Considerations [18].

3.2.4. Information transfer and interaction strategies for radiation protection

In addition to training and qualification, the transfer of information between the operating and decommissioning staff of a plant on radiological and occupational hazards is an important tool for the protection of workers. Characterization of the site can be streamlined by knowledge about the operational phase. The history of operational situations and events can provide a wealth of knowledge to radiation protection staff during decommissioning and can minimize unanticipated situations or conditions.

This information can be obtained through written and pictorial documentation as well as intellectual recollection. Potential sources are plant operational records and reports and interviews with long term workers, including retirees. Knowledge transfer of this valuable information is especially important between new and experienced staff and between generations, especially in the case of deferred dismantling of a plant where information valuable to understanding hazards, history of SSCs etc. may be lost.

> Example from the Belgian Reactor 3 (Belgium): The prototype pressurized water reactor first went critical in 1962, was permanently shut down in 1987 and its dismantling was close to completion in 2019. The operator identified a lack of knowledge of SSCs as a problem during decommissioning. Often plant specific knowledge had passed along with previous workers into retirement, as the reactor had not been built with easy decommissioning in mind.

The licensee is required to retain documents that will be needed for prior radiological evaluation and characterization at least up to the end of the operating lifetime of the installation, i.e. before decommissioning starts. Operational records or reports that may reflect decommissioning issues can be an important tool for knowledge transfer between generations. Routine reports or records may provide insights on the impacts of historical occurrences, such as contaminated or uncontaminated liquid spills, fuel failures, historical operational procedures, results of surveys, design drawings, modification records, records of incidents, and annual reports on health and safety performance. In case of deferred dismantling, these reports can be used for knowledge retention and transfer, and may be used for later planning (e.g. annual reports including the description of decommissioning work, task related dose reports for certain measures, problems and their solutions, and a listing of the problematic locations within the plant such as hidden contamination).

Example from the Japan Power Demonstration Reactor decommissioning project (Japan): A contamination map made in the radiological characterization, prior to starting decommissioning activities, showed good coincidence with the records concerning contamination from events that occurred in the operational phase (see Appendix IV).

Example from the Connecticut Yankee NPP (USA): A lack of information transfer identified during decommissioning included the following:

- Unrecorded contaminated soil not detectable by routine surveys because it was covered with lead sheet and then concrete;
- Previously undocumented Sr-90 in soil and groundwater.

Regarding the availability of the collected information at the early stages of a decommissioning project, the licensee is expected to implement measures in order to ensure that:

- Information remains accessible (“readable”) at all stages of the decommissioning project (protection against aging; use of new electronic storage mediums);
- Information is stored in compliance with all the requirements on information security and regulatory issues such as the control of access, copies at different locations, as well as protection against any conventional risks (e.g. fire, flooding).

Even if regulations for the recording and storage of data exist in several countries, additional attention is needed, especially when a deferred decommissioning strategy has been chosen.

Operating experience from nuclear installations is an important source of information for planning and implementing a decommissioning project. Experience exchange can be useful for transfer of information, including visits to a reference facility to see how decommissioning and the associated training are performed. In some countries, the operating organizations send personnel to external decommissioning sites for training. In the international reporting systems for operating experience (IRS, IRSRR, FINAS), events from nuclear installations in the decommissioning stage, in particular events related to occupational radiation protection issues, are not adequately represented at present, although such events are within the scope of the reporting systems.

The Information System on Occupational Exposure (ISOE) provides a forum for radiation protection professionals from NPPs and national regulatory bodies worldwide to improve the management of occupational exposures at NPPs through the collection and analysis of occupational exposure data and trends, and through the exchange of lessons learned. ISOE was launched in 1992 and is jointly operated by the IAEA and the OECD/NEA. It has a database, which contains extensive data of the operational phase and associated operating experience, including radiation protection data (e.g. dose reports, outage reports) from major NPP maintenance or modifications (e.g. replacement of steam generator or reactor head). Some of those data could be useful for the purposes of decommissioning planning. In addition, ISOE has initiated a project to extend the scope of the current database to occupational exposure during decommissioning of NPPs. ISOE members have access to contact details of radiation protection managers from various sites around the world, and specific queries can be addressed directly to them. For further information, see http://www.isoe-network.net/.

The knowledge acquired by long term workers, including retirees, is a valuable source of information. The staff of some nuclear installations undergoing decommissioning has found it useful to interview these workers, to take advantage of their knowledge of the plant operational conditions and events that may aid in the characterization of the plant, including historical contaminated or uncontaminated liquid spills, fuel failures, source term or moisture carryover from contaminated circuits to non-contaminated circuits.

Transfer of information and sharing of experience are key elements during decommissioning projects to enhance efficiency of the technical operations and to ensure a high level of safety at the workplace. Information transfer and sharing of experience may be achieved during planning meetings, training programmes, during scheduled daily or weekly meetings, and during meetings for planning of measures (pre-job briefings) and assessment of work already completed (post-job debriefings). In addition, experience exchange can be useful for transfer of information, including visits to a reference facility to observe how decommissioning and the associated training are performed. Moreover, these activities provide a venue for the active transfer of information and need to be properly documented so that this information is not lost.

Interaction between the radiation protection manager and plant decommissioning management is essential not only during the initial stages of decommissioning planning but also frequently as decommissioning progresses. Good communication is a key to effective job planning and execution. Interaction with radiation protection personnel at several levels within the plant organization is essential, from the highest levels of management to interactions between radiation protection technicians and workers performing decommissioning tasks (e.g. dismantling). Subsequent to thorough job planning, effective communications between radiation protection and workers are necessary to ensure safe and effective execution of the task at hand. Pre-job briefings are important to ensure the "leaders" in the radiation protection staff and workforce understand and agree upon the overall plan and established controls (radiological and non-radiological hazards or conventional safety issues), and on the course of action when unanticipated conditions occur.

Shift briefings, focusing on the work plan and controls, are also planned and conducted. Workers and radiation protection staff can meet to discuss and document any differences in the (radiological and non-radiological) conditions encountered during the task, any problems encountered during execution of the task and possible solutions to resolve problematic issues. As during plant operations, post-job debriefings may occur as soon as practical upon completion of a specific decommissioning task. These activities need to be thoroughly documented.

Numerous subcontractor firms will be engaged at various stages of a decommissioning project. Therefore, interaction between the management of these firms and the licensee's radiation protection management is essential to ensure that expectations in workers' performance are understood and properly implemented (e.g. expected radiation protection work practices, work permit adherence).

> Example in EDF (France): A specific group is in charge of coordination of activities between all working groups (contractors and staff) present on the site. A "prevention plan" is set up and is applied to avoid negative interaction between different works. This plan is updated with project evolution.

Examples of involved parties and of objectives for sharing information are given in Table 1.

TABLE 1. EXAMPLES FOR INFORMATION TRANSFER DURING DECOMMISSIONING

Involved parties	Contact opportunities	Objectives
Operator's staff and itinerant workers	Training programme Pre-job briefings Post-job debriefings	Knowledge transfer to new staff Communication of work procedures Assessment of work already completed
Radiation protection manager and plant decommissioning management	At the initial stages More often as decommissioning progresses	Effective planning and execution of decommissioning
Radiation protection personnel and workers	Training programme	Knowledge transfer to new staff
Radiation protection management and management of subcontractors	Pre-job briefings Shift briefings Continuously	To ensure the "leaders" in the radiation protection staff and workforce have a common understanding and agreement on the overall work plan and established controls (radiological and non-radiological hazards) – Focused on the work plan and controls. – To discuss and document any differences in the conditions (radiological and/or non-radiological) encountered during the task, any problems encountered during execution of the task and possible solutions to resolve problematic issues. – Ensure that expectations in workers' performance are understood and properly implemented.

3.3.OPTIMIZATION OF PROTECTION AND SAFETY

In the nuclear industry, implementation of the optimization principle is the most important aspect of ensuring adequate occupational radiation protection. Optimization of radiation protection can be implemented at the very beginning of the decommissioning project by selecting effective radiation protection and decommissioning techniques. The optimization of protection and safety (as defined in GSR Part 3 [1]) is a process of determining the level of protection and safety that results in the number of exposed individuals, their doses and the likelihood of them being exposed, that is as low as reasonably achievable (ALARA), taking economic and societal factors into account. Optimization of protection is not equal to minimization of dose, but rather an evaluation of both the risks and the necessary resources for the protection of individuals, to determine the protective measure that is the best option under the prevailing circumstances [19].

Paragraph 3.26 of GSG-7 [2] recommends:

"A structured approach to the selection of appropriate measures for protection and safety should include the following steps, with account taken of exposures from normal operations and of potential exposures:

(a) Identify all practicable protection options that might potentially reduce the occupational exposure;
(b) Identify all relevant economic, social, radiological and, where appropriate, non-radiological factors for the particular situation under review that distinguish between the identified options (e.g. collective dose, distribution of individual dose, impact on public exposure, impact on future generations and investment costs);
(c) Quantify, where possible, the relevant factors for each protection option;
(d) Compare all options and select the optimum option(s);
(e) Where appropriate, perform a sensitivity analysis (i.e. evaluate the robustness of the solutions obtained by testing different values for the key parameters for which recognized uncertainties exist)."

A graded approach in terms of occupational radiation protection is related to the planning, conducting and supervising of dismantling activities including dose, risk assessment and ALARA with a higher level of detail for more challenging radiological conditions. An example is provided in Appendix I. There needs to be a suitable level of involvement of management and other interested parties. This includes a stepwise approach from general planning of dismantling projects down to specific procedures for dismantling of SSCs with a detailed description of work steps and related radiation protection measures. A higher level of detail is also needed if information affecting occupational radiation protection is not or only partially available, for example when new techniques or equipment need to be introduced.

Assessment of expected individual and collective dose is a tool for the planning of decommissioning work. Because the radiation work environment and the scope of work are continuously changing during decommissioning, this assessment needs to be performed or repeated close to the time when the work is to be performed. Furthermore, update of planning with actual information on radiological characterization is always possible. For dose estimation purposes, application of different computer codes may be useful.

A comparison of the expected doses with actual doses after completing the work may be used in order to examine the work planning process. Assessment of individual doses may also be used for the control of work, (e.g. setting guidance levels for doses with the obligation of revised planning if guidance levels are reached).

An optimization tool that could be used is the concept of dose constraints which was defined by the ICRP [19]. The concept of dose constraints is also established in Paragraph 3.22 (c) of GSR Part 3 [1] which states:

"The government or regulatory body shall establish or approve constraints on dose and on risk, as appropriate, or shall establish or approve a process for establishing such constraints, to be used in the optimization of protection and safety." [2]

For occupational exposure, the relevant dose constraint is on individual doses, established and used by licensees to set the range of options in optimizing protection, as illustrated in Fig. 5.

[2] Although risk is mentioned in GSR Part 3, no use is currently made of risk constraints for occupational radiation protection in relation to decommissioning.

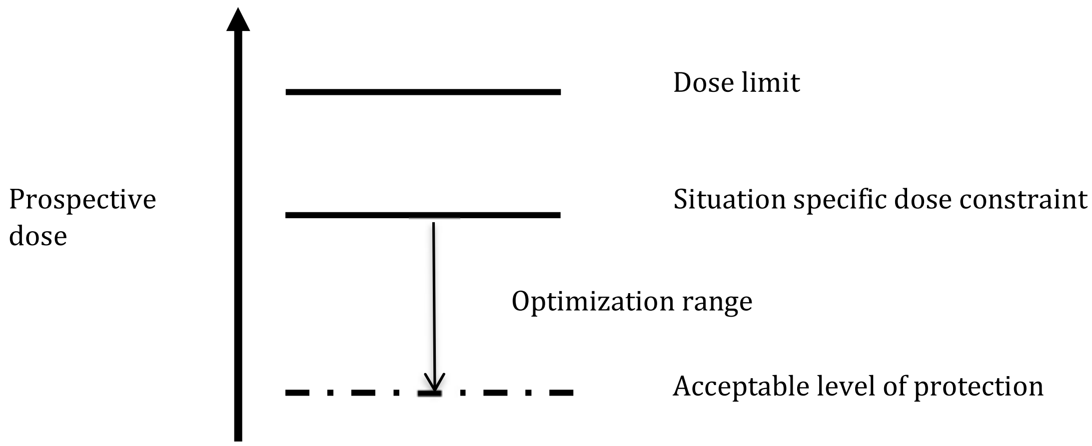

FIG. 5. Concept of dose constraint in optimization of protection.

For practical application, in addition to dose constraints for the planning of decommissioning activities, further planning values for optimization are used (e.g. dose targets, dose goals, dose budgets). If an estimated dose for a work task does not exceed the selected value, the planned work task may be considered as acceptable and be subject to optimization of protection. Planning values could be used on a task by task basis and on a time basis (e.g. daily, monthly, quarterly). Practical examples exist in different countries.

> Example from EDF (France): Dose constraints are set in coordination between the contractors and the licensee. These constraints are set for a long period (for example for the work duration or for one year), and for each task (e.g. support, decontamination, waste processing, compliance). The individual dose constraint values are set between 2 and 10 mSv per year. Written procedures are developed before the decommissioning work starts to ensure workers' doses are kept below the limits. Examples of actions that might be taken to avoid exceeding constraints are to change the work procedures, to add protection or shielding, or sometimes the replacement of workers.

Further information is provided in NEA/CRPPH/R(2011)1 [20].

Furthermore, dose control tools used for conducting decommissioning activities include e.g. action levels, investigation levels, and dose budgets.

> Example from Canada: Action levels are designed to alert licensees before regulatory dose limits are reached. By definition, if an action level specified in a license is reached, a loss of control of some part of the associated radiation protection programme may have occurred, and specific action is required. The specific action under the Radiation Protection Regulations consists of establishing the cause for reaching the action level, restoring the effectiveness of the radiation protection programme, and notifying the regulator within the period specified in the license. Action levels are typically site and facility specific. Further details can be found in Ref. [21].

3.4.PLANNING FOR DISMANTLING

The overall plans for decommissioning projects and associated steps serve as a basis for general dismantling planning. For practical work, more detailed planning with respect to safety and radiation protection aspects will be necessary. Depending on the specifics of the situation and condition, the level of detail and focus will vary. The planning documents may form the basis for work permits.

Careful planning and knowledge of the available decontamination and dismantling techniques are essential to ensure that exposure of workers to radiation is kept ALARA. Feasible dismantling techniques could be compared with the aid of a selection criteria based on individual and collective dose. Practicable options of protection measures and dismantling tools may be identified by reviewing decommissioning experience of other nuclear installations. There is considerable decommissioning experience from a variety of plants and using various techniques including the consequences for radiation protection matters (e.g. generation of aerosols, secondary waste). For example, different types of decontamination methods for NPP primary cooling systems are available, such as chemical decontamination.

Decisions on the types of technique and equipment are made on the basis of both radiological criteria and non-radiological criteria. Comparisons between different techniques and equipment are useful if circumstances and methods are similar. For example, hydraulic scissors are usually used for cutting small diameter pipes to avoid generation of airborne radioactive particles due to loose surface contamination (free contamination) present inside the pipe. However, gas cutting technique may be used due to its remote operation ability, although secondary waste and aerosols will be generated, and combustion may be an issue in some areas.

While engineering solutions for occupational radiation protection are always be considered when planning decommissioning operations and always be a priority, there can be sound reasons for an alternative approach relying on safe systems of work and PPE (e.g. short time tasks). One example is the selection of shielding, where the expected dose reduction gained from shielding is compared with the exposure incurred by installing the shielding. Other examples of engineering solutions include movable ventilation systems, temporary containment systems (e.g. tents to avoid spread of contamination), and the selection of already developed industrial solutions instead of purpose made nuclear equipment.

> Example from the Bradwell NPP site (United Kingdom): Figure 6 shows an example of a typical temporary structure used for a contamination area work. This type of structure can be erected within a few hours, allowing a large amount of flexibility in work delivery and planning.

FIG. 6. Containment tent, similar to those used by the emergency services in response to chemical and radiological incidents for personnel treatment and decontamination (courtesy of Bradwell, United Kingdom).

Some useful tools for decommissioning may be found in non-nuclear industries and can be adapted if necessary, for decommissioning purpose. The licensee is responsible for the equipment used for decommissioning and needs to be an intelligent customer for off the shelf equipment that has not been designed for nuclear use.

Example from the Bradwell NPP site (United Kingdom): A source of technology from an unexpected industry is the use of agricultural vacuuming technology by workers during the decommissioning of the fuel cooling ponds. The vacuuming technology was used to remotely move ion exchange resin and other particulates with high associated radiological dose rates. The technology was adaptable as the waste was of a similar consistency to slurry and grain used in agricultural settings.

Practical guidance on the application of the optimization principle, including decision-aiding techniques for the selection of options for dose reduction, is provided in Ref. [3]. Various examples of decommissioning techniques and protection measures can be found in Technical Reports Series No. 395, State of the Art Technology for Decontamination and Dismantling of Nuclear Facilities [22].

A system of work permits maybe used for detailed planning. These permits need to be supported by radiological safety reviews that assesses in detail the specifics of the proposed work, specifies any hold points and includes contingency plans. Work permits address either specified work without time limits or with a time limit typically ranging from days to months. In some countries, specific work permits exist to address the controls specific to the hazard (e.g. an additional fire permit, or a permit for work in hazardous surroundings such as asbestos). In other countries, the work permits contain all hazards and protection measures, including fire and other hazards. More information about work permits can be found in Ref. [23].

Criteria needs to be in place to define the need for more detailed planning and supervision of work packages. Such criteria can be considered for the expected individual and collective dose as well as specific conditions challenging occupational radiation protection (e.g. radionuclide compositions with Am-241 and/or other alpha emitters, working in small rooms with inhomogeneous dose rates).

An example for a guideline document, defining the process and criteria for detailed planning of decommissioning in Germany, is provided in Appendix I.

Detailed planning documents is expected to contain all information necessary to derive, justify and verify safe work and ensure that exposure will be ALARA. Difficult working conditions will increase exposure time of the workers. An example of measures to identify the influence of physical working conditions is given in Appendix II.

For detailed planning, information about the radiological situation, the actual arrangements of SSCs, the dismantling itself and planned protection measures is necessary. This includes the following elements:

— Description of rooms and areas where dismantling will take place;
— Description of SSCs in the area and clear instructions which of them are to be dismantled and which are not to be dismantled (serves as a basis for risk consideration);
— Description of conditions for starting the work (e.g. safe electrical status of systems, pressure relief of systems, isolation of systems or part of systems to be dismantled from operating systems or operating part of such, accessibility of the respective rooms, preparative decontamination or cleaning, status of ventilation);
— Information on which dismantling work or projects can or will be performed in parallel and why negative impact is excluded or how it will be avoided;
— Detailed radiological characterization data;
— Principal work sequence with allocated cutting, transport, radiation protection and other equipment and detailed steps potentially relevant for exposure of personnel;
— Transportation routes and equipment;

- Access to rooms including air locks if applicable;
- Emergency and rescue routes;
- List of monitors, samplers and other radiation protection equipment as well as protective equipment selected for the work package under planning;
- Detailed allocation of specific equipment for radiological relevant work steps;
- Necessary adjustments of stationary or mobile radiation protection monitors (e.g. changes of warning levels for dose rate monitors or aerosol monitors);
- Consideration of specific risks and potential occurrences and planned counter measures;
- List of ALARA measures considered in planning as well as optional measures for selection during the work. This can be related, for example, to selection of cutting equipment which can minimize release of contamination but has limitations in terms of e.g. material and geometry of the objects to be cut. Consequences for radiation protection measures need to be considered (e.g. need for further local filtered ventilation);
- Briefing and instruction of the personnel especially for any specifics of the rooms in terms of e.g. radiological situation, available space, critical work steps;
- Estimation of internal and external individual and collective dose for work steps and whole work package. Dose for the different personnel involved (e.g. radiation protection staff, dismantling staff, supervising staff) are separately estimated;
- Evaluation of dose estimates with respect to dose constraints and other planning values. Estimation of the duration of the work and work steps are included with some conservatism in order to allow and motivate for “safe and sound” work rather than “quick and dirty”;
- The dose estimation is not limited to dismantling but also contains preparatory work, clean-up after dismantling, and activities related to waste handling. The latter is typically part of the work package until the waste is transferred to radioactive waste teams at predefined waste collection areas;
- Layout, schemes and pictures defining and illustrating the local situation.

Detailed planning necessitates an effective radiological characterization although a conservative approach to workers’ protection may be possible in cases where limited information is available. It might not be easy to find a conservative approach due to contradicting protection goals. For instance, unnecessary radiation protection measures can give rise to conventional risks. Wearing air supplied (ventilated) whole body suits due to unknown alpha airborne contamination level can impact the work in narrow rooms where heavy components have to be handled with a certain risk of transport incidents. Furthermore, work in such suits typically takes longer than with lighter clothes and, hence, will increase external exposure. An example of the impact of protective suits on the exposure time is provided in Appendix III.

Similarly, appropriate respiratory protective equipment needs to be selected to ensure the necessary level of protection considering the industrial hazards. For example, wearing air supplied whole body suits may be inappropriate when cutting into systems for dismantling. More information on respiratory protection can be found in Ref. [24].

Mock-ups and 3-D simulation of the local situation may be necessary or helpful for planning and understanding of the local conditions and individual work steps.

> Example from the Bradwell NPP site (United Kingdom): During decommissioning, mock-up trials were used to gain an understanding of the ion exchange resin and how it would behave upon retrieval. The trials took 1600 person-hours and practiced both planned and contingency tasks. The experience gained proved invaluable, especially when the project team had to deal with unexpected complications.

The use of software to model workplaces and operations to be performed could provide an efficient support for the preparation phase as well as during the dismantling operations. Optimization as well as protection of workers can be implemented by means of software-based simulations. Figure 7 shows some views obtained using such simulation software. These software programs, which are useful for planning and training, need to be used with care, and need to be validated by measurements.

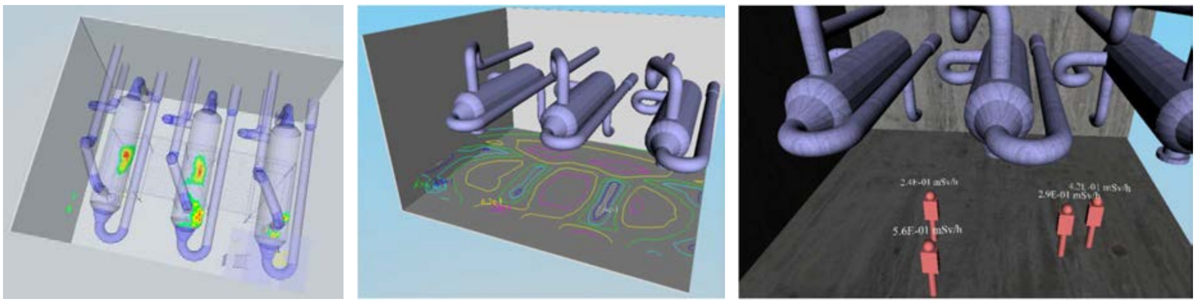

FIG. 7. Screenshots from a work simulation software (courtesy of Bradwell, United Kingdom).

3.5.RADIOACTIVE WASTE MANAGEMENT

Management of radioactive wastes is an important aspect to be considered in the planning and implementation of measures for occupational radiation protection for decommissioning. Improperly handled radioactive waste could necessitate further waste processing and, consequently, lead to additional exposure to radiation. Therefore, thorough preplanning is necessary, including adequate facilities and areas for processing and temporary storage of radioactive waste.

> Example from the Bradwell NPP site (United Kingdom): The two Magnox reactors ceased operation in 2002 and completed defueling in 2006. The Low Level Waste Management Facility (LLWMF) was opened in 2009 to process the waste produced during decommissioning. The building was designed to be able to load three half height ISO containers side by side, but the more versatile the building is the more useful it will be (see Fig. 8).

FIG. 8. Waste container constructed for receiving wastes generated during decommissioning (courtesy of Bradwell, United Kingdom).

Important occupational radiation protection features of the LLWMF design include:

- Compartmentalised building – railed curtain partitions can segregate areas to form airborne contamination containments. The building ventilation extract system can be controlled to adapt to the demands of each area;
- Brick walls/partitions using high density shielding bricks such that waste shipments awaiting consignment do not elevate the working area dose rate or

interfere with monitoring instrumentation criteria. The low background created has enabled an off-site clearance monitoring station to be set up within the same building;
- Multiple large access doors to enable large items to be brought in whole for further treatment under better radiological and environmental conditions;
- Several cranes whose pivot ranges overlap, enabling continuation of work during individual crane downtime.

Some considerations in the planning of radioactive waste management include:
- Need for balance between waste volume reduction and occupational exposure;
- Adequately sized laydown areas for dismantled SSCs and material;
- Establishment of reference dose rate and contamination level for laydown area controls, including control of background level;
- Decontamination of concrete;
- Handling of mixed waste;
- Packaging and transportation of radioactive waste including absorbents.

Storage areas (e.g. for dismantled SSCs, concrete, soil) need to be adequately sized to provide sufficient space for radioactive waste segregation and provide adequate distancing to minimize the dose to workers from the accumulation of equipment and materials. A good practice is to shield waste packages of high dose rate with those of lower dose rate. Recommendations on segregation of radioactive waste are provided in IAEA Safety Standards Series No. SSG-40 Predisposal Management of Radioactive Waste from Nuclear Power Plants and Research Reactors [25], and No. SSG-41, Predisposal Management of Radioactive Waste from Nuclear Fuel Cycle Facilities [26].

Housekeeping and cleanliness of plant and laydown areas are important to minimize the potential for the spread of contamination and reduce worker radiation exposure. In addition, dose rate and contamination threshold levels are expected to be established and enforced in these areas.

Large components (e.g. reactor pressure vessel, steam generators, reactor heads, pressurizers, bridge cranes, reactor coolant pumps) are also major contributors to radioactive waste. Prior to removal of these components, senior management responsible for decommissioning is expected to consider if these components will be decontaminated, surfaces treated and/or segmented in order to reduce the potential for the spread of contamination, to reduce workers' exposure or downgrade the waste classification for transportation and disposal.

Concrete structures including walls, floors and ceilings can be a significant contributor to radioactive waste generation. When reduced to rubble, the volume of concrete can expand up to approximately 40% more than the original volume. Therefore, the contribution of concrete as radioactive waste cannot be underestimated and needs to be thoroughly assessed when planning for decommissioning.

Handling of mixed wastes, containing both radioactive and hazardous materials (e.g. lead seals in underground piping, and lead and asbestos contaminated wiring and cables) are considered in the planning process to avoid exposure by unnecessary treatment and cross contamination.

For most nuclear installations, the procedures and processes for radioactive waste packaging and transportation during decommissioning are similar to that for operating nuclear installations those during operation, with specific country regulations; however, these activities will be on a much larger scale with continuous movement of equipment and materials into and out of laydown areas. For the on-site and off-site transportation of these materials, appropriately trained and qualified personnel with expertise in radiation protection is necessary to minimize exposure to workers. Requirements for the predisposal management and disposal of radioactive wastes are established in GSR Part 5 [27] and SSR-5 [28], respectively. Requirements for radioactive waste management in decommissioning are established in GSR Part 6 [4].

4. RADIOLOGICAL CHARACTERIZATION AND SITE PREPARATION

4.1.RADIOLOGICAL CHARACTERIZATION

Radiological characterization represents the determination of the nature, location and concentration of radionuclides at a nuclear installation. It comprises of dose rate measurements, evaluation of contamination levels as well as radionuclide compositions. Characterization is supported by knowledge about the operational phase. The results from the radiological characterization impact many aspects of decommissioning, including effluent sampling, waste management, routine surveys (e.g. dose rates, surface and airborne monitoring), clearance of materials, training and instrumentation. Care is needed on deciding the extent of characterization needed initially and during the decommissioning process, to inform the methodology to be used and minimize dose and contamination hazard. Interviews with long term workers (and maybe retirees) and well managed documentation from the operational phase contributes to an effective radiological characterization.

The main purpose of the initial radiological characterization is the selection or adjustment of the general decommissioning strategy. This includes decisions regarding main decontamination work as well as an understanding of the associated necessary changes to the radiation protection programme. Reasons for such changes include the level of contamination relevant for decommissioning and the presence of alpha emitters, tritium (H-3) and other radionuclides impacting occupational radiation protection. Furthermore, a good understanding of activation as well as contamination that can penetrate into the building structures and inside components and systems are expected to be in place.

> Example from the Connecticut Yankee NPP (USA): Good planning was implemented based on the radiological characterization of air samples present at the outset of decommissioning. Characterization studies discovered a high portion of alpha emitters relative to historical samples, compared to the easily detected Co-60 nuclide (beta emitter). As a result, air sampling during decommissioning applied a correction factor of 50 to the derived air concentration (DAC) for Co-60 contamination to account for the alpha emitters, which are more difficult to detect than Co-60.

Extensive radiological characterization surveys may result in unnecessary exposure to the workers performing the characterization, therefore it is necessary to justify any such surveys. The purpose of any characterization is to dictate the method used and data needed. There may be areas of the plant that are inaccessible or very hazardous before the decommissioning begins. Such areas can be surveyed as the decommissioning progresses but before any decommissioning work starts in the area. Decisions are carefully balanced in terms of weighing radiological consequences of an early characterization against the probability of later characterization impacting the dismantling process.

Nuclide compositions in the nuclear installation are expected to be well understood, and nuclide vectors need careful derivation and consideration of characterization data. The following aspects need to be taken into account:

— Radionuclides important during decommissioning may differ from those important during operations. Nuclide vectors relevant to operations may no longer be relevant when decommissioning starts;

— Some representative samples may be analysed for the complete range of radionuclides based on state-of-the-art analysis techniques;
— Nuclides that are of minor significance during operations may become important during decommissioning – notably alpha emitters. The possibility that fuel is leaking always needs to be anticipated;
— For different occupational radiation protection purposes (e.g. inhalation protection, surface contamination, clearance), different nuclide vectors characterizing the same material might be bounding.

Specific measures are necessary to determine the contamination level on non-accessible areas or surfaces covered by oxide layers, preventing the detection of alpha particles by direct measurement. Radionuclide characterization may need to be based on sampling and laboratory analysis looking for alpha, beta and gamma radiation and can also be supported by in-situ gamma spectrometry. Historical cladding failures are anticipated, resulting in americium, curium, plutonium and neptunium contamination in some parts of the plant. During decommissioning, the ratio of beta to alpha activity often ranges from 50:1 to 500:1 but can be as low as 1:1. Plutonium-241 (a pure beta emitter) decays with a half-life of 14.35 years to Am-241 and so the amount of Am-241 increases with time ("in-growth", see Fig. 9). Also, tritium needs to be carefully analysed because it easily penetrates and migrates throughout adjacent concrete until it reaches a state of equilibrium concentration.

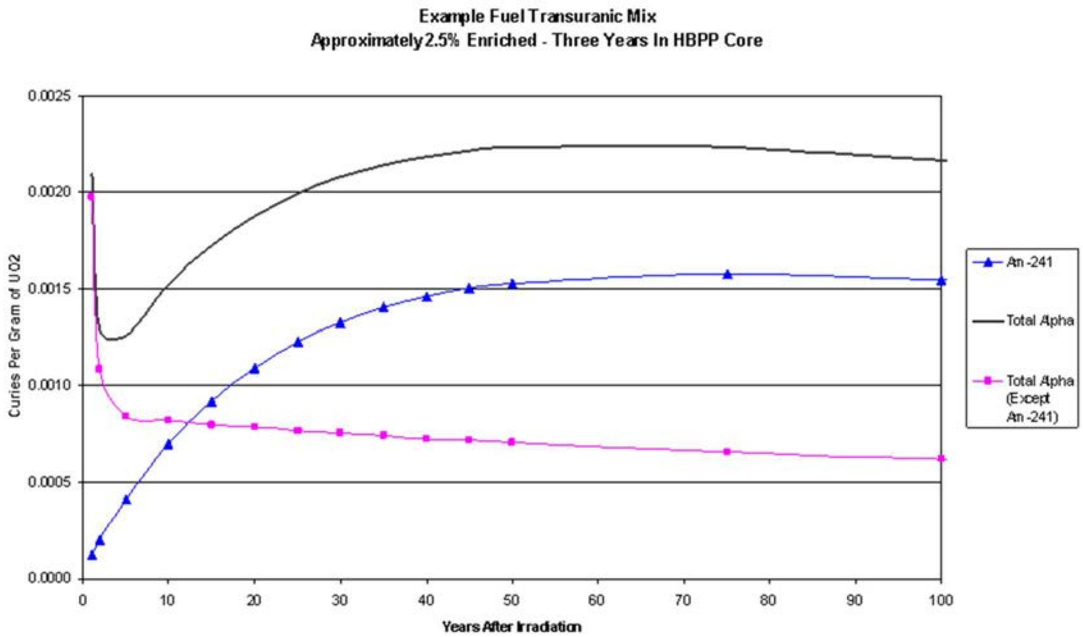

FIG. 9. An example of an alpha decay curve (courtesy of Humboldt Bay, USA).

Example from the Bruce Power NPP site (Canada): Air sampling of contamination was not screened for alpha emitters due to an incorrect assumption that the alpha concentration could be understood through historical ratios to beta/gamma air sampling. When air sample results were measured offsite for alpha emitters, it was found that the ratio of beta/gamma to alpha was in some places as low as 1:1. This implied a much higher gross DAC present in the air. As a consequence, it was calculated that some 557 workers received an internal exposure. This could have been prevented or moderated with a better understanding of the potential contaminant. Full details can be found in Ref. [29].

From previous decommissioning projects, the allocation of a nuclide vector to a system or building has limited applicability. As dismantling actions progress, nuclide compositions will change due to cross contamination amongst systems and by decay. Whereas decay effects can easily be considered, dispersion and transport within systems are difficult to calculate. Utilization of conservative nuclide vectors can be useful as it simplifies the decision making and process. However, there may be practical limitations caused by detection limits of measurement equipment as well as potentially higher risks. As a result, unnecessary protective measures may increase occupancy time and raise industrial safety concerns.

The initial radiological characterization for overall planning of decommissioning is not typically detailed enough nor does it contain all necessary information for detailed work planning; therefore, an ongoing and more detailed characterization process is necessary. A detailed radiological characterization is necessary and typically consists of the following elements:

- A detailed survey map containing dose rate measurements in the room/area, for each SSC and in more detail for the SSC to be dismantled. This includes the range of dose rates at typical work locations, dose rates at local hot spots as well as minimum dose rates at low dose rate areas. Measurements include dose rates for different distances to understand the variation of dose rate. The influence of the filling level of systems (pipes as well as tanks) has to be considered, especially if measurements are taken when a system is prepared for dismantling and liquids are to be released;
- A detailed survey map containing contamination measurements in the room/area, for each SSC and in more detail for the SSC to be dismantled. Special care is needed for inner contamination of systems which have to be cut. The status of the data (before/after decontamination or cleaning) needs to be clearly indicated to avoid any misinterpretation;
- Information about actual nuclide composition, including the presence of alpha emitters. It is also known that the nuclide composition within one system can vary significantly so that nuclide data measured at one location are not necessarily representative for the full system to be characterized;
- Information about nuclide vectors based on measured and calculated nuclide composition need to be derived. Predefined sets of nuclide vectors can be determined from the initial radiological characterization. The application of such a predefined nuclide vector needs to be verified for the given purpose (e.g. setting an aerosol monitor threshold, evaluation of air samples) and measurement equipment. Aerosol monitors may be sensitive for beta and alpha radiation (see Appendix V). Analysis of air samples is typically based on gamma spectrometry so that different nuclide vectors or different scaling factors might be applied for different equipment. Assessment of surface contamination with contamination monitors could necessitate a nuclide vector specific to surface contamination.

Although the radiological characterization could be performed as explained above, situations can occur where such information is not available. In the absence of information, the effort needs to be balanced with the benefit. No matter how good the characterization is performed, there are likely unexpected issues that need to be addressed.

Gamma cameras can be used as a tool for characterization because they can determine localized nuclide compositions including hot spots (see Figs 10 and 11). Many nuclear sites use this technique during decommissioning or maintenance. However, careful analysis is advisable for complex geometries, considering shielding effects and distance from potential radiation sources.

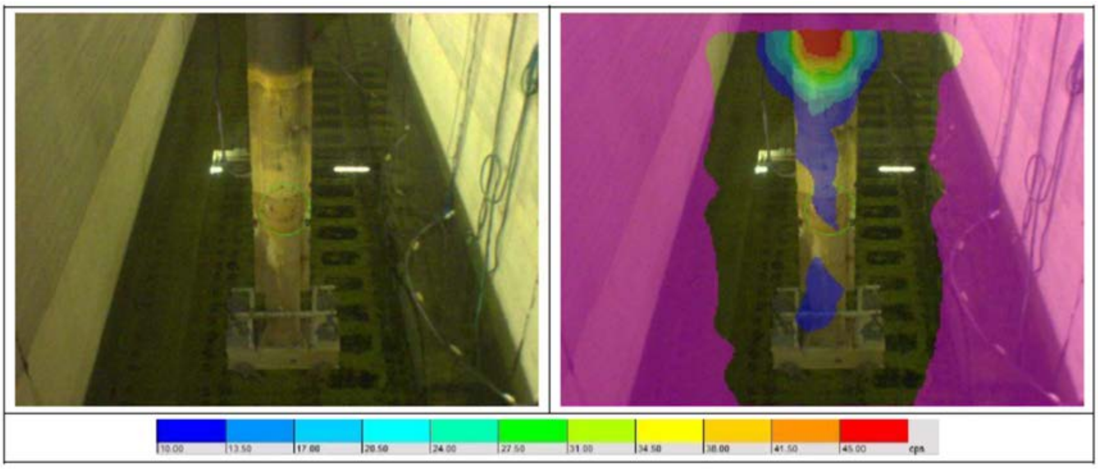

FIG. 10. Gamma-ray imaging surveys undertaken at Hinkley Point A Site (United Kingdom) by Cavendish Nuclear in February 2015. The survey results identified stretches of Cs-137 contamination around the walls of the fuel cooling pond and the higher section of the crane mast (courtesy of Hinkley Point A site, United Kingdom).

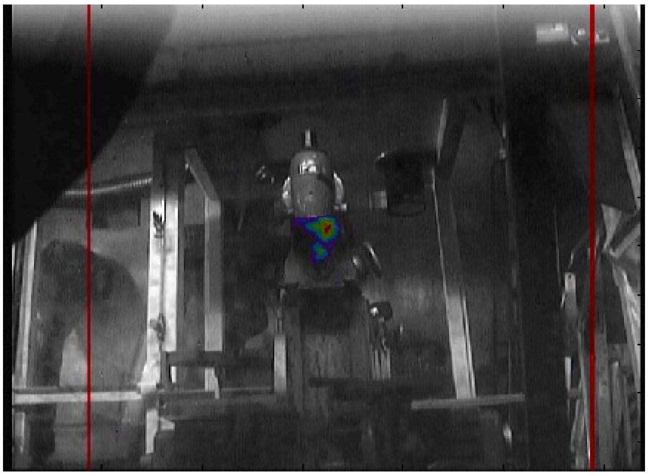

FIG. 11. Plutonium hot spot (courtesy of CEA Valduc, France).

There are several reference documents describing and discussing radiological characterization, see for example Refs [30, 31].

4.2.SITE PREPARATION

Prior to the permanent shutdown of a nuclear installation or during transition from operation to decommissioning, the licensee is required to initiate studies and identify what systems, equipment and infrastructure from the operational stage will need to be maintained or adjusted and what new systems, equipment and infrastructure will need to be installed.

4.2.1. Designated areas for radiation protection

A general classification of areas and zones will be based on the results of radiological characterization and operational experience. Corresponding controls and measures will be defined accordingly. In accordance with GSR Part 3 [1], registrants and licensees need to designate controlled and supervised areas to control exposure and prevent the spread of contamination in normal operations. These areas need to be delineated by physical means or, where this is not reasonably practicable, by some other suitable means (such as displaying warning symbol, restricting access). All countries have requirements and/or guides to set up radiation protection areas. Although there are similarities in the use of these areas (and of zones within areas) by various countries, the terminology and detailed criteria may differ. Some countries use additional criteria for the definition of controlled and/or supervised areas for decommissioning, such as levels for dose rate, aerosol concentration or surface contamination (including tritium or alpha contamination).

The controlled and supervised areas established for the operational phase may need to be changed during decommissioning. This can, for example, be caused when contaminated systems which are normally closed will have to be opened or when nuclides not usually expected during operation (e.g. transuranium elements or tritium) have to be considered. Expansion of existing or designation of new controlled areas (e.g. temporary building for buffer storage) may also be necessary. In addition, some buildings may be dismantled which may have been the part of the boundary of a controlled area. Furthermore, periodic review and adjustments of zones and related radiation protection measures are necessary during the decommissioning stage, for instance when systems have been dismantled and dose rates and contamination levels are reduced.

Area classification schemes used during the operational phase can also be applied during decommissioning considering dose rate and contamination level, for example supervised and controlled areas, “green”, “yellow”, “red” contamination and dose rate informed zones. For further information regarding classification of areas on the basis of dose rate and contamination level, see for example Ref. [32].

Within controlled or supervised areas, local contamination and dose rate informed zones can be installed. Those zones could have mobile measurement equipment and provision for changing of clothes. The advantage of such zones is that they can be easily installed and removed when no longer needed during the decommissioning progress. Areas, rooms or parts of those with elevated dose rates are marked with signs and dose rate information and secured with indicating chains or mobile fences.

Thresholds and action levels are identified for reassessment of protective measures. These protective measures include cleaning and decontamination, selection of appropriate dismantling technique, installation of additional mobile or stationary ventilation systems or air filters, additional monitoring equipment for workplaces, and protective clothes and respiratory protection. Action levels are set below the regulatory levels to give an early indication, allowing for adjustments and decisions as necessary. Depending on the kind of threshold/action level, exceedance of such levels may imply further investigations and reporting to inspectors and authorities. Reporting and investigation levels need to be clearly defined.

General order and cleanliness in radiation protection areas are important to keep contamination levels low and promote a positive atmosphere and motivation of decommissioning personnel. Cleanliness of the facility reflects a good work environment that could be beneficial by minimizing radioactive contamination and thereby avoiding internal contaminations of workers.

> Example from the Chooz A NPP (France): Low levels of contamination throughout the whole installation resulted in low level internal doses (see Fig. 12). The decision was taken to clean the whole installation to continue the decommissioning in good occupational radiation protection conditions.

FIG. 12. Chooz A decontamination (2014). Left side – decommissioning of the fuel building. Right side – pipework before and after cleaning (courtesy of Chooz A, France).

Experience shows that it can be beneficial not only to clean but also to paint areas to be decommissioned. This will make decontamination easier as decommissioning progresses, and it will positively influence workers' attitudes. However, the decision to fix contamination with paint will mask the presence of alpha contamination thereby making clearance measurements more difficult to obtain. Removal of the paint may be necessary to perform a good radiological characterization.

If the nuclear installation is left under a care and maintenance regime because of deferred decommissioning, it is likely that contamination control coatings may degrade. Also, it is likely that physical containment may degrade over time leading to reduced cleanliness and an increased risk of radioactive contamination. These issues need to be considered during decommissioning planning.

At the boundary of different radiological areas and zones, exit monitoring are provided for workers, equipment and materials. During decommissioning, workers will need to move between areas and zones to a greater extent than during operation of the nuclear installation. Additional entrances and/or exits at controlled and supervised areas might be needed to accommodate a larger number of workers and transport of material and equipment. For temporary exits, administrative measures and mobile equipment can be used instead of permanently installed equipment, and the use of such temporary exits has to be strictly limited and controlled.

In accordance with para. 3.90 (g) of GSR Part 3 [1], registrants and licensees provide, as appropriate, at exits from controlled areas the following:

(a) Equipment for monitoring for contamination of skin and clothing;
(b) Equipment for monitoring for contamination of any objects or material being removed from the area;
(c) Washing or showering facilities and other personal decontamination facilities;
(d) Suitable storage for contaminated PPE.

The radiation protection programme is expected to consider the practical aspects of exit contamination monitoring of workers. Monitoring regimes may need to change to reflect the change in hazard; for example, monitoring for alpha contamination usually necessitates longer counting times to meet clearance criteria. Additional monitoring equipment may be necessary to ensure that the new monitoring regime does not impact the effective movement of personnel and material. State-of-the-art instrumentation for exit monitoring of contamination could be installed, to effectively detect any spread of contamination and reduce influence by human factors. In some countries, additional radiation monitoring at the entrance of the nuclear installation is performed using radiation portal monitors and/or quick scan monitors. Entrance monitoring may help to identify contaminated workers from other nuclear sites or workers who have undergone nuclear medical treatment.

For contamination control of small personal items, special equipment may be installed at the controlled area exit to allow removal of items. Other items typically will be controlled by radiation protection personnel. Nuclide specific criteria and geometry calibration is necessary. Where dedicated instrumentation is not available, radiation protection personnel may be needed to perform specific assessments.

Typically for transport and waste management, the level of acceptable contamination on equipment and packages for transport within buildings, on site and off site is defined. The respective levels established in IAEA Safety Standards Series No. SSR-6 (Rev. 1), Regulations for the Safe Transport of Radioactive Material [33], are considered as a minimum. Special procedures for monitoring and control of contamination and dose rates are expected to be in place for transport of larger items, equipment, as well as radioactive waste removed from controlled areas.

4.2.2. Workplace monitoring

Appropriate workplace monitoring needs to be in place for radiological assessment in controlled and supervised areas. Paragraph 3.96 of GSR Part 3 [1] states:

"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."

Decommissioning plans describe the radiological conditions and identify radiation surveys and measurements that will be necessary to support decommissioning operations. The workplace monitoring programme will be more extensive than was the case during routine operations. This is because there is a greater likelihood of radioactive material being spilled or released to the working environment.

A programme for workplace monitoring is needs to be stablished for decommissioning activities in accordance with the hazards at workplaces. This also takes into account occupational hazards such as chemicals and other hazardous substances (see Section 5). This programme may be part of the licensing procedure or of a safety assessment prior to the start of decommissioning activities. Hazards at the workplace may change during decommissioning and procedures for assessment of changes may be necessary. Monitoring is designed not only to measure the expected normal radiological situation, but also to indicate any breakdowns in controls leading to changes in radiation or contamination levels. This includes, among others, continuous assessment of the background radiation for monitoring equipment and consideration of ventilation air flow patterns within the working environment.

Three types of workplace monitoring are considered:

(a) Routine monitoring to demonstrate that the working environment is satisfactory for continued decommissioning operations and that no change has taken place that would necessitate a reassessment of operational procedures;

(b) Task related monitoring to supply information about a particular task or decommissioning operation and to provide, if necessary, a basis for immediate decisions on the execution of the task;
(c) Special monitoring following major alterations of the installation (e.g. that would affect shielding, containment, ventilation).

Monitoring for airborne contamination gets more important and is more complex than monitoring for surface contamination. Airborne contamination can be present as:

- Particulates (such as aerosol, dust or smoke);
- Gases (Kr-85, Ar-41, gaseous radionuclides);
- Vapours (small droplets of liquid containing radionuclides, tritium).

A report on alpha monitoring and control guidelines for operating NPPs was published by the Electric Power Research Institute (EPRI) [32] and is useful in relation to decommissioning. Radon interference can cause challenges to alpha-in-air monitoring. For nose blow tests, additional information can be found in a report of UK's Health Protection Agency [34].

> Example from EDF (France): In order to perform "nose blow sampling" a clean area is utilized, additionally, the workers must shower before to eliminate any cross contamination of the samples with hands or face. EDF utilize nose blow sampling as an indicator of loss of control over controlled radiological areas.

Practical information on workplace monitoring and contamination is available in Ref. [35] and an IAEA TECDOC on workplace monitoring is under preparation [36].

4.2.3. Individual monitoring

Characterization of the radiological hazard provides crucial input to the decision on personal dosimetry needed for decommissioning. Dosimetry used for operations, typically a legal dosimeter and an electronic personnel dosimeter, may need to be adapted for decommissioning. Assessment of individual doses addresses internal and external exposure and use of relevant assessment methods (dosimetry programme, bioassay programme, workplace monitoring).

External dosimetry for decommissioning is similar to the operational phase. However, some specific aspects with regard to higher levels of surface contamination and the potential for beta dose also need to be considered. IAEA-TECDOC-1731 [37] provides information on the possible need for eye dosimetry.

> Example from the Barsebäck NPP (Sweden): A study in relation to decommissioning looked at occasions when people could receive significant eye doses, to what extent a body thermoluminescent dosimeter measuring $H_p(10)$ is representative of $H_p(3)$ eye dose, and how effective protective equipment is. The study showed that no routine measurement of dose to the lens of the eye needs to be done given the current plant status. It was also found that photon radiation (rather than beta radiation) dominates at the plant and that the thermoluminescent dosimeter registers a dose value that is representative for the dose to the eye lens. Relatively large distances to the potential sources as well as beta radiation shielding in the eye protection seem to be the reasons.

During operation, monitoring of internal dose is usually estimated by whole body counters. During decommissioning activities, other additional methods may be routinely applied. For example, it may be necessary to develop a programme for bioassay assessment where alpha (e.g. assumed to be present because of fuel failure) or tritium contamination exists. Such programme may necessitate taking samples of urine or faeces from a selection of workers. Detailed information is provided in GSG-7 [2].

> Example from EDF (France): The bioassay intake assessment during decommissioning have had unanticipated consequences. The assessments provide confirmation of airborne alpha contamination; however, during the sampling period, individuals were restricted from entering controlled areas for several days. As a consequence, this reduced the capacity of contractors to fulfil their remit and hence, caused problems between the contractors and the management of the licensee.

Personal air sampling may also be used to monitor internal exposure. There can be differences from country to country on protection factors provided by respiratory protective equipment. If personal air sampling is not used, then other equipment such as air samplers and local air monitors at the workplaces may be necessary.

4.2.4. Monitoring equipment

Various types of monitoring equipment can be used during decommissioning:

- Stationary, mobile and remote dose rate monitoring equipment;
- Stationary and mobile monitors and samplers for airborne activity, for workplaces, persons or other areas;
- Hand-held monitors for direct measurement of surface contamination on objects and persons;
- Hand and foot, and whole body monitors for surface contamination measurements of persons;
- Organ and whole body counters for measurement of internal activity/dose;
- Measurement chambers (e.g. 4π or others; gas filled or scintillation detectors) for materials and equipment;
- Drum measurement chambers for radioactive waste;
- Wipe test measurement equipment as low level counters, mobile reading equipment (for alpha and beta radiation);
- Clearance chambers for clearance measurements of materials, drums, boxes (typically 4π, scintillator based);
- Special equipment for H-3, C-14, Sr nuclide measurements (laboratory based, sample preparation necessary);
- Gamma spectrometry (laboratory based or in-situ).

> Example from EDF (France): For decommissioning sites, the contamination monitoring system used during operation is supplemented by:
>
> - Permanent air sampler filters that are changed daily and monitored after 1 day and 8 days to avoid non-gaseous radon descendants. A typical detection limit with this method is between 1/100 DAC and 1/10 DAC. These air samplers are used to indicate low level contamination trends;
> - Mobile airborne monitors that are used to detect a fast and high airborne contamination trends. A typical activity detection limit is 1 DAC;
> - Tritium monitors;
> - Personal air samplers.
>
> *The implementation of these devices is reviewed regularly as the work progresses.*

Hand-held scintillator based surface contamination counters are more frequently used because they do not need a gas supply. For practical application, however, some limitations are considered. Photomultipliers are sensitive to shock damage and are affected by localized magnetic fields. Even minor damage to the thin foil through which radiation enters the detector allows ambient light to enter and swamp the photomultiplier. Cables connecting ratemeters and probes are also a common problem. For some scintillation counters, while the contribution of beta radiation to the alpha channel is expected to be negligible, any alpha activity will normally contribute significantly to the beta channel count rate thereby giving incorrect beta channel readings. Also, scintillation counters are typically more sensitive to low temperatures giving inaccurate readings and limits their application in outside areas in cold seasons. Calibration of the equipment as well as setting of threshold and warning levels are considered if different nuclide vectors[3] are needed (see Section 4.1 and Appendix V).

4.2.5. Systems and facilities influencing radiation protection

In each nuclear installation, there are different systems and facilities that can influence occupational radiation protection. Their availability needs to be considered in the planning of the decommissioning project and throughout the decommissioning process. This can directly influence the implementation of occupational radiation protection or defines conditions for the planning of dismantling. The most important systems and facilities are:

— Ventilation systems;
— Lighting systems;
— Power supply systems;
— Water supply and drainage systems;
— Stationary monitoring systems;
— Breathing air supply;
— Laboratories;
— Personnel accommodation facilities.

Decisions for maintenance, removal or modification of such systems and facilities necessitate considerations for that system or facility, and its adequate performance. Other requirements such as fire safety need to be also considered. In some cases (e.g. deferred dismantling), some of the systems may not be operational at the time of decommissioning or may not meet current requirements (e.g. old ventilation system). In such cases, modification or installation of new systems and/or use of portable equipment may be appropriate.

In the planning stage, radiation protection personnel ensure the availability of sufficient and stable power supplies for various types of equipment like radiation monitors, contamination monitors, and control equipment. Other equipment might need significant increased power as, for example, air compressors necessary for protective suits. Modifications or upgrades of the existing systems (e.g. additional lighting) may be beneficial for occupational protection although this may cause some additional exposure. For example, more light at the workplace may improve work performance time, decrease likelihood of failure and repetition of work, and decrease exposure to other hazards.

Water supply and drainage systems will be necessary for SSC decontamination, dismantling operations, personnel decontamination and personnel change room facilities. Depending on the type of decontamination and applied dismantling techniques, water supply may be crucial to

[3] A nuclide vector conservative for occupational radiation protection is not necessarily conservative for other purposes, such as waste characterization or clearance.

minimize the spread of contamination. Water supply and drainage systems may also affect the ability to conduct personnel decontamination. Personnel accommodation facilities (e.g. facilities to store and change clothes and personnel protective equipment, showering and washing facilities) are to be maintained until the end of decommissioning.

Equipment used at laboratories for radioactivity measurements during operation may not be suitable for decommissioning purposes and may have to be supplemented. A good understanding of the differing radiological hazards during decommissioning helps to determine appropriate measurement equipment and its location. For example, some existing measurement equipment may not be sensitive enough to detect low alpha or beta contamination. The requirements and availabilities of such systems are assessed initially and as decommissioning progresses.

5. CONSIDERATION ON NON-RADIOLOGICAL HAZARDS

Decommissioning of nuclear installations is associated with numerous radiological and non-radiological hazards. The objective of decommissioning is to remove both the radiological and non-radiological hazards (see e.g. SSG-47 [11]). During the decommissioning stage, some new types of hazards, or increased hazards compared to routine operations and outages, may be present. These can include non-radiological hazards such as:

- Falling from heights;
- Electric shock from cutting cables;
- Oxygen deficient atmospheres from confined spaces such as tanks;
- Poor air quality caused by insufficient ventilation (chemical and dust risks);
- Asbestos from lagging on pipes;
- Chemical hazards (e.g. polychlorinated biphenyls (PCB), ammonia);
- Fire caused by thermal cutting techniques (e.g. plasma cutting) and non-thermal cutting techniques (e.g. use of grinders and saws);
- Heat stress from working in plastic suits;
- Poor lighting conditions;
- Noise making alarms and warnings inaudible (e.g. high radiation level, high activity in air, fire alarm);
- Dropped loads from cranes and other lifting equipment;
- Falling debris.

Prior to execution of planned work, radiation protection and conventional industrial hazards are assessed with agreement on protection measures between radiation protection staff and the occupational health manager. This can help to avoid conflicts between requirements for radiation protection and requirements for other occupational hazards.

Existing methods for quantification of conventional risks need to be used [5]. Plant walk-downs will support the identification of these hazards.

PPE is worn commensurate with workplace hazards. As in any construction or operational environment, hard hats, work gloves, safety eyeglasses and sturdy safety shoes, with toes comprised of either steel or composite materials, are worn during the decommissioning activities. Specialized equipment such as rubber suits may be necessary when working with specific chemicals that may have been used during plant operation (e.g. boron, ammonia) or for decommissioning. Protection from falling, as defined in the country’s safety regulations, could also be used in conditions when workers may locate themselves in elevated areas.

The potential for electric shock if power sources are not de-energized is also a concern and may be considered during the planning process. An adapted tagging and clearance system may be in place not only for electrical safety but also for other conventional hazards, such as pressure, temperature, and hazardous liquids.

Prior to entry into potentially dangerous oxygen–deficient atmospheres (i.e. <19.5% O_2), areas in confined spaces need to be tested for oxygen content and corrected as necessary for workers' entry. A self-contained breathing apparatus is never used in oxygen-deficient environments beyond the initial assessment of an area, and workers are normally not be allowed to work using such an apparatus. Oxygen-deficient environments are identified and corrected prior to allowing access into these areas.

Asbestos (as shown in Fig. 13) is a respiratory concern and to be properly handled. In the case that asbestos in materials is identified before decommissioning, sampling and usually external laboratory analysis need to be performed. Only a few asbestos laboratories are permitted to handle radioactive materials and, therefore, such a "licensed" laboratory has to be contracted for this purpose. Asbestos abatement techniques, including proper tenting, and handling of asbestos-containing materials need to be properly planned and executed to ensure that workers' exposure to asbestos is minimized.

FIG. 13. Micrograph picture of asbestos.

Fire hazards, for example due to welding or thermal cutting, need to be considered. Equipment, procedures and trained personnel are made available to prevent and respond to fire during decommissioning activities.

Heat stress from environmental working conditions and wearing additional PPE can also be a concern for workers. Portable ventilation units can be used to reduce the immediate temperature of the area; however, the use of fans is limited to clean areas due to the potential for the spread of contamination and airborne contamination. When selecting protective clothing or PPE for ensuring industrial safety or for use in radioactively contaminated areas, materials or fabrics used (e.g. cloth, paper, rubber) are considered for potential heat stress and extreme cold conditions.

In many countries, there are different regulatory bodies for conventional safety and radiation safety. If conflicts between radiation protection regulations and occupational health regulations exist, they need to be resolved. One approach is to use memoranda of understanding to eliminate uncertainty and confusion on assigned responsibilities. Industrial hazards are increasing throughout the decommissioning process and, therefore, any decision about the precedent between radiation protection and occupational health needs to be carefully weighed and agreed upon by the different competent regulatory bodies. Qualification in occupational health may prove more important during decommissioning than operation. Additional education and training in occupational health and protection measures may be necessary for staff on nuclear installations during decommissioning, as well as for the nuclear regulatory bodies or authorities responsible for such aspects.

APPENDIX I. DEFINING THE PROCESS AND CRITERIA FOR DETAILED PLANNING OF OCCUPATIONAL RADIATION PROTECTION DURING DECOMMISSIONING

An example from Germany is the guideline IWRS II [38], which is included in NEA/CRPPH/R(2011)1 [20]. The IWRS guideline deals with the radiation protection of the personnel for planned activities in relation to maintenance, modification, waste management and dismantling work in nuclear facilities and installations. Part II of the IWRS guideline specifies the radiation protection measures during the operation and the decommissioning of a facility or installation. It is binding for all German NPPs.

The flow chart of IWRS Part II, which is taken from Ref. [20], is reproduced in Fig. 14 and defines the level of involvement of responsible radiation protection personnel in detailed work planning. Radiological conditions, i.e. ambient dose rate level and adverse conditions concerning contaminations as well as the expected individual and collective dose, are considered as selection criteria.

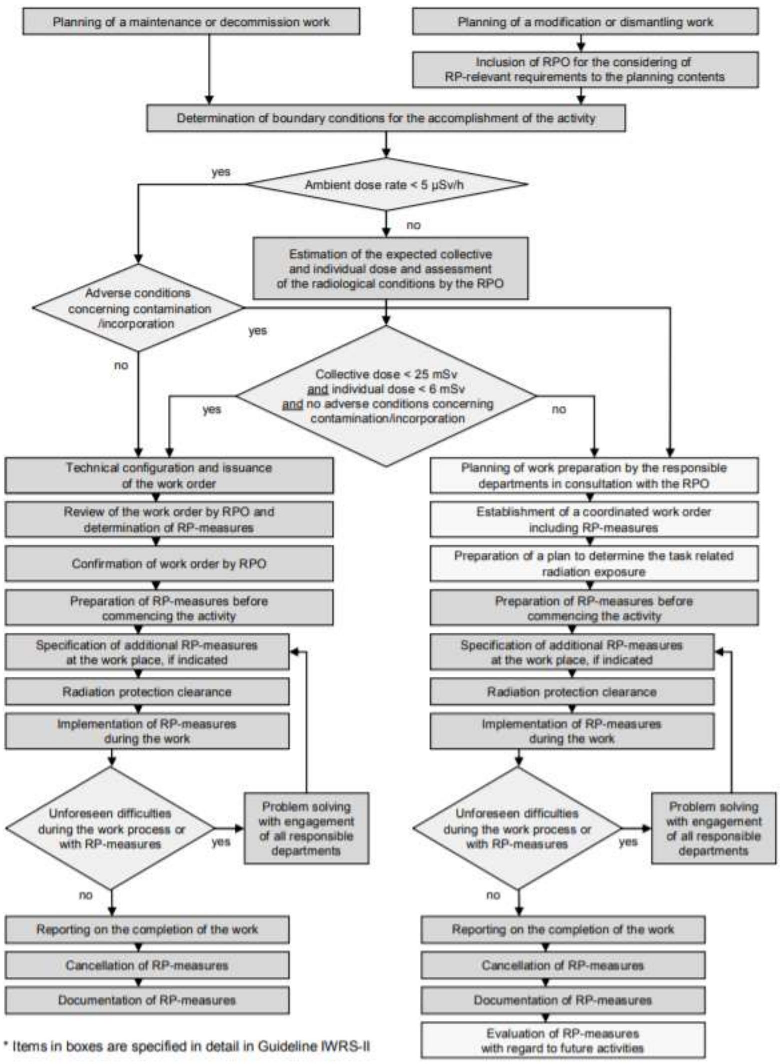

FIG. 14. Flow chart of the IWRS II guideline (reproduced from Ref. [20]).

APPENDIX II. SAMPLE WORK PLANNING

The example presented in this appendix indicates the impact of working conditions on the duration of exposure. The NEA Report [23] presents measures performed on NPP sites to identify the influence of physical work conditions.

Table 2 indicates that the preparation of work has to be carefully performed to reduce doses during decommissioning.

TABLE 2. IMPACT OF WORKING CONDITIONS ON THE EXPOSED TIME [23]

Working Conditions	Impact on the duration of exposure
Inadequate lighting	+ 20% In comparison with working with adequate lighting
Noisy conditions, or difficult communications due to masks, without Audio links	+ 20% In comparison with jobs in using audio links to communicate with other
Working Space: Not very congested area	+ 20% In comparison with work in an open area
Working Space: Highly congested area	+ 40% In comparison with work in an open area

APPENDIX III. EXAMPLE OF THE IMPACT OF PROTECTIVE SUITS ON EXPOSURE TIME

The impact of protective suits on exposure time is given in below table which indicates interdependence of different protection goals that needs to be balanced [23]. For example, respiratory protection influences work time and, thus, external exposure. The exposure time can be increased by up to 65% depending on work type and protective equipment.

TABLE 3. IMPACT OF PROTECTIVE SUITS ON EXPOSURE TIME

Work Type - 1	Work Type - 2	Work Type - 3
• Continuous • Concentration • Precise work • Heavy effort • Duration < 2 min • Very restricted workspace • Uncomfortable posture (Example: Installation of maintenance 'Spider in stream generator channel head)	• Continuous • Concentration • Precise work • Heavy light effort • Duration < 10min • Restricted workspace • Uncomfortable posture (Example: Remove, place and adjust of 2 limit switches on a 2 inch' value)	• Continuous • Concentration • Imprecise work • Heavy light effort • Duration < 10 min • Not much workspace • Uncomfortable posture (Example: Unscrews, remove and screw of 12 nuts on a 12 inch' valve)

Non ventilated cotton clothing

Cotton overall mask + mask	34% (± 17%)	34% (± 14%)	19% (± 14%)

Non ventilated impervious clothing (PVC or Tyvek)

Non ventilated chadoc ventilated mask	34% (± 19%)	65% (± 20%)	21% (± 13%)
Impervious clothing + mask	29% (± 8%)	46% (± 18%)	25% (± 13%)
Impervious clothing + ventilated hood	28% (± 12%)	27% (± 16%)	22% (± 10%)

Air fed pressurised clothing (PVC)

Air fed pressurised Mururoa	30% (± 11%)	37% (± 25%)	8% (± 4%)
Air fed pressurised chadoc + ventilated mask	51% (± 12%)	57% (± 25%)	16% (± 14%)
Shrunken air fed pressurised Mururoa	21% (± 13%)		

APPENDIX IV. SAMPLE CONTAMINATION MAP

This Appendix provides an example from the Japan Power Demonstration Reactor for successful information transfer with respect to contamination records in a turbine building (1963 – 1985).

A contamination map made during radiological characterization, prior to starting decommissioning activities, showed good coincidence with the records concerning contamination from events that occurred in the operational phase. These events are summarized in Table 3.

TABLE 3. CONTAMINATION EVENTS THAT HAVE OCCURRED IN THE OPERATIONAL PHASE

Event date	Affected system	Characteristics of the event
9 August 1964	DDS	DDS overflow
17 January 1967	RWCU	Floor contamination (V66-5 gland leak)
1 April 1967	MS	Floor contamination (Bypass valve leak)
23 February 1968	C	Floor contamination (CDR room)
20 December 1971	C	Floor contamination (CDR room)
1 May 1972	DDS	DDS No.2 overflow
21 November 1975	MS	Floor contamination (Blowdown system)
8 January 1976	MS	Floor contamination (Valve leak)
26 January 1976	Floor drain	Floor contamination
23 March 1976	CDS	CDS bottom crack

Notes:

C: Condensate system; CDR: Condensate demineralizer regeneration; CDS: Clean drain sump tank; DDS: Dirty drain sump tank; MS: Main steam system; RWCU: Reactor water clean-up system.

APPENDIX V. SAMPLE PREDEFINED SETS OF NUCLIDE VECTORS

An example from Germany explains the interdependence of nuclide vectors on calibration and radiological criteria.

For practical use of monitoring equipment, warning thresholds need to be determined on the basis of radiological criteria. These criteria are dependent on the radionuclide composition and could include e.g. DAC and contamination levels. For example, acceptable airborne contamination levels for alpha contamination are up to three orders of magnitude lower than those for beta contamination. As a result, the corresponding warning thresholds for nuclide compositions with higher alpha ratios will be much lower. An example for a beta emitter is the lower acceptable airborne concentration for Sr-90 compared to Co-60 or Cs-137.

The sensitivity of the equipment may also be dependent on radionuclide composition. Sensitivity is expressed either as a calibration factor or dose conversion factor. For example, surface contamination monitors are typically more sensitive for Sr-90 than for Co-60 because of the higher beta energy of Sr-90.

Generally, a conservative approach for setting warning thresholds could be used to address variation of the real nuclide composition; however, this approach has practical limitations. For example, very low threshold levels can lead to false alarms resulting in unnecessary protective measures. This could also lead to reduced level of attention and acceptance by workers. Limitations are of special importance if sensitivity and radiological criteria are both reduced to address the variations in nuclide compositions.

In a more sophisticated mathematical approach, the ratio between the factors determines which nuclide vector is appropriate to address variation in the real nuclide composition. This ratio has to be calculated for each radionuclide and summed up. The following is a simplified example where both effects can be factorized. This can be applied for example if gamma spectrometry is used for sample analysis.

Nuclide vectors are usually predefined. A predefined nuclide vector is enveloping for a real nuclide composition if the following inequality (1) is valid:

$$DAC(NV) / CF(NV) < DAC(NC) / CF(NC) \quad (1)$$

where:

NV is a predefined nuclide vector;

DAC(NV) is the derived airborne concentration leading to the annual dose limit for the nuclide vector NV;

CF(NV) is the calibration factor for the nuclide vector NV based on gamma spectrometric analysis of an air sample;

NC is a normalized nuclide composition;

DAC(NC) is the derived airborne concentration leading to the annual dose limit for the nuclide vector NC;

CF(NC) is the calibration factor for the nuclide vector NC based on gamma spectrometric analysis of an air sample.

By analysing which NV from a set of predefined nuclide vectors just fulfils the equation above, unnecessary conservativism can be reduced by selecting a nuclide vector with minimum conservatism but adequately addressing the radiological requirements. The availability of nuclide specific sensitivity data for the measurement equipment is a precondition for the application of this approach.

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ABBREVIATIONS

ALARA	as low as reasonably achievable
CNSC	Canadian Nuclear Safety Commission
DAC	derived air concentration
EDF	Electricité de France
EPRI	Electric Power Research Institute
INPO	Institute of Nuclear Power Operations
INSC	Instrument for Nuclear Safety Cooperation
IRPA	International Radiation Protection Association
ISOE	Information System on Occupational Exposure
LLWMF	low level waste management facility
NEA	OECD Nuclear Energy Agency
NPP	nuclear power plant
PPE	personal protective equipment
SSC	structures, systems and components
WANO	World Association of Nuclear Operators

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