IAEA Nuclear Energy Series

No. NW-T-2.8

Basic Principles

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MANAGING THE UNEXPECTED IN DECOMMISSIONING

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

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

Decommissioning is, by its very nature, a process involving unexpected events, with the attendant need to adopt precautions, to recognize events when they occur and to deal with them safely, efficiently and in a manner that is environmentally responsible, and to learn lessons applicable to both ongoing decommissioning projects and future projects. When the nature of a decommissioning project is found to be substantially different to that expected, it often results in unplanned work to investigate and redefine the nature of the project, which may introduce delays and cost overruns, and which has the potential to expose decommissioning staff to additional industrial hazards and unplanned exposure to radiation.

Some unexpected events during the decommissioning are described in publications that are used as references for this report, but no systematic coverage of the nature, taxonomy, impacts of, contingency arrangements for and response to such events was previously available as an IAEA publication. To respond to this need, a series of consultants meetings, which included the participation of a number of international experts, were held to draft, review, amend and finalize this publication. The IAEA officers responsible for the initial collection of references and the compilation of this publication were M. Laraia and V. Michal of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The decommissioning of redundant nuclear facilities usually involves decontamination, dismantling and demolition of facilities that were designed and constructed many years ago. At the time of design and construction, nuclear knowledge was incomplete, and, not surprisingly, much of the effort expended was aimed at getting the plants to work safely and cost effectively, with little consideration given to how they would be decommissioned at the ends of their lives.

In addition, experience in decommissioning programmes around the world has shown that during their lives, these early plants were often modified as knowledge of nuclear science developed, and, in many cases, modifications were incorporated without the level of configuration management (CM) that would be expected today.

The result is that despite careful planning of decommissioning programmes, there are often surprises when facilities are opened for dismantling purposes, or when material is removed from hot cells, etc. Many of these unexpected discoveries have already been faced by decommissioning teams, and have been addressed satisfactorily. This enables them to be documented and their solutions published, so that future decommissioning programmes may be able to anticipate the problems, or, if such problems manifest themselves, to provide ready-made solutions.

Furthermore, for those engaged in the design, construction and operation of new facilities, knowledge of the problems caused by lack of consideration of decommissioning, should be taken into account during these phases in the life of a facility, making the task of decommissioning teams easier when the new plants are decommissioned in future years.

Designers, operators and decommissioners of nuclear facilities represent the main target groups for this publication, but regulators will have a strong interest in reviewing plans and inspecting decommissioning works with a focus on mishaps and unexpected events. Stakeholders such as local communities will generally be eager to be informed of any such events in a timely manner, in order to be reassured that radiological and other impacts are being kept to a safe minimum.

Unexpected events and findings during the decommissioning of nuclear facilities have been referred to in the past as unknowns; however, many of the problems encountered during implementation of decommissioning are well known, it is simply that they were not expected to arise. In some other cases, the problem may not have been encountered in the decommissioning team's experience, forcing the development of new techniques, tools and procedures to address the unexpected problem, with the attendant delays and cost overruns that this often involves.

The IAEA has published a large number of publications related to a wide variety of decommissioning topics. Many of these describe unanticipated problems as a result of errors in documentation, equipment degeneration, material inventory discrepancies, radioactive wastes and many others. A few examples are mentioned in IAEA publications (e.g. Refs [1–3]), but the subject of unforeseen events during decommissioning has not been addressed systematically.

This publication sets out some of the examples of where unexpected events in a decommissioning programme have led to a need to either stop or reconsider the work, rethink the options and move forwards on a different path. Hence, this publication focuses on those events that may lead to serious consequences during decommissioning. As a reference publication, it details lessons learned in order to ensure that future decommissioning projects are sound, or in the event that unexpected problems are found, it is possible to compare them with similar difficulties experienced by others. By this means, the relevant lessons may be adopted in order to reduce additional costs, time delays and radiation exposures.

Unknowns in decommissioning cannot be eliminated, regardless of the efforts applied. This is especially the case in old facilities where documentation may have been lost, or where modifications were carried out without updates to the publications. As a result, when planning for decommissioning, it is prudent to assume that such problems will occur and ensure that arrangements are in place to deal with them when they arise. This approach will not only improve the efficiency of the decommissioning project, but will also improve the safety of the operations.

This publication considers the various phases during the life cycle of a nuclear facility that can ultimately lead to unexpected events during decommissioning: the design phase, the construction/commissioning phase, the plant operations phase, and finally, the decommissioning planning and implementation phases. Examples of actions, decisions or omissions during each of these four phases of the life of a facility are provided, and some analysis has been conducted in an attempt to identify the underlying issue(s) that may lead to unexpected difficulties during the decommissioning period. Extensive information and guidance has been provided on organizational and managerial factors as root causes for unexpected events.

The publication evaluates the need for implications of taking preparatory measures in view of possible occurrences, and separately how to mitigate the impacts should any such events occur. Specific areas assessed include the following, and guidance is provided for each of these:

— Organization;
— Funding;
— Planning;
— Legislation and regulations;
— Information;
— Training;
— Stakeholder involvement;
— Modifications to existing programmes.

This publication makes it clear that opportunities exist in all stages of the lifetime of a facility, to either increase or decrease the likelihood of unexpected events during the actual decommissioning. Care should therefore be taken at all stages of a plant's life to ensure that a decommissioning plan is produced, reviewed, used to inform routine modifications and kept up to date. Finally, regardless of the status of a facility, whether at the concept stage or at the decommissioning stage of its life cycle, it is never too early to begin thinking and planning for decommissioning.

1.2. OBJECTIVE

The objective of this publication is to assemble current and historical experiences reported worldwide, and to disseminate useful experience and lessons learned. It reviews and evaluates reported cases related to unexpected events.

A further objective of this publication is to classify and set out some of the examples of where unexpected findings in a decommissioning programme have led to a need to either stop or reconsider the work, rethink the options and move forwards on a different path. The publication focuses on those findings that may lead to serious operational consequences during decommissioning. By doing so, it is intended that future decommissioning teams may use this as a reference publication that details lessons learned in order to ensure that their decommissioning strategies are sound, or in the event that unforeseen difficulties occur, the decommissioners are able to compare them with similar difficulties experienced by others. This will enable them to adopt the relevant lessons in order to reduce additional costs, time delays and radiation exposures.

In addition to identifying unexpected events, this publication also identifies steps that could have been taken by those involved to anticipate the events, thus avoiding the need for mitigating actions, often at short notice. This may help those planning decommissioning programmes to anticipate the problems encountered by others and plan to avoid them. One of the key messages of this publication is that it is never too early to begin planning for decommissioning. Therefore, another objective of the publication is to be useful to organizations at all stages of the life cycle of a plant, including the early stages of design and construction, to help them consider the ultimate need to decommission, and to plan for decommissioning. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3. SCOPE

The nature of unexpected events in nuclear decommissioning is very variable. This publication covers the most typical events that have been recorded, with a focus on those with radiological implications, it brings together the experiences from a number of decommissioning programmes and gives examples of where unexpected events were encountered. It identifies the nature of the events and the solutions developed by those involved, and provides lessons learned. Sources of information include technical literature and personal experience provided by the experts who contributed to the drafting of this publication. It is intended that future decommissioning programmes, encountering unexpected situations, may find the experiences described in this publication useful, in helping them to determine suitable mitigation activities.

This publication does not deal with risk management per se, but there is a close link between unexpected events and risk management. The reader can use many of the features and experiences contained within this publication to mitigate the risks that are associated with unexpected events that may occur in decommissioning projects, and also as a guide to anticipating risks that may, in the normal course of events, have been overlooked or unimagined.

This publication is not intended to cover every possible unforeseen situation. There are many unforeseeable issues that may arise during a decommissioning project, which can result in delays, cost overruns and other undesirable effects. These can, for example, include loss or reduction in funding availability, changes in national/international legislation, and changes in local regulatory processes and standards. These effects cannot be categorized in the same way as technical issues, and are not included in this publication.

Decommissioning after severe accidents carries with it a special set of uncertainties, because the fundamental configuration of the plant is usually changed, or at least is suspect. This requires a different approach to the preparation of decommissioning plans, and is not covered specifically in this publication, but generic considerations are given in Appendix I.

For ease of use, it is important to have a structure that creates taxonomy (see also Section 6) of unexpected events. This could be achieved in several ways; however, in this publication, the unexpected events have been grouped to reflect the project life cycle in which the root cause was either embedded in the original design, or was created during the construction/commissioning phase, during the operations phase or during the decommissioning process itself.

The experiences gained during these various phases in identifying and resolving possible unexpected events are recorded and considered to estimate the impact on safety, timing and costs, and to suggest provisions and contingencies to manage them.

This publication applies to all types of facility, including nuclear power plants, research reactors, fuel cycle facilities, manufacturing plants, medical facilities, research and university laboratories, and other research facilities. It does not apply to mill tailings, waste disposal sites or waste repositories. The closure of these facilities is discussed in other IAEA publications.

Unexpected findings during decommissioning are not necessarily linked to any specific type of nuclear facility, but are more connected with the age, history and operational behaviour of plants, and inadequate maintenance or inspection procedures. Research facilities where regular experimentation has resulted in many modifications over a prolonged period of time tend to be more prone to the discovery of unexpected problems than sites such as nuclear power plants where operations were routine. Nuclear power plant sites are not, however, immune to problems.

1.4. STRUCTURE

The structure of this publication takes the reader through the various aspects of decommissioning unknowns that need to be considered. Background material detailing the context of the publication is given in Section 1.1 above, and is followed by details of its objective and scope. Section 2 introduces a selection of typical actions that can have unforeseen consequences in decommissioning and which originate in the various stages in the life cycle of a nuclear facility. Section 3 then details the general criteria and factors relating to how the various discoveries can be addressed in practice.

Sections 4 and 5 should be viewed in parallel. Section 4 describes the infrastructure and provisions to prepare for an unexpected event, while Section 5 highlights how such arrangements should be employed and how to tackle the unexpected event, should it occur in practice. Section 6 presents the various lessons learned from specific examples of unknowns experienced across a range of decommissioning projects. Conclusions are given in Section 7.

Appendix I gives guidance on the situation where a plant is being decommissioned following a severe accident. Appendix II provides guidance on the use of robotic devices, because these are frequently used to overcome access problems associated with unexpected events and associated severe contamination. The appendices are followed by a list of references cited in the main text.

Illustrative cases are given in the annexes, which detail various international case histories relevant to the scope of this publication.

Finally, a glossary of terms and a list of abbreviations used in the publication are given.

2. ORIGINS OF UNEXPECTED EVENTS EXPERIENCED DURING DECOMMISSIONING

In preparing this publication, the life cycle of a plant was used to categorize the origins of actions that resulted in unexpected events during decommissioning.

For the purposes of this publication, the life cycle is defined as consisting of the following four phases (relevant aspects of these phases are given in brackets):

- Design (CM, material selection, plant layout, plant services, pipework and cable runs, housekeeping support);
- Construction and commissioning (site layout, construction infrastructure, temporary utilities);
- Operations (normal and abnormal operations);
- Decommissioning (decommissioning planning, characterization, decommissioning activities, waste management operations, operator versus contractor interactions).

Examples of actions, decisions or omissions during each of these four phases of the life of a facility are provided, and some analysis has been conducted in an attempt to identify the underlying issue(s) that led to unexpected difficulties during the decommissioning period.

2.1. UNEXPECTED EVENTS ORIGINATING DURING THE DESIGN PHASE

During the design phase of early nuclear facilities, the focus was on making the plant operate, and little attention was paid to the inevitable decommissioning that would be required at the end of the plant lifetime. Even with the limited knowledge that was available at that time, some foresight could have been applied that would have resulted in the inclusion of design features, or simple modifications to designs, that could have saved a great deal of time and money and resulted in better optimization of radiation protection during decommissioning. It is important that lessons learned from decommissioning projects are carried forward into the design of new facilities [4].

There are many examples of the occurrence of unexpected issues in decommissioning that could have been avoided at the design stage. Some of the design principles that can be applied are given here; however, much of the detail may be project specific, and is contained in Section 6 and the annexes.

2.1.1. Configuration management

Regardless of the design that is being implemented, management of the design configuration is essential, not only to ensure that the design is fit for purpose and has been developed in a safe and controlled fashion, but also to ensure that the decommissioning plan reflects the as-built status of the plant.

2.1.1.1. Overview

In many older nuclear power plants and facilities using nuclear materials, documentation containing the design basis or safety information may be widely dispersed, contain errors or be lost or non-existent, even though the plant may have been functioning for an extended period of time. Furthermore, after several years of plant operation, including the cumulative effects of maintenance, modifications, obsolescence and upgrades, there may not be a high degree of assurance that the facility configuration information still reflects the actual plant status. In the absence of a CM programme, the design basis, supporting reports (e.g. drawings, modifications and design codes) and physical plant layout may have diverged over time, creating special challenges and unknowns that must be dealt with at the time of decommissioning. The potential for loss of configuration control is highest in plants that are subject to constant development, such as research and prototype facilities.

CM is defined as the process of identifying design requirements (what is required), facility configuration documentation [5] (what is said to be there) and physical configuration of the facility (what is actually there). Effectively integrating CM principles at the design phase of any nuclear facility is a fundamental safety requirement; it will promote and ensure consistency during construction, commissioning and operation, and will reduce the potential for unknowns during decommissioning. In general, facilities that have weak CM are likely to be legacy facilities — modern facilities are expected to be fully compliant with the CM criteria.

CM recognizes that the three elements (design requirements, facility configuration documentation and physical configuration) must be in equilibrium, as illustrated in Fig. 1 [6].

Design requirements are technical requirements, derived from the user specification, relevant technical standards, regulatory requirements and the design process, which impose limits on the final design, including the consideration of safety margins and the operating envelope, and which are reflected in the design documentation. Design requirements to be documented could include those that affect:

— Function;
— Installation;
— Performance;
— Operation;
— Maintenance;
— Decommissioning.

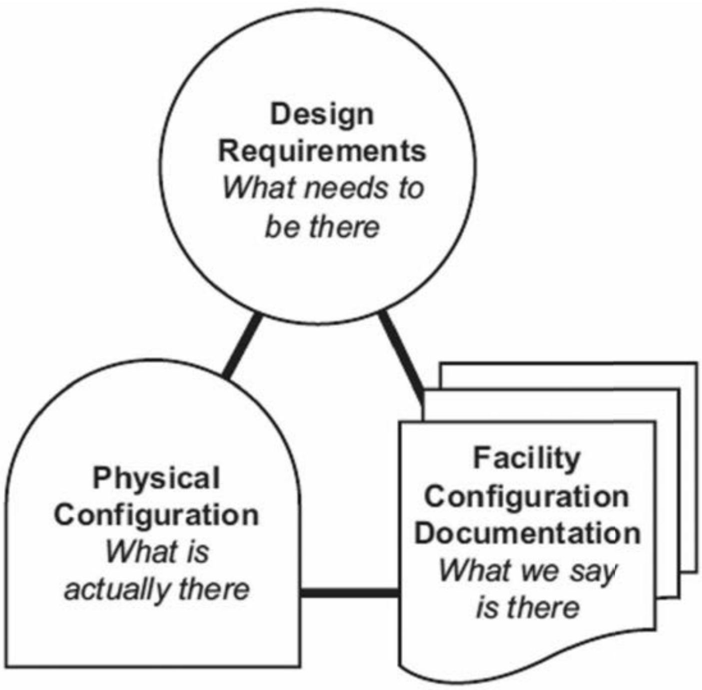

FIG. 1. Configuration management equilibrium model.

Facility configuration documentation is the set of all publications that contain configuration information defining how the plant was designed, how it was operated and how it was maintained. Facility configuration publications include:

- — Design documentation (calculations, material selection criteria, functional requirements, etc.);
- — Operating procedures;
- — Maintenance procedures;
- — Surveillance procedures;
- — Drawings;
- — Procurement documents;
- — Training documents;
- — Regulatory documents.

Physical configuration applies to the installed and subsequently commissioned structures, systems and components (SSCs), to the physical configuration and to the actual physical location.

2.1.1.2. Configuration management controls

Decommissioning may be regarded as a major modification, resulting in changes to the plant to be decommissioned. In many cases, the plant will not be able to be decommissioned as it stands, and will need to be modified by the inclusion of, for example, additional access ports, additional heating, ventilation and air-conditioning (HVAC), new services such as power and, often, new/additional shielding. It is essential that the plant configuration should be accurately known before these modifications are planned and implemented; this, in itself, requires that a competent CM system be in place early in the decommissioning planning phase.

When this CM fails, it can result in costly delays. For example, during decommissioning of the old hot laundry, CFA-669, located at the Idaho National Engineering Laboratory, Idaho, USA, in the central facilities area, containers of various chemicals were left in the boiler room when CFA-669 was shut down in 1981. The labels on some of these containers were missing, and some containers were in poor physical condition. Disposal of these chemicals required considerable time and effort, resulting in unanticipated costs and project delays, because the chemicals were not identified and documented during predecommissioning and decommissioning characterization [7].

The steps below are typical of the CM processes that are commonly employed.

2.1.2. Material selection

During the design phase of a nuclear project, the selection of low activation materials [4, 8, 9] will simplify the decommissioning activities. In cases where the purity of an essential material cannot be guaranteed, consideration should be given to the activation species that will be produced, and, in particular, their activity levels and half-lives. A careful selection of reactor materials may avoid or minimize problems such as those being faced in the decommissioning of light water reactors where ^{60}Co is generally the critical radionuclide during the dismantling and removal of activated components. In modern designs, the cobalt contents are kept to a minimum. Similarly, in decommissioning graphite moderated reactors, ^{36}Cl is a major problem for radioactive waste disposal, and the concentration of precursor elements should be minimized.

In addition to material selection to minimize activation, selection of materials that are not prone to contamination or that are easy to decontaminate should also be encouraged, as this will facilitate decommissioning. Not all of the unexpected events in decommissioning are associated with radioactivity. Other hazardous materials such as asbestos or polychlorinated biphenyls (PCBs) should also be avoided, unless there are no alternatives. In such cases, arrangements should be made to deal safely with the material at the end of life. If there is a possibility of the hazardous material becoming activated or contaminated, a dedicated waste management plan and waste route to disposal should be included in the design and be subject to CM during the lifetime of the plant (see Sections 6.9, 6.32, 6.35 and 6.37).

In early pond designs, concrete was simply painted with waterproof paint, but over time, this deteriorated and resulted in significant contamination of the bulk concrete of the walls. Stainless steel liners are now the preferred method of avoiding such contamination. Other lower cost solutions may also be available; however, the possibility of dry storage of materials and avoidance of contamination of pond water should also be considered at the design stage.

Some materials are more prone to corrosion than others. In the event that they become activated, their corrosion products can become mobile and result in extensive contamination, which may even extend beyond the boundaries of the facility.

After a long period of disuse, corrosion can significantly affect structure and impair the performance of systems that are expected to support decommissioning. Figure 2 shows corrosion in a spent fuel pond at the Vinča research reactor, Serbia.

2.1.3. Plant layout

The responsibility for the layout of a nuclear facility typically lies with the plant designer. The criteria that the plant designer uses to locate buildings are many and varied, and are usually associated with enabling the construction to be accomplished and making the facility work in an optimum fashion. In particular, the need to minimize transport routes for nuclear materials and radioactive waste is usually given significant thought.

These requirements are, however, moderated by the need to fit all of the required plants onto the available footprint of the site and to ensure that the optimum construction sequence can be achieved.

However, it is also important to consider the decommissioning of the site and to allow space for access of decommissioning plant and equipment, for the transport of radioactive waste and also for the temporary storage of radioactive waste during the decommissioning period. Considering the decommissioning sequence as well as the construction sequence may allow some buildings to be used as waste treatment and/or storage facilities later, and their location and design at the outset to facilitate this should be taken into account (see example in Fig. 3).

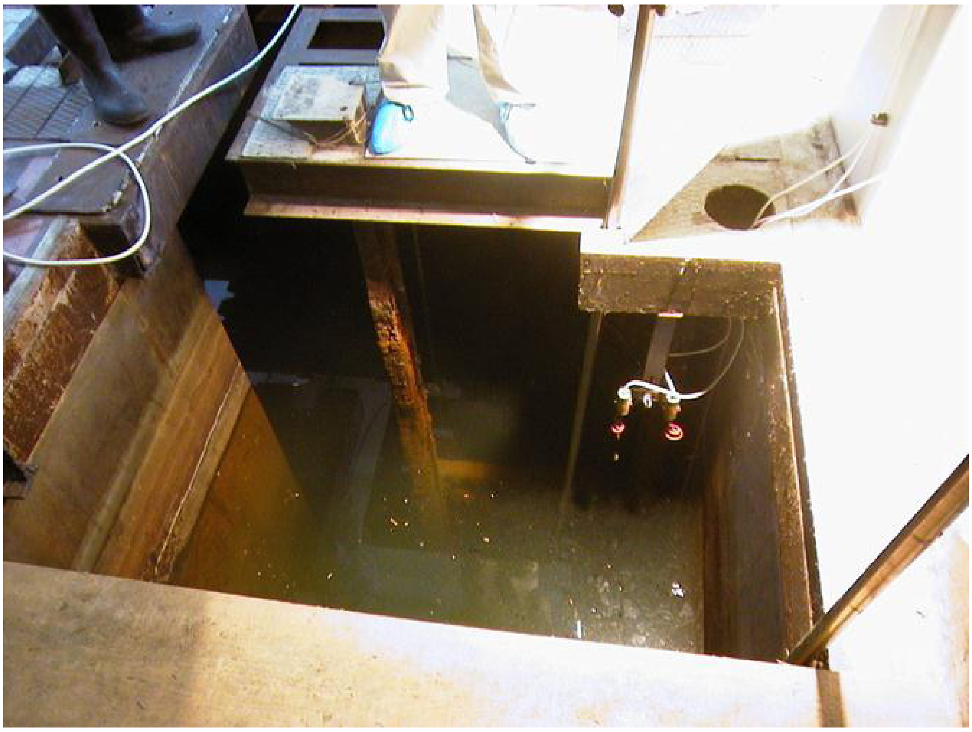

FIG. 2. Corrosion in a pond structure, Vinča research reactor, Serbia.

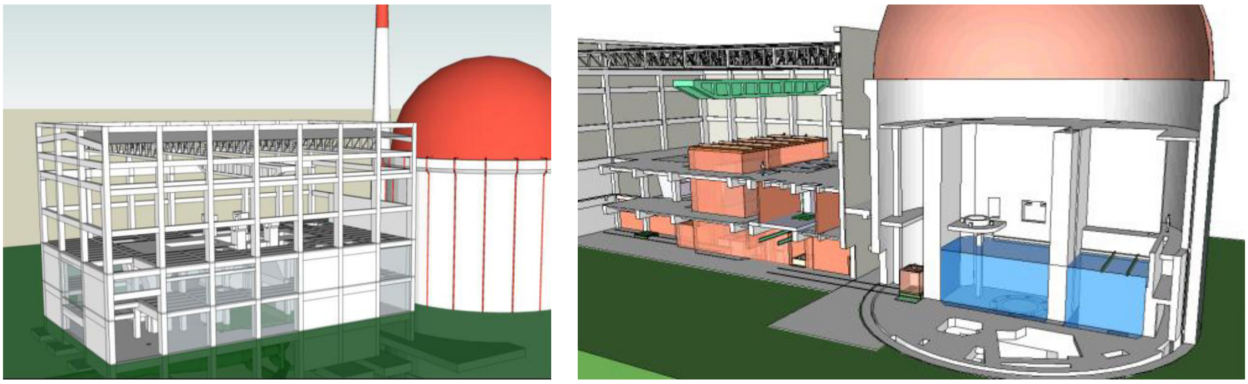

FIG. 3. Conversion of turbine building into an auxiliary installation for treatment, conditioning and storage of radioactive waste, José Cabrera nuclear power plant, Spain. Images courtesy of Enresa.

FIG. 4. A nuclear site with chimneys, Palindaba, South Africa; photograph courtesy of NECSA.

In particular, where tall buildings and chimneys are required (see example in Fig. 4), the location of other buildings in their vicinity should be considered, to ensure that the chimneys can be decommissioned and demolished safely, without posing a risk to other buildings nearby. Ideally, the decommissioning sequence should involve removing the other buildings first and then allowing the chimneys to be demolished safely and efficiently.

Experience has shown that accidents may happen or that unexpected events may occur when the decommissioning staff are required to work at heights above ground level. If possible, during the design of a facility, the opportunity should be taken to maximize the extent of work that can be carried out at ground level, and when decommissioning is planned, it should be done in such a way that the time spent at height is minimized. As an additional safeguard, when working at height cannot be avoided, the provision of adequate, permanent stairways and working platforms should be considered, where possible. In addition, provision should be made for the installation of lifting equipment by which people or large, heavy items can be raised or lowered safely to the ground.

2.1.4. Plant services

Services, such as electrical power, water and other fluids, HVAC ducting and others, often connect buildings together. Considering the decommissioning sequence at the time of design will enable isolation of these to be carried out efficiently and with confidence, so that buildings can be isolated in turn, without disrupting the performance of other buildings that may still have an operational role. This is particularly true of multiunit nuclear power plants and chemical process plants where several chemical processes are carried out in sequence in connected plants.

2.1.5. Pipework and cable runs

Embedded or buried pipework and cabling present particular problems unless very careful CM of the design drawings is undertaken. A visually inspectable cable or pipe is beneficial, and will make verification of competent isolation and safety easier. This has to be weighed against the integrity of the pipe or cable during the lifetime of the plant, because embedding and burying are accepted methods of protection.

Underground buried tanks and pipes have been extensively installed in most nuclear facilities to take advantage of gravity flow and avoid the use of pumps for the transfer of radioactive liquids. In some cases, this has resulted in leakage and contamination of the environment, which is only discovered at the time of decommissioning. State of the art design prescribes that any underground/buried components should be contained in lined or coated structures and that coaxial pipes should be used to carry such liquids.

Another common source of unexpected events during decommissioning is associated with highly congested services in a room (see example in Fig. 5). Often, cables, pipes and vessels are located close to one another to minimize the space required. However, during decommissioning, this can lead to difficulties because it may not be easy to identify which pipe, cable or vessel is isolated and available for decommissioning. During the design phase, consideration should be given to the ease with which such services can be identified to ensure that they can be isolated and decommissioned without danger. In the case of pipes, vessels, pumps and valves, which may contain radioactive fluids, it is possible that one item shields another, thus making it difficult to be certain which one represents the radiation source.

FIG. 5. Example of congested room layout posing difficulties for decommissioning.

Ensuring that loops in pipes, where unavoidable, are fitted with drainage points will make emptying and flushing of pipework easier, whereas active liquids trapped in such pipes can be problematic and expensive to remove, and may result in decommissioning staff doses being increased unnecessarily (see also Sections 6.4, 6.18, 6.21 and 6.34).

2.1.6. Housekeeping support

It should be borne in mind that within controlled areas, any waste material that accumulates has the potential to be considered as radioactive waste. Leaving small gaps in structures and areas where wind borne waste can accumulate should be avoided, because this will increase the potential for material buildup and waste creation.

2.2. UNEXPECTED EVENTS ORIGINATING DURING CONSTRUCTION AND COMMISSIONING

During construction of nuclear facilities, opportunities are often taken to change plant designs to improve performance and safety, or to correct design errors. In some cases, these changes may seem trivial and represent an improvement; however, they can have a detrimental effect on the ability to decommission. In addition, if such modifications seem trivial, the change may not be documented, as a result of which, an unexpected event may arise during decommissioning. One example of this type of unexpected event is related to a decision to fully weld bolts to prevent their loosening, when the original design drawings had called for them to be only point welded. However, the drawings were not updated, and so the decommissioning plan resulted in the design and manufacture of remote equipment that was only powerful enough to break point welds. This had to be completely redesigned to cope with fully welded bolts when the modification was discovered [10].

2.2.1. Site layout

The detailed layout of the plant that is created during the design phase may also have been changed during the construction phase if, for example, ground conditions are discovered that require an individual plant within a larger facility to be relocated. Care must then be taken to ensure that the significance of the relocation is fully considered from the standpoint of decommissioning, rather than assuming that if the design of the plant itself has not changed, the relocation will have no effect.

The decision to expand the facilities on sites may result in plants that have an acceptable safety case, but which may be located in positions where their proximity to other plant(s) that will be operational during the decommissioning phase makes decommissioning difficult or impossible. In such circumstances, it may be necessary to delay the decommissioning until the other operational plants are also ready to be decommissioned, resulting in the need to maintain redundant plants, often for many years, with attendant impacts on care and maintenance costs [4, 11]. An example of such facilities is illustrated in Fig. 6. It is also possible that the location or expansion of

FIG. 6. Jaslovske Bohunice nuclear site in Slovakia, with A1 and V1 nuclear power plants in the decommissioning phase and V2 nuclear power plant in operation. Photograph courtesy of JAVYS.

a plant will prevent access during decommissioning for the delivery of decommissioning plant and equipment and the removal of waste materials, or at least result in increased costs for these activities.

2.2.2. Construction infrastructure and temporary utilities

The construction phase of a nuclear plant requires the installation of many temporary services such as power, water, compressed gas and others. It has been common practice in old plants to disconnect these when the permanent facility services are installed and commissioned, and then to simply leave them in the ground. Examples of these are given in Ref. [2].

If this is permitted, it is almost certain to lead to unexpected and undocumented services being discovered later in the operational life of the plant, and almost certainly during decommissioning.

Discovering an unexpected cable will result in a delay while it is traced and proven to be redundant. In the absence of detailed drawings, it may be necessary to excavate a significant length of the cable to prove that it is no longer connected. Inadvertently encountering live wires during decommissioning can also have more serious consequences (see also Sections 6.20 and 6.23).

There have also been instances of buried diesel tanks, fuel pipes and other buried services that were used during the construction phase and which still contained diesel or diesel residues. Often, such tanks will have corroded, and the potential then exists for safety issues, environmental discharges and the creation of mixed waste, if the land is also contaminated with radioactive material.

2.3. UNEXPECTED EVENTS ORIGINATING DURING OPERATIONS

Even where the original design of a facility has, to some extent, taken decommissioning into account, changes may take place during operations that can have a profound effect on the ease with which the facility can be decommissioned later. Operations can be split into normal and abnormal, with significant differences between the two.

Normal operations not only result in the activation and/or contamination of plant items, but may also produce changes in the status of the plant as a result of plant modifications. This is especially common for research reactors. In some of the older facilities that were designed, constructed and operated before nuclear knowledge reached its current state, even normal operation of the plant created unforeseen difficulties. An example of this is the Dounreay fast reactor in the UK, where the metallic breeder fuel elements bowed in the neutron flux and are now stuck. This fact has been known for many years, so the current decommissioning plan has an activity associated with the stuck breeder removal. Even here, the actual state of the plant has led to some late changes to the decommissioning plan [12].

Abnormal operations are difficult to legislate for in the initial design of the plant, although this concept is now incorporated into new reactors, for example, generation III/generation III+ reactors. A good example of this approach is the inclusion of a core catcher facility below the reactor cores of new light water reactors. These are designed to contain molten core components — corium [13].

For lesser accidents, the impact on the decommissioning plan can still be significant. At the Bohunice A1 nuclear power plant, Slovakia, the failure of a fuel element resulted in significant contamination of the primary circuit with plate-out of fission products (FPs) in a variety of locations. While this was not as dramatic as a complete core failure and meltdown, the impact of the accident on the decommissioning plan for the reactor was very significant (see Section 2.3.2).

Therefore, dealing with unknowns that arise as a result of the operational regime of the plant is important, and requires the operator to maintain an accurate log of the operations that took place and, if possible, the consequences for the plant. Similarly, when creating a decommissioning plan, it will be important to obtain the detailed operations logs and predict the status of the plant in order to minimize the appearance of unknowns during the decommissioning operations themselves.

2.3.1. Normal operations

In normal operations, one of the main impacts for decommissioning is associated with irradiation effects. This is true of most plants, but particularly true in the case of reactors where neutron irradiation can have a major impact on the characteristics of materials. The effects of neutron irradiation are well known and documented, but there have been examples where a material was selected for use in a reactor and subsequently caused higher than necessary radiation levels during decommissioning (e.g. the use of Stellite valve faces in water reactors causing deposition of cobalt rich crud inside cooling circuits).

Contamination of materials is also an important consequence of operations. Items that were clean when they entered the plant are often contaminated as a result of being in controlled areas. This is particularly true in the case of reprocessing plants where the fuel cladding is deliberately breached. Contamination is often very mobile, and it is common to find that areas where there should have been no contamination have, in fact, become contaminated. If this is not discovered until the decommissioning programme begins, it can have a very severe impact on the programme and often results in the need for activities to be carried out remotely or using robotic equipment, when this was not originally planned.

The operation of nuclear facilities generally creates radioactive waste. The volume of this and its nature will be a function of the nature of the plant in question, and, more importantly, the disposition route will be a function of the nature of the waste.

A typical issue at research reactors is the generation of waste during experiments and other one-off activities. Experience shows that, in many cases, experimental apparatus and secondary waste (e.g. contaminated trash, filters) are left behind, often undocumented, following completion of the experiments. This is a serious complication for decommissioning, which may start decades after the conduction of experiments, when any recollection of their origin is lost. Good housekeeping is essential for timely start and smooth implementation of decommissioning. Moreover, massive amounts of uncharacterized material create a potential for unexpected events.

In some cases, operational wastes have been created for which there are no straightforward disposition routes. Examples of this are the core and fuel element graphite for the Magnox reactors and advanced gas cooled reactors (AGRs) in the UK and high-power channel-type (RBMK) reactors in other locations. Until the disposition route for this material, which has an extremely long half-life, is identified, the core graphite is being retained inside the reactor pressure vessel. This is one of a number of factors that govern the deferred dismantling strategy for these reactors. The fuel element graphite (e.g. sleeves) is typically being stored in on-site temporary intermediate level waste stores (see example in Fig. 7).

FIG. 7. Dismantling of a graphite silo, Vandéllos 1 nuclear power plant, Spain. Photograph courtesy of Enresa.

There are cost implications for maintaining these reactors in a safe condition for an extended period of time, and, in the absence of a proven disposition route for graphite, it is not possible to assign an accurate cost to graphite disposal at the present time.

Mixed wastes are also a problem that can emerge late in the planning for decommissioning. During normal operations, oil, PCBs and other materials can become mixed with radioactive materials. Some of these (e.g. PCBs) are extremely difficult to dispose of safely, and when they are contaminated with radioactive species, the problem is greatly compounded.

Sites where the nuclear facility was constructed on a formerly used site can present similar problems. In the UK, many of the early nuclear facilities were constructed on former World War II military aerodromes. These had underground fuel pipes running from storage areas to fuel distribution points across the site, and in the years since their construction, they have leaked fuel oil into the ground. This is difficult to deal with in normal circumstances, but if the soil has also been contaminated as a result of nuclear operations, the problem can be very much worse.

2.3.2. Abnormal operations

In the event of an incident or accident at a nuclear facility, the extent to which the operators are able to control the outcome will be dependent upon the nature of the fault. At Chernobyl Unit 4, Ukraine, the operators had little opportunity to take actions that would have affected the ease of decommissioning, while at Three Mile Island Unit 2 (TMI-2), Pennsylvania, USA, the operators managed to effectively contain most of the contamination within the reactor pressure vessel, reducing the leakage of radioactive species to a very low level. In contrast, the accident at Windscale pile 1, UK, in 1957, spread contamination outside of the site, and has created a variety of unknowns for decommissioning (see Annex IV–2).

Similarly, during the first accident at Bohunice A1 nuclear power plant in 1976, operators were able to close the open fuel channel of the reactor by using the refuelling machine, and thus avoided a significant loss of coolant and potentially huge spread of contamination. However, in the second accident in 1977, the development of the accident scenario was out of their control. Partial melting of the active core occurred, contaminating the primary circuit. The secondary circuit then became contaminated through leakage in the steam generators [14].

There have been numerous other incidents where a relatively minor accident, which caused no injury, had a disproportionate effect on the cost and timescale of decommissioning. This tends to be the case when there are highly mobile, highly active species involved, such as in reprocessing plants [15–17].

This publication does not consider the detailed decommissioning of facilities after severe accidents, but there are abnormal operations that may be low on the international nuclear event scale, which nevertheless can have significant impacts on the decommissioning plan for the facility. What is important is that when an accident does occur, the subsequent investigation should also consider the impacts on the decommissioning plan, and this plan should be updated to take into account all consequences of the event.

It is important to include some surprising impacts that can occur as a result of less severe abnormal events. If the public relations consequences of an event are significant, though the event itself is trivial, it can have a major impact on the way in which the site licensee is perceived by the public, and the regulator may feel inclined to take extreme action (Annex IV–1.3).

2.4. UNEXPECTED EVENTS ORIGINATING DURING DECOMMISSIONING

This section deals with unexpected events that have been identified during decommissioning projects, where the underlying cause is not traceable back to the design, construction/commissioning or operations phases.

Decommissioning requires careful planning, and unexpected events originating during the decommissioning programme, when they occur, are usually caused either by inadequate planning or by some failure of those concerned to follow the procedures set out in the plan. Either way, this usually results in project delays and cost increases, and could result in additional dose uptake by decommissioning staff.

2.4.1. Decommissioning planning

A key element of successful decommissioning is early, proper, accurate and complete planning, including estimates of necessary funds to complete the task safely. However, unexpected events make additional demands on funding, requiring contingency funds to be set aside and made available in the event that they are needed. Some methods of reducing the likelihood or impact of unexpected events are given below. These can reduce the impact on the decommissioning programme, reduce the potential dose uptake to the staff and also reduce the amount of contingency funding that must be set aside in case of need.

Planning can only be as good as the input of all collected information. Good planning requires accurate knowledge of the site, including verification of the as-built set of drawings, systems, equipment and historical operational documentation. Sources of information for planning include construction drawings, commissioning data, operations logs, core power history, calculations of activity, maintenance records, modification documentation, and descriptions and reports from any incidents during operation. It cannot be overemphasized that it is never too early to begin the decommissioning planning process [18].

Contacting former employees can also provide valuable historical information about the site, which is often missing, especially when the facilities are very old, of prototype character and/or were associated with weapons programmes where secrecy often reduced the extent to which some events were recorded and documented. In such cases, employees of these facilities retire, taking valuable and typically undocumented experiences with them. The term tacit knowledge is often used in the literature to refer to this concept [19].

Significant numbers of personnel and quantities of material resources are needed to recapture and/or recreate this type of lost and undocumented information by rehiring retirees. Nonetheless, while such recollections may be useful, they need to be checked, as it has been found that different employees often have widely differing recollections of the same event.

In some cases, the information necessary to support safe and efficient decommissioning may not be available. In these cases, it may be possible to obtain the information during normal operations as a precursor to decommissioning and store this in a dedicated decommissioning database to be used to plan decommissioning later [3, 20]. A way to avoid unknowns from incomplete or missing drawings is to use three dimensional (3-D) computer aided design (CAD) documentation, based on scans, digital photographs and high resolution imaging systems, to construct detailed images of the current state of the plant. This is particularly useful when the quality, completeness or accuracy of historical drawings is either not known or doubted. Scanning of large areas is, nowadays, commonly used to verify existing drawings and replace any that are missing or significantly out of date (see example in Fig. 8).

This procedure was used as an alternative to entering confined spaces at the Idaho National Engineering and Environmental Laboratory (INEEL), to obtain data on equipment tags, part numbers and configuration [21]. Digital cameras were used from outside the confined space, eliminating the need for entry by decommissioning staff. This technique has been used to photograph equipment tags of size 6 mm^2, thus avoiding radiation exposures that would otherwise have been necessary to obtain the data.

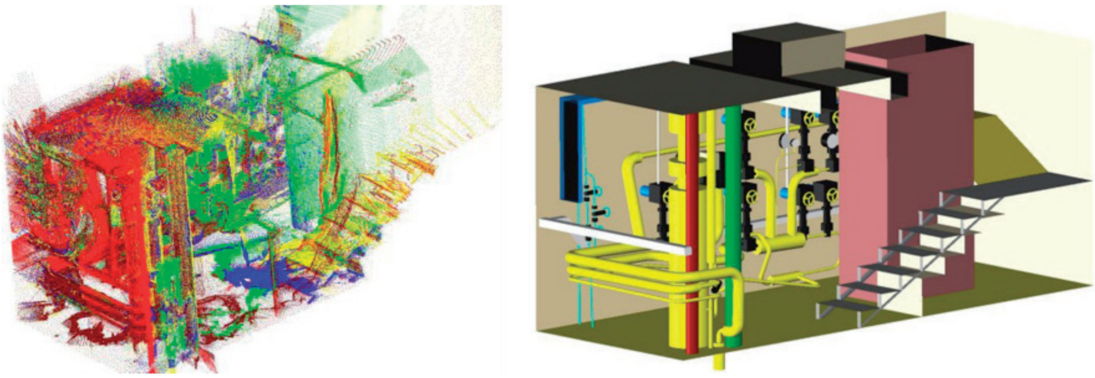

FIG. 8. Example of laser scanning output applied to A1 nuclear power plant, Bohunice, Slovakia. On the left is an example of the direct output of a laser scanner (cloud of points) and on the right is a 3D model created from the cloud of points. Images courtesy of VÚJE.

An important element of decommissioning planning to avoid unexpected events is to ensure that the decommissioning planning is complete. The duty of plant and equipment that have been used to support normal operations may not be suitable for decommissioning. Examples include cranes and other handling equipment.

Weights that were acceptable during operations may be exceeded in decommissioning as a result of the need to move shielded flasks, or the official certification of a lifting device may have lapsed and/or the device may be defective. Adequate decommissioning planning will include an assessment of the suitability of all such equipment for its new decommissioning role.

In principle, any available information source should be used to resolve unknowns and mitigate unexpected events during decommissioning. Theoretical models, based on results of tests, are generally needed when sampling is not routinely possible. A good example of this type of work is the calculation of the activation of components in research and power reactors, which is needed to estimate the total amount of activation in a reactor prior to decommissioning. The modelling and calculation results depend, to a large extent, upon existing operational data (e.g. neutron flux, fuel burnup rate). For the calculations, commercially available computer codes are available. Codes such as MCNP or SCALE are commonly used, but require dedicated training; more complex codes may require specialist involvement.

While the calculation of the activation penetration into bioshields can be undertaken using computer codes, this approach should, where possible, be assisted and/or verified by taking core drilling samples.

Computer codes supporting decommissioning and 3-D modelling are now in common use to visualize the dismantling processes in order to avoid the collision of tools with obstacles, simulating accessibility to dismantling areas, as well as the transport of empty and filled packages such as drums, casks or vessels. Halden Planner Tools, developed by the Halden Institute in Norway, make it possible to calculate predicted radiation doses associated with different scenarios for recovery from an unexpected event, enabling the one with the lowest dose to be selected. This type of work is very useful in high radiation areas with limited or restricted access, but depends, to a large extent, upon the quality of the existing documentation, as-built drawings, details of equipment installed, etc.

The RadMap system incorporates geometrical, radiological and material information into an as-built CAD system [22]. The 3-D data acquisition, verification and finally the reconstruction of the geometry are performed with a laser scanner. The radiological data acquisition, based on gamma spectrometry and exposure measurements, is performed with a sensor that enables the operator to localize, identify and quantify gamma ray hot spots. The radiological and material/component data obtained by this process are encoded and formatted in a CAD model. The gamma spectrometry data are analysed by dosimetry software and converted to create a complete radiological model of the target environment. The data are processed in specially developed software modules to calculate the expected radiation exposures in the 3-D space.

Another module compares different potential intervention scenarios, and, at the simplest level, engineering plans and radiation maps are produced. With systems of this type, it is possible to optimize the radiation exposures of the personnel involved and to limit the number of unknowns in decommissioning.

A further example is VISIPLAN, a dose assessment software program developed by SCK•CEN, Belgium, to assist the as low as reasonably achievable (ALARA) analyst in work planning studies [23]. VISIPLAN assists both in the calculation and in the communication of radiological information to demonstrate the ALARA principle (see example in Fig. 9). A similar application, consisting of a static CAD based definition of the working environment, and a dynamic part involving the interactions of the workforce, tools and materials with the CAD based work environment, was produced for the Japan Atomic Energy Research Institute Reprocessing Test Facility decommissioning project [24]. VISIPLAN has the following attributes:

— The code is based on a 3-D model, including material, geometry and sources;
— The point kernel dose calculation method, with buildup correction, is used;
— The code allows calculation of dose assessment for tasks, trajectories and scenarios, and it estimates individual and collective doses;
— Special tools are available for source sensitivity analysis and source strength determination from measured dose rate sets.

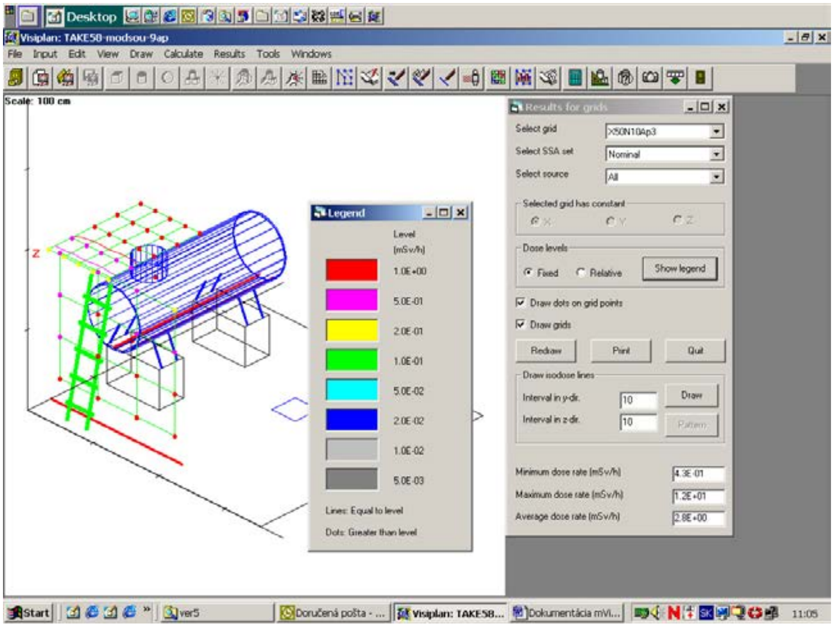

FIG. 9. Example of VISIPLAN calculation. Image courtesy of VÚJE.

Computer models may be used in combination with 3-D scanning systems to verify the actual situation before dismantling, and/or to complement the technical documentation. The equipment and the software needed are relatively expensive, but are commercially available and are becoming popular owing to their multiple potential uses.

The Halden Institute has developed virtual reality tools, which can be very effective in reducing dose uptake. These are particularly useful when work is required in high radiation areas by enabling the decommissioning staff to rehearse their activities in detail, thereby reducing the time spent in the radiation field.

Finally, it should be noted that poor management and organization may have a negative impact on safety performance and increase the likelihood of unexpected events. This includes factors such as:

— Schedule pressures, frequently shifting priorities, etc.;
— Unwillingness by workers to raise concerns;
— Motivational factors.

2.4.2. Characterization

The characterization of plant and materials plays an important role in the planning and execution of decommissioning activities. Inadequate characterization of the plant to be decommissioned has a very high probability of creating surprises when decommissioning begins. See Ref. [1] for an extensive treatment of characterization objectives, methods, instruments and experience.

Characterization is not only associated with the radioactive materials that may be found in a facility. It also includes the condition of the plant and equipment, the presence of non-radioactive but hazardous waste, and mixtures of hazardous and radioactive materials.

A direct (gamma radiation) survey is the primary means to radiologically characterize components and structures in view of decommissioning. One disadvantage of direct surveys is that they expose workers to radiation and should therefore be limited, in time and space, to what is really needed for decommissioning planning. In this regard, gamma cameras have become increasingly popular over the last 10–15 years, in order to reduce exposures to the surveyors and to focus attention on hot spots. However, gamma surveys are unable to provide much information about inaccessible components (e.g. those shielded by other components) or areas. Moreover, physical access for sampling remains essential to characterize alpha and weak beta radiation contamination. Samples may then be subject to radiochemical separation and are finally counted in a dedicated laboratory.

The ability to characterize a facility accurately may begin in advance of the decommissioning project, and must be the subject of a detailed characterization plan. The creation and maintenance of a characterization database may be a routine operation in some cases. The correct level of sampling must be determined to minimize costs. This may involve taking a smaller number of samples and using calculations to extrapolate or interpolate data from other parts of the plant. In such a case, the samples should be conserved under a management system to ensure that they remain available in case they are needed again to carry out further calculations, or for quality audit purposes. However, it is sometimes the case that the data required for decommissioning cannot be obtained until the decommissioning activity begins (e.g. radiation characteristics where the source may be temporarily shielded by water) (see also Section 6.34).

The characterization is so important that it is essential to prepare a characterization plan. This will not only include the sampling and investigation activities, but will also result in plans to have assay, analysis and testing facilities available on the decommissioning site, or where this is not feasible or is very expensive, to make alternative arrangements in advance of need.

For example, a reactor — especially a heavy water moderated reactor — will produce significant quantities of tritium during its lifetime. This can penetrate into the building structures, such as the concrete of the reactor building, producing a large volume of secondary radioactive waste. The extent of this may not always be documented, especially in older facilities and research reactors. These materials can have a significant impact later in the decontamination and release phase of the decommissioning process by increasing decontamination activities and waste volumes, adding to both time and cost. Although characterization is essential, its extent must be carefully managed. Characterization must be adequate to give confidence in the intended decommissioning method and its cost and duration; however, once sufficient information is obtained, there is little merit in continuing the process because the cost versus benefit gains may reduce. In some cases, tolerating the lack of information and increasing the level of supervision, monitoring and use of mechanical tools may be more cost effective than extending the characterization process.

In addition, care must be taken to ensure that characterization is also an element of decommissioning, which can, itself, result in unexpected events. For example, taking a sample of concrete from a wall could result in damage to a buried cable, or sampling soil could disturb or break a badly corroded pipe.

2.4.2.1. Hazardous material

Asbestos is a commonly identified problem in many facilities dating back to the 1960s or earlier. Asbestos removal procedures are well established in non-radiological environments; however, additional precautions are necessary when working in a radioactive environment (see example in Fig. 10). In addition, the means of disposal of contaminated asbestos must be considered. Only when a detailed understanding of the full nature of all waste streams has been prepared, and a waste management plan that deals with the materials from their creation to disposal created, will it be possible to plan, with confident timescales, the likely dose burden and cost.

PCBs are commonly found in many engineering environments, and this is equally true of nuclear facilities. Owing to their superior technical properties (e.g. water insolubility, fire resistance, long life, chemical stability, high thermal conductivity and elevated electrical resistance) and their low cost, PCBs have been widely used in many installations [25]. When such materials are used in controlled areas, they can become radioactively contaminated, and must be treated as hazardous radioactive material [26].

2.4.2.2. Uncertainties in physical characterization

Inaccessible rooms, channels, canals and underground structures are difficult to characterize because it may not be possible to take samples prior to actual removal of the component in question (see example in Fig. 11).

FIG. 10. Asbestos removal at Trino nuclear power plant, Italy.

FIG. 11. Removal of underground structures, Argonne National Laboratory, United States of America.

Characterization of the radioactivity content may have to be estimated by reference to operational radiological records, and design and as-built drawings (see Sections 6.6, 6.12–6.14 and 6.39). While these approaches may give an estimate of the activity to be anticipated, the actual levels may be significantly higher, leading to the need for a reassessment of decommissioning methods when decommissioning begins. Leakage of groundwater into and from such structures may also affect the levels of activity and their structural integrity. In the latter case, this can make decommissioning very difficult, as it may not be possible to enter the underground facility on safety grounds, thus making radiological characterization even more difficult.

2.4.2.3. Uncertainties in theoretical models used to support characterization

The estimation of the activation content in a reactor and its biological shield may be performed using computer codes. The results are dependent on the knowledge of the various material properties (e.g. trace element concentrations), as well as on the characteristics of the operation (e.g. neutron flux, cycle burnup and the modelling of the reactor geometry and/or biological shield). Missing data are replaced by assumptions, thus creating opportunities for misinterpretations and errors in modelling. In general, reactor activation models are increasingly inaccurate as the distance from the reactor core increases. The error margins in calculations will be exacerbated by such uncertainties, and safety considerations may lead to the adoption of a more conservative interpretation of the results. For example, a conservative interpretation may suggest that a high level of fissile material was consigned to a facility being emptied. As waste is removed, it is assayed, and the quantity of material found is very low. This could suggest that the remaining material is contained in a progressively reducing volume to the point where criticality becomes a major concern, while in reality, the actual quantity was much less than that predicted.

Modelling may nonetheless be used to estimate the level of activity likely to be found, in order to make a case for intrusive measurement, or, if the model shows that the radiation levels are unlikely to be high, to justify preparations for personnel entry to decontaminate before decommissioning. This approach may be particularly useful for alpha contaminated facilities where detection of the activity may be difficult; however, this once again depends upon the structural integrity of the facility as stated above. In general, models used to estimate concentrations and distributions of surface contamination are less reliable and more plant specific (thus requiring tailoring to the plant under characterization) than activation models.

2.4.3. Decommissioning activities

While potentially unexpected issues may be detected during the characterization stage of a decommissioning project, it is usually during the performance of decommissioning actions that unexpected events occur, and where their impact is greatest.

Examples of the discovery of problems late in the day are greatest where the issue is concealed. Typical examples include the presence of alpha contamination in areas where none should be present, for example, during the decommissioning of fuel cooling ponds. In the case of the alpha contaminated facilities, it may be difficult to measure the contamination from the outside, and only when a sampling survey is conducted before decommissioning starts is the contamination detected. Another frequent case is when an area that was assumed to be radiologically clean in the decommissioning plan is later found to have some residual contamination. This may be due to more sensitive detectors being available or more stringent release criteria being employed. This is an unwelcome, unexpected event that is likely to cause delays and increase decommissioning costs.

In the case of ponds, the presence of the water often shields highly active components to such an extent that their presence goes undetected. Where the pond water is clean with good visibility and no significant quantities of sludge are present, it is less likely that there will be a surprise in the decommissioning project. However, many ponds in old facilities have cloudy water, significant quantities of sludge, biological substances and discarded components, and it may be difficult to measure the activity levels from these (a wide range of issues related to pond decommissioning are reported in Ref. [27]).

2.4.3.1. Safety hazards from unexpected events

The manifestation of unknowns in decommissioning can include safety issues, environmental problems, waste disposition issues and technical difficulties that cause delays, often associated with the need to design a custom made solution to an unexpected problem. This subsection deals with some of the safety implications of unexpected issues during decommissioning.

Unknowns can inherently conceal conventional safety and radiological hazards, requiring precautionary measures to be undertaken. Old facilities that have not operated or have been kept under surveillance for long periods of time pose particular risks due to the unknown nature of some items of the plant.

In many cases, the lack of arrangements for the safe and environmentally acceptable disposition of waste has resulted in the accumulation of contaminated material, the condition of which may be difficult to assess during the predecommissioning characterization process. Even in countries with no nuclear power production, the decommissioning of plant and equipment involving sealed sources can often be more difficult, because these are more difficult to control.

The decommissioning of old facilities in countries with fewer resources poses particular problems. Their nuclear facilities often move from operation to decommissioning due to unforeseen political or economic reasons. In such an environment, the facilities may find it difficult to justify the significant expenditure on decommissioning, which has no perceived financial return.

Materials are often therefore packaged unprocessed in drums or similar containers and stored in unsuitable rooms, cooling ponds or other facilities, where shielding can be provided. This type of practice is rarely adequately documented. Over the years, corrosion processes in the packages can lead to undetected leakages or failures of the containers when they are moved, resulting in contamination and/or overexposure of operators, with the potential for ingestion posing a real threat to health. Radiolysis produces hydrogen, and the pressure buildup can result in chronic containment failure. The lack of climate control in buildings may subject the packages to pressure cycles as a result of room temperature variations. In the same way, humidity conditions can accelerate package degradation from the outside.

There are also conventional safety concerns when buildings such as these are used. Condensation from high humidity atmospheres can spread contamination, render floors dangerous and affect the integrity of electrical components.

Plants that have been abandoned may need to be recommissioned when decommissioning begins (see example in Fig. 12). This can be a hazardous process, and, in some cases, it may be more appropriate to design and install a new facility such as a crane or switchboard.

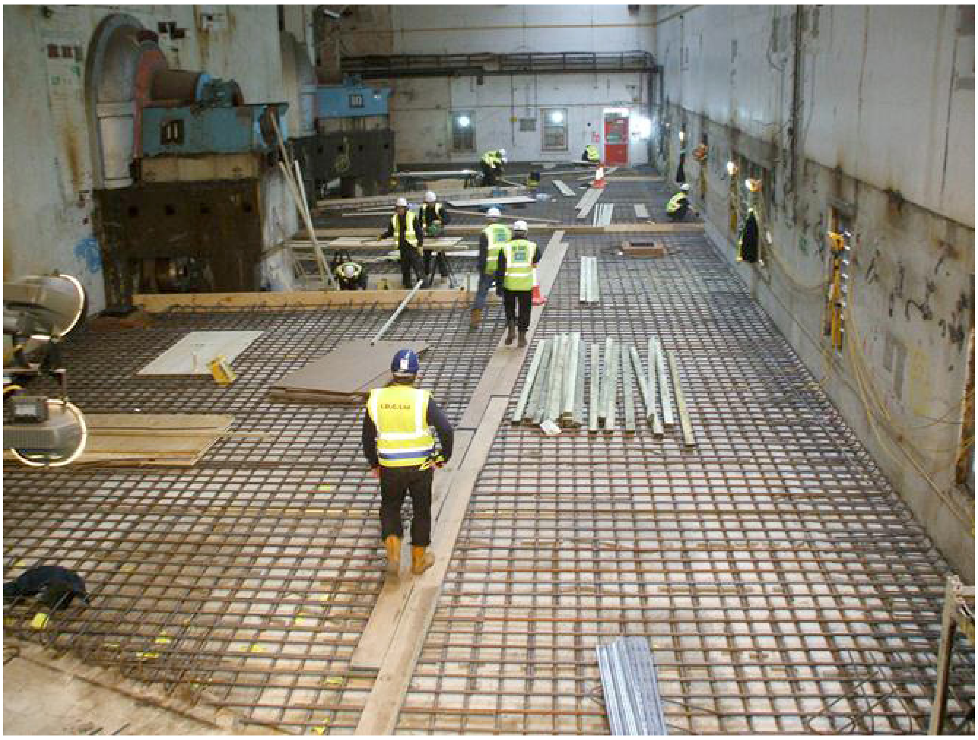

FIG. 12. Conversion of circulator halls for use as a storage facility at Bradwell nuclear power plant, United Kingdom. Photograph courtesy of Magnox Ltd.

If an accredited device, such as a crane, has not been subject to routine accreditation for a long period of time, it may be in an acceptable state, but it is not approved for use. Allowance must therefore be made in the decommissioning programme for a detailed inspection and requalification of such components, or the inclusion of funds and time in the programme to replace them. In some cases, areas can be converted to new uses that better fit the purposes of the decommissioning project.

Another safety concern of extreme importance is contaminated liquids. Even if facilities are declared to be dry, contaminants such as heavy water or sodium can still remain in small cavities, siphon-like pipes, compensators, etc., and can be discharged in an uncontrolled manner during dismantling, thus exposing workers (see Sections 6.4 and 6.21) and contaminating the surrounding areas. In addition to the safety of those involved in the operation, the unexpected release of such liquids may breach the environmental discharge authorization [1].

Poor or undocumented underground channels, pipes and electrical lines outside the facilities pose particular safety concerns. Contaminated liquids will naturally flow in pipes, channels and drains, but will also follow the routes of buried cables and pipes from the outside surface, even if the liquids in the pipes, etc., are not contaminated. Situations such as these pose the possibility of contaminating areas that were previously characterized as clean or assumed to be so, and their removal may adversely affect the operation of the other facilities that they serve. The details should be known from the design documentation, but modifications, repairs and loss of design information can lead to safety concerns, which, even if they do not occur, can slow down the decommissioning process.

2.4.3.2. Impacts of unexpected events on decommissioning schedules

The unforeseen events mentioned above, in addition to their safety significance, are likely to adversely affect the decommissioning schedule owing to the need to fully identify potentially live/contaminated services, trace their routes and effect a safe isolation. In addition, this often requires the remediation of contaminated ground before the decommissioning can commence (see example in Fig. 13).

Despite best efforts, in decommissioning, contamination incidents are not uncommon. The decontamination of large areas after an inadvertent discharge or migration of liquids or gases depends on the type and origin of the contaminants, the material of the structures or equipment, as well as the extent of the contaminated area. It is usually necessary to halt decommissioning and establish a restricted area until decontamination has been carried out or suitable control measures established. The contamination of plant that is essential to the decommissioning programme can be a particular problem. Machines such as robots or diggers are notoriously difficult and time consuming to decontaminate. Furthermore, the decontamination and the original spillage generate additional radioactive waste that may not have been considered in the decommissioning plan. In some cases, the extent of

FIG. 13. Measurement of soil after decontamination by the Moscow-region company Radon, Russian Federation.

this can be very large indeed. In particular, where ground contamination was unknown, the volume of waste can be considerable, and the cost of its remediation/disposal extremely high.

Contamination caused by leakages outside buildings can result in time consuming decontamination processes and, more often, remediation efforts involving the consignment of large quantities of soil as radioactive waste. Soil washing methods have been used in some locations. However, their effectiveness is often limited to reducing the level of waste, for example, from intermediate level to low level. While this may seem to be beneficial, because the specific activity is reduced, the volume tends to increase, so that the cost of disposal can still be very high. The cost of the treatment can be also significant [27].

Upon the discovery of leakage of radioactive material, immediate action is usually necessary in order to avoid further spread of the active plume increasing still further the volume of waste to be dealt with. Dealing with this waste can introduce severe delays to the decommissioning programme, add to the waste volumes produced and increase the overall decommissioning cost.

The use of equipment at the extremes of its design limits, after it has been in service for many years and then potentially left for some time, can lead to problems. Careful recommissioning is essential before use to support decommissioning, and, in many cases, replacement is a better option, assuming space exists to remove the old device and install a new one.

There are examples of where an unexpected event has been addressed too quickly by the staff, as a result of which the work undertaken has been unsuccessful, or, in some cases, has made the situation worse [12]. Some of the aims of this publication are to provide a series of examples of typical problems that are encountered, describe the remedial action taken and identify lessons learned, so that future decommissioning projects may avoid similar errors.

Although unexpected problems tend to be site and project specific, there are some generic problems that are likely to be encountered at specific decommissioning sites. As an example, fuel fabrication plants, designed in the distant past, almost always have uranium and americium that have penetrated deep into the plant base slab, and which sometimes have passed through it into the soil.

Some examples of inadequate characterization are given in Section 6 and the annexes.

2.4.3.3. Non-radiological unexpected events

Characterization does not only apply to the radiological condition of a plant or cell. A detailed knowledge of the state of the decommissioning equipment is also necessary if unexpected events are to be avoided. Equipment that has not been in service or subject to regular inspection for a long time needs to be thoroughly examined before use.

When decommissioning a facility within a larger building or site, it is usually necessary to isolate the power supply to the building and also to isolate other services such as water, drainage and pressurized gases. However, it is also usually necessary to have such services available to facilitate the decommissioning itself. Typical examples are the need for electrical power to supply lighting, breathing air to support airline suits and water to support decontamination.

There have been instances where the lack of accurate documentation of power supplies has led to incomplete isolation of power supplies (see numerous cases in Section 6) and other instances where the isolation of the supply has removed power from another facility where the power is needed (see the Dounreay 11 kV cable case in Annex IV–1.3). Preparing a plant for decommissioning may require the existing services to be isolated and new supplies to be installed, simply to support the decommissioning process. In these cases, once the supply has been completely isolated, the new supply should be run in a conspicuous location and colour coded to mark it as a temporary decommissioning supply. Once the decommissioning process is complete, it is then only necessary to remove the colour coded decommissioning supply, and the facility can be demolished.

The time required for the isolation of services and the installation of temporary supplies can be significant, and, where possible, service surveys should be carried out well in advance of the decommissioning plan to prepare the plant. In some cases, radical isolation involving the disconnection of services at a main substation, for example, may be necessary, requiring the provision of temporary supplies, not only to the building being decommissioned, but also to other facilities that are to remain in operation. In electrical circuits, a common problem is associated with borrowed neutrals where a three phase supply exists in a building, but where there is no neutral conductor readily available. If a neutral connection is taken from another circuit, this will enable the circuit to function, but when the neutral conductor is disconnected, its potential can rise to the supply voltage through another circuit, thus causing an electric shock to the person carrying out the disconnection. Such circuits are extremely difficult to detect because they are only live when a device in another building or room is switched on.

While the plant and equipment within a building need to be checked to ensure that they are fit for purpose, the building itself may need to be surveyed. Buildings that have been left abandoned for a long time may have deteriorated structures, roofs and access stairways (see example in Fig. 14).

If these are to be used by decommissioning staff, it is important that they are checked and maintained before use to avoid accidents (e.g. collapse of a roof or gangway). In addition, the duty of the building may be significantly different during decommissioning, so that even if the building meets its original design intent, it may need to be reinforced for decommissioning purposes (e.g. to allow access for heavy machinery).

2.4.4. Waste management operations

Waste management is an inevitable element of decommissioning. In the decommissioning plan for a facility, an assessment is necessary of the types, volumes and disposition routes for all anticipated waste materials.

Frequently, an unexpected event results in the creation of an increased volume of waste, or waste of a different type that needs a different disposition route. This is particularly true when mixed wastes, such as contaminated oils or contaminated asbestos, are encountered.

Even if the unexpected event itself does not result in a significant delay, the waste that results may need to be stored temporarily, or, in extreme cases, a new treatment process or disposition route may need to be specified.

One way to minimize the impact of waste management issues on the efficiency of the decommissioning process is to have an integrated waste management strategy. This usually results in the appointment of specialist waste management staff and specialist waste management facilities that can not only process wastes as they arise as planned, but which can also respond quickly when an unexpected waste stream is encountered. Even if it takes time to define a disposition route, the waste management system will be able to specify acceptable temporary packaging, storage and monitoring facilities that can be used to deal temporarily with the waste, thus enabling decommissioning to continue without undue delay.

FIG. 14. Abandoned research reactor building, Georgia.

If a container is breached, and no plan or equipment are available to deal with the resulting contamination, the consequences can be extreme. Operator inhalation is possible, and contamination spread is almost unavoidable, requiring time and effort to deal with the spill. To prepare for such an eventuality, preparations should include the establishment of a tented area around/over the package, and arrangements to manage releases of material, if these occur.

Experience has shown that a contingency plan for all waste movements should be prepared, and repackaging/overpacking equipment designed and made available before waste management operations commence. Low level waste is commonly stored in 200 L drums, and there are many designs already available for overpacks for these.

Temporary shielding materials, generic shielded flasks and approved transport routes should be prepared as part of the decommissioning plan and made available for use in contingency situations. This should include temporary waste stores to be used to accumulate and monitor waste at short notice, in case of need, or facilities made available to transport waste off-site to approved locations if possible.

2.4.5. Operator versus contractor interactions

During decommissioning, contractors are often employed to provide expert assistance to the facility's decommissioning team. In the case of large nuclear installations, the list of specialized contractors may include, among others, transport contractors and remotely operated equipment specialists. The use of contractors may increase the overall cost effectiveness of the decommissioning project by improving the efficiency of specialist tasks and therefore reducing the need for specialist staff training [28].

Nowadays, most decommissioning projects are assisted by contractors and other external specialists. However, the operator (licensee) remains legally responsible and should never abdicate its supervisory and coordinating role; in particular, it is the operator's responsibility to ensure that all incidents on-site — whether they happen to be contractors or operator staff — be reported and assessed in a timely and comprehensive manner.

While contractors are expected to greatly facilitate the planning and implementation of decommissioning, they introduce an element of change, which, if not properly managed, has an added potential of causing unexpected incidents. This can be due to the following facts, among others:

- Lack of familiarity with the facility's SSCs and layout;
- Possible lack of training for working in radioactive environments;
- The need for contractors to harmonize working practices with the operator's staff, for example, when working in mixed operator–contractor teams or adhering to health physics instructions;
- Ranking and lines of reporting and communications.

It is to be noted that, despite the accuracy and completeness of contractual agreements, the occurrence of incidents and, in general, any unexpected events may induce a conflict between the operating organization and the contractor involved. This is often linked to improper transfer of knowledge, for example, inaccurate drawings being handed by the operator to the contractor. The latter can then blame the operator if the inaccuracy of the drawings is felt, partially or entirely, to have caused the incident. The potential for litigation is more acute if the incident causes serious financial and other damage. Who pays the bill is not an easy question under the circumstances. Contractual agreements are often not clear enough to discriminate responsibilities.

A relevant case is quoted in Ref. [29]:

> "Unanticipated radioactive contamination was discovered during excavation for a concrete pad at the West Valley Demonstration Project where large casks containing radioactive, glass logs encased in 10-foot [3 m] by 2-foot [0.6 m] stainless steel canisters…will be stored until a national repository is available. The level of contamination, found in a fill area at the south end of the site, was not disclosed. The testing of the samples temporarily halted excavation while radiological teams determined the extent of the contamination. Contaminated soil was placed in five modular packs."

It was reported that the contractor and the US Department of Energy (DOE) officials were unable to agree whether the additional excavation costs would be part of the contract costs or an add-on that the US DOE would have to pay.

3. ADDRESSING UNEXPECTED EVENTS

Section 2 identified potential sources of activities or omissions that can potentially create unexpected events in decommissioning. Although these underlying causes can be traced to events early in the planning, design, construction or operation of a plant, it is certain that the consequences will have to be dealt with as an element of the decommissioning programme. As a result, while the stages described in Section 2 are useful in identifying where in a facility's life cycle the decommissioning problems may be inadvertently created, they are less relevant when the problem of how to deal with the unexpected events actually arises.

In considering the sources of defects or omissions in planning, design, etc., which were identified in Section 2, it is safe to assume that for those plants designed some time ago, successful decommissioning without the emergence of unexpected problems is unlikely. As a result, it is a fundamental observation of this publication that all decommissioning programmes must assume that unexpected events will occur, and that contingency plans and facilities should be put in place to address these. Inevitably, the events to be addressed are unknown at the planning stage, and so the detailed infrastructure to deal with them cannot be specified. However, in general, these problems will be solved by a combination of people and resources, while the speed with which they will be addressed may be moderated by legislation, availability of information, funding, planning requirements, training requirements and the need (if any) for wider stakeholder participation.

A US DOE investigation of accidents (though not limited to decommissioning) has identified a number of common causal factors [30]. According to the study [30], key factors include:

— Less than adequate identification and communication of hazards;
— Work control documents (WCDs) that do not properly characterize the hazards;
— WCDs that do not effectively identify/communicate hazard controls or controls that are already in place to prevent accidents or injuries;
— Work planning that does not integrate previous operating experience into the early work planning stages.

Other observations include the following:

— Failure to adequately identify activity specific hazards, and controls not tailored to the specific hazards;
— Over-reliance on computer based hazards analysis tools and predetermined (canned) controls;
— Poor quality WCDs, with confusing, out of sequence or incomplete work steps;
— Lack of worker and subject matter expert involvement in WCDs;
— Procedures that are too broad in scope create the vulnerability that work will be performed outside of the intent of the WCDs;
— Poor quality of WCD verification and validation;
— Supervisors not enforcing compliance with WCDs or initiating stop work when needed;
— Workers not questioning supervisors when work instructions lack clarity, and workers not exercising stop work authority;
— Procedural non-compliance, with work performed outside of work controls, and workers not exercising stop work authority;
— Verbal communication issues between work groups, and between managers and workers;
— Lack of effectiveness reviews to ensure that corrective actions associated with work planning and control (WP&C) result in improvements;
— Lack of incorporation of lessons learned into future WP&C;
— Lack of rigour in some US DOE and contractor assessments of WP&C.

The results of the analysis by WP&C related keywords are shown below, in order of dominance, and illustrate where typical deficiencies in work safety management can be found:

— Procedures and documents;
— Supervision and management;
— Work planning;
— Personnel errors;
— Procedure compliance;
— Safety compliance;
— Communication.

The infrastructure that needs to be available in order to deal with unexpected events is described in Sections 4 and 5. This structure needs to be in existence at all times; however, those nominated to be involved need not be allocated to these duties on a full time basis, but must be available to be assembled rapidly to solve unexpected problems when these occur.

Section 4 describes the generic infrastructure components that are necessary to prepare for unexpected events, while Section 5 gives examples of how these infrastructure elements are used to solve the unexpected problems in a safe and efficient manner when they occur. Therefore, the structure of both sections is similar, one dealing with the time before unexpected events occur, the other dealing with the time after they occur.

The principles of safety management (which are not per se part of this publication) can be used to illustrate the approach followed in Sections 4 and 5. One of the most difficult issues in safety management is safety performance measurement. In Ref. [31], safety performance measurement is considered in two forms: active measurement and reactive measurement. In active safety measurement, opportunities are taken to seek evidence that safety is being considered in the planning and management of all activities in the facility, while reactive safety measurement collects accident and ill health statistics. The active measurements are part of the contingency planning arrangements described in Section 4, while the reactive measurements are taken during the decommissioning operations described in Section 5. Reactive safety includes not only accidents, but equally importantly, near misses. This is important because there is a correlation between the numbers of near misses and more serious accidents, as described by the Bird Triangle [32], which illustrates ratios between reported types of injuries suffered by workers. Understanding the circumstances surrounding a near miss can be valuable to employers, and represents an opportunity for personal risk assessment because it often identifies the risk before it happens. However, according to Ref. [33], many organizations and employees resist reporting these incidents. Near misses go unreported for a variety of reasons. These include fear of retaliation, peer pressure, concern about a safety record, complicated reporting forms and lack of feedback.

To overcome hesitancy in reporting near misses, the following advice can be given:

— Clarify the expectation that employees report unsafe conditions or risks;
— Provide employees with safety training;
— Offer strategies to measure how reporting near misses improves safety performance;
— Recognize and reward employees for proactive safety engagement.

In addition to reviewing individual near misses for their potential to disclose broader organizational and technological deficiencies, it is also essential to assess any near miss trends as a measurable indicator of safety performance. An IAEA publication [34] offers a comprehensive presentation of the value of near misses in this regard.

4. CONTINGENCY INFRASTRUCTURE

In Section 3, it was identified that there is a need for a permanent contingency infrastructure to be available within a decommissioning organization. This must be the subject of a comprehensive contingency plan. This plan cannot be too detailed, but should include a contingency management policy which demonstrates that due attention is being paid to the likelihood of unexpected events and that these will be managed. In one possible approach, the management arrangements could be structured in accordance with the HS(G)65 [31] management model, as described in Section 4.1 below.

Staff tasked to provide this contingency management do not need to be allocated on a full time basis, but should be available to be allocated to this task when the need arises. The elements of this contingency infrastructure are:

- *Organization*: The people who will assess the problem and find solutions.
- *Funding*: The availability of contingency funds that can be used to finance the resolution of unexpected problems.
- *Planning*: Arrangements by which current plans are modified to take account of the unexpected activity.
- *Legislation and regulations*: The legislative and regulatory infrastructure that manages liaison with statutory and international bodies when these must be consulted to address the unexpected event.
- *Information*: The information infrastructure necessary to support the assessment and analysis of the unexpected problem and to deal with interactions with other areas of the decommissioning programme.
- *Training*: The infrastructure created within the organization to arrange for training (including rehearsals) for activities hitherto thought to be unnecessary.
- *Stakeholder involvement*: The identification of infrastructure arrangements by which the emergence of the unexpected event is communicated outside the project team where this is considered necessary.
- *Modifications to existing programmes*: For example, to waste management, quality assurance or health physics programmes.

These elements are separately addressed in the following sections. The same elements are addressed in Section 5 from the viewpoint of actions to be taken upon the occurrence of unexpected events.

4.1. ORGANIZATION

The organization for the provision of contingency management is very similar to the organization to manage emergencies. Staff will have their normal duties to perform; however, in the event of an emergency, they will have been trained in other activities, and will be able to take responsibility for additional emergency related tasks.

For the management of unexpected events, staff will be identified in a variety of disciplines so that when an unexpected event occurs, they can be called upon to form a special team to address the event. This could result in their being excused from their normal duties, or if possible, undertaking tasks in addition to those that they would normally perform.

Preparation of organization management arrangements will be specific to the type of plant being decommissioned and the specific decommissioning activities being performed. What is important here is that the composition of the contingency organization should be kept up to date with the nature of the activities taking place and the possible unexpected events that can occur.

One way to ensure that this is undertaken is to use the management system described in the UK Health and Safety Executive's guidance documentation HS(G)65 [31]. The structure of this is shown in Fig. 15. This guidance documentation refers to the management of safety, but it can be used to manage any aspect of the decommissioning or operation of a facility. For contingency management, the process begins with the determination of a contingency management policy. This is a high level document that declares the organization's intent to be prepared to address unexpected events. This is followed by the creation of an organization that will be brought into operation in order to address the events when they occur.

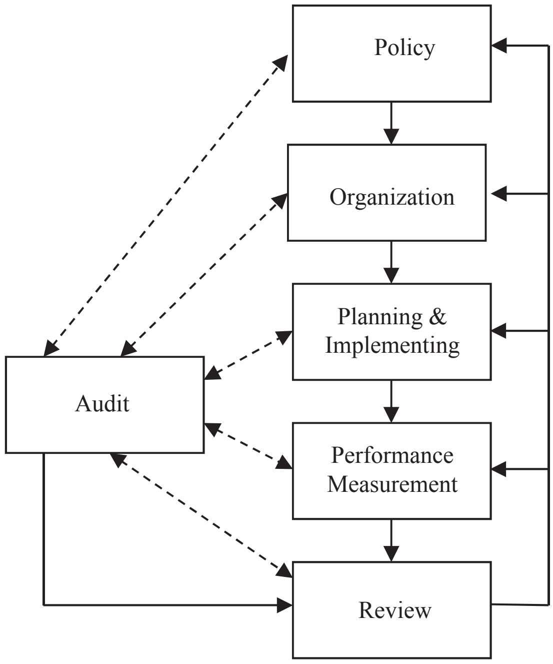

FIG. 15. HS(G)65 management model.

A set of planning and implementing processes and procedures will be prepared. These are the procedures that will be used by the staff in order to meet the requirements of the policy. They will include safety procedures, financial procedures, quality assurance procedures, environment procedures, etc.

The success of the system will be subject to some form of performance measurement. This is usually one of the most difficult areas of the management process, yet one of the most important. Following the performance measurement, a review is carried out of the findings, and if opportunities are identified for improvement, these are applied, where relevant, to all the preceding aspects, including the high level policy itself.

An element of the review process is the use of an external audit function (shown by the solid line from audit to review in Fig. 15) to ensure that lessons learned from inside and outside the facility can be introduced. This audit function will also carry out routine quality audits (shown by the dotted lines in Fig. 15) of the whole system for governance purposes, to ensure that it is being followed and is delivering the benefits it promises.

Because of the performance measurement and review cycle, the system will force the management system to adapt to changing circumstances. As the decommissioning activities change to reflect the nature of the work being undertaken, the performance measurement metrics will change, and the results of the review process will drive changes to the other aspects of the system and keep it up to date with the state of the decommissioning, ensuring that the organization and the procedures and processes it uses are constantly fit for purpose.

The details of the organization will be very dependent upon the:

— Nature of the decommissioning activities;
— Proposed rate of decommissioning;
— Need to comply with the local regulatory requirements;
— Extent to which activities are being carried out by the decommissioning team’s staff and by those of external contractors.

Regardless of the detailed organization, it will be necessary that organization members who are allocated responsibilities to respond following unexpected events are aware of this, and that sufficient flexibility is built into their job descriptions and training to enable this to happen.

Decommissioning teams should seek to identify all possible types of event that are likely, and to ensure that adequate arrangements are in place to address anything that could reasonably be foreseen. Recurring events should be given most attention, as these may denote a systematic failure of the decommissioning organization.

4.2. FUNDING

The infrastructure required to support normal and contingency operations clearly needs to be funded. However, flexibility must be available in the funding authorization process to allow changes at short notice. In the event of the discovery of an unexpected event, it may be necessary to release contingency funds from an identified contingency budget, or, depending on the seriousness of the event, to slow down or stop work on another project while funds are diverted to address the unexpected event.

In some cases, the need to address the unexpected event may be urgent, and it must be accepted that the diversion or release of funds may need to be approved at short notice, with appropriate arrangements being in place to allow this to happen.

The planning infrastructure described below will need to take this into account when rescheduling a larger scale decommissioning programme, if an unexpected event occurs in one of its projects.

4.3. PLANNING

The need for a contingency management plan was described above. This section considers the planning and implementing procedures that will be used by the contingency organization. The planning arrangements to be addressed in the contingency infrastructure are essentially developments of those arrangements that will already be in place for the planning of the decommissioning programmes under normal circumstances.

The risk management arrangements that will be part of the portfolio of responsibilities of the planning department should have identified potential events that could occur and have made provisions for their occurrence. Therefore, in some cases, the unexpected event may be fully, or partially, allowed for in the decommissioning plan. Risk management is not dealt with in this publication as a specific topic. It is a feature of the unexpected events discussed here, that they were not anticipated as risks (poor or incomplete risk management) or that they could not have reasonably been anticipated and were therefore excluded from the risk identification activity.

In other cases, a need to make major changes to the scope, schedule and cost of a decommissioning project will result from the unexpected event, and the planning process needs to be able to respond to this quickly.

Moreover, if the consequences of the unexpected event are serious and affect other projects (either on other segments of the whole site decommissioning programme or outside it, for example, on operating plants), the whole decommissioning programme may need to be reviewed. This could happen if there is widespread contamination by radiological materials, hazardous materials, etc., that originated in the affected project, but has spread to affect others.

Alternatively, the severity of the event may require funds to be diverted to address the event, with the need to stop or slow down other decommissioning projects (Section 4.2). Other resources, such as the staff, waste management capacity and others, may also need to be reallocated, which will have a major impact on the overall decommissioning programme, influencing not only the work on the site, but also affecting local and remote contractors if contracts need to be cancelled. This, in turn, may have an attendant impact on the local socioeconomic situation or even further reaching impacts.

4.4. LEGISLATION AND REGULATIONS

Compliance with the laws of each Member State is an obvious requirement; however, in the case of some unexpected events, particularly the more serious ones, it may be necessary to seek regulatory approval to carry out tasks that would be outside the normal scope of activities for a plant or the technical specifications in force. This work will still have to be subject to regulatory oversight, and will be assessed in accordance with the national regulatory processes, consistent with the national legislation, to demonstrate that it is safe before the task is carried out. Additional procedures will be required to ensure that any temporary changes to the plant configuration to allow the task to be carried out are reinstated before normal decommissioning recommences.

Similar changes to discharge authorizations and environmental compliance may be needed to ensure that benefits to the environment are observed by allowing a temporary change to the authorization. This will also be carried out in compliance with the local environmental legislation and with demonstration to the regulator that the resulting environmental discharges are as low as reasonably practicable under the circumstances of the unexpected event.

In the case of complex, hazardous decommissioning tasks, it is likely that detailed safety cases will have been produced, assessed and approved by the relevant due process. If an outcome of the unexpected event is that this safety case is no longer valid, a new one must be prepared, often at short notice, and detailed arrangements need to be included in the regulatory compliance procedures, to obtain approvals or to vary legislative limits, etc., in the event that this is necessary.

The organization of the decommissioning company will need to have adequately trained legal and safety staff with approved procedures to be used to enable liaison with the regulatory bodies to be undertaken when unexpected events occur.

4.5. INFORMATION

The information requirements for contingency planning are very important to prevent or mitigate unexpected occurrences. Obtaining this information will require the availability of access to search facilities that can contain drawings, reports and other technical information very quickly, and to sort it using keywords. Inevitably, the fastest way to accomplish this is to ensure that all of the likely information necessary to deal with an unexpected occurrence is catalogued and available electronically. In the case of data that are already available in electronic format, the inclusion of metadata that can be used to filter is a typical feature; however, metadata are rarely available for materials that were created in the 1960s or earlier. The IAEA publications [3, 35, 36] are the key references as far as safety relevant information management for decommissioning planning and implementation is concerned. Two IAEA technical reports describe the criteria and practical guidance to collect and store decommissioning related records, and the long term aspects of record keeping are given special attention [3, 20].

It will, nonetheless, be necessary to have a means of searching for important information, even when this is only available in paper format, by storing the locations of the information in electronic format and using search engines to help identify the locations.

In order to avoid unnecessary, expensive work, the decommissioning plan for the site should be used to create an information hierarchy. This will identify essential information, regardless of any unexpected events, and also, by considering the things that may go wrong, identify a contingency set of information that can be obtained and stored as part of the project decommissioning database so that it is available in the event of need.

Such arrangements will need to be recognized by the decommissioning planners and built into the decommissioning schedule and cost database.

Typical information that may be required in unexpected events is listed below, and also necessarily includes some information that will be needed as part of the normal decommissioning planning process:

— As-built documentation, CAD aids, inspection systems and documentation updates;
— Characterization data for each room/plant: equipment lists, supplier details, radiological conditions, contamination information such as quantity and type of radionuclide contamination, and specific room data such as dimensions, etc.;
— Reports from operational events, schedules of hazardous, historic nuclear materials, issues arising from historic operations, possible liquids in pipes, tanks, etc., and details of materials lost during experiments;
— Details of approved repackaging required for materials characterized or uncharacterized, and method statements for release of materials that are still on-site that need to be rechecked and eventually repackaged;
— Maintenance reports of damage to pipes and high voltage lines;
— Modification history of equipment;
— Locations of underground pipes and tanks, and maps of soil contamination;
— Radiation levels and availability of shielding control arrangements;
— Emergency precautions, guidance, provisions for restoration, decommissioning, hold points for checks and contingencies.

This information should be obtained, or at least its location determined, as early as possible in the decommissioning project life, and all those who may need to have access to it, including the emergency response staff, should be aware of it and of how to gain access to it. To facilitate access to the data, it is essential that the format be specified to ensure that data retrieval is efficient and user friendly.

There may be some data that could be necessary in the event of a specific type of unexpected event that cannot be found at all. Where appropriate, these should be determined before the decommissioning project begins, or plans should be prepared that indicate how they will be obtained and the equipment and the probable time that will be needed to obtain them. From a review of the information databases, omissions should be identified so that actions may be taken to remedy such a situation prior to any unexpected event taking place. Clearly, a pragmatic approach should be adopted to prioritize the necessary searches to those aspects that may be sensitive in the creation of possible future problems, for example, missing data on highly activated components, containment systems, etc.

Some typical tasks facing decommissioning planners are:

— In addition to engineering data, the radionuclide contamination or irradiation status of the facility must be determined or calculated.
— If blind penetrations are to be performed, the work area and surface to be penetrated will need to be inspected, any hazards identified and appropriate controls will need to be implemented. If any floors, walls or ceilings are to be fully penetrated, the other side of the structure will also need to be checked for hazards.
— All available construction and as-built drawings should be reviewed for hidden hazards, such as electrical utilities, and obstructions, such as rebars.
— Survey equipment should be used to check the facility for hidden hazards, and any hazards identified should be recorded.
— Any electrical supplies that have been identified as hazards need to be de-energized and locked out.
— It should be determined whether the organization has a procedure for identifying and dealing with wiring errors.
— Appropriately rated personal protective equipment (PPE) needs to be identified and provided to workers.

Some of the data that may be required following an unexpected event may need to be obtained from other nuclear sites, from manufacturers, from suppliers, from informed research and development (R&D)/academic organizations or from the IAEA itself. These should be recognized, and arrangements made and exercised routinely to ensure that the means of identifying such sources and obtaining the information are available and efficient.

In some cases, measurements may be made to identify information that could not have been obtained at the start of life. For example, at Oak Ridge National Laboratory (ORNL), Tennessee, USA, after a change to the water purification system in the pool of the Oak Ridge research reactor, a noticeable increase in corrosion of the aluminium liner was observed. However, the depth of the corrosion was not known, and so the potential threat to the integrity of the liner could not be determined. A sophisticated, non-contact system was developed to analyse the extent of pit corrosion of the liner, based upon a newly developed system of Fourier transform profilometry. This was used to perform a 3-D shape imaging measurement to quantify the extent of the corrosion [37].

Information is only useful if it reaches those who need it in a timely and accurate way, and in a manner that can be used with minimal likelihood for misinterpretation. As a result, the infrastructure of the company should pay particular attention to the means of communicating information so that it is complete, accurate and easy to interpret when needed.

4.6. TRAINING

Training of staff in all aspects of decommissioning and waste management should mean that even though an event is unexpected, the capability of the staff to address it is already known and the staff are able to deal with it.

This will lead to the need for training programmes aimed to responding to typical (if, in principle, unexpected) events. Training in areas such as the erection and use of temporary shielding, making provision for loss of shielding in lead bromide windows or water loss from ponds are good examples of where generic training can be provided and the actions tailored to the event when necessary.

In some cases, it will be necessary to design and manufacture special purpose equipment such as shielded flasks, handling machines, cutting and boring equipment, etc. If these machines are new, staff will need to be trained to use them safely, because they are unlikely to have detailed experience in their use.

Often, recovery from unexpected events requires staff to enter radiation fields that are higher than would normally be considered acceptable, but to do so for short periods of time. Having space available in which mock-ups of the affected plant can be constructed, enabling staff to rehearse the recovery method in a radiation free environment, is a valuable way of reducing the time actually spent in the real plant and the dose subsequently incurred.

Dealing with typical emergencies is a subject that is usually a legal requirement on the part of the licensee, and regular rehearsal of these, witnessed by external agencies such as the safety and/or environmental regulator, are a routine part of training for staff identified as having a role in emergencies, in the site emergency arrangements plan; announced and unannounced exercises are frequent activities on all nuclear sites. Consideration may be given to integrating these rehearsals with some potentially less serious but disruptive events that could occur in a decommissioning project.

4.7. STAKEHOLDER INVOLVEMENT

The adoption of an open and transparent communication policy requires that all stakeholders will be advised, through regular meetings, of the planned activities to be undertaken on the site. Taking due account of an unexpected action, following an incident, arrangements should be put in place to advise the stakeholders of the occurrence retrospectively. Detailed information about stakeholder identification and involvement in a decommissioning project is given in an IAEA publication on stakeholder involvement [38].

The contingency infrastructure should therefore include a communications plan and a stakeholder engagement plan. If the unexpected event is serious and requires the immediate communication of a safety or environmental concern that could affect the general public, this will already be included in the routine site emergency arrangements. However, in a case where an unexpected event does not require the urgent dissemination of information to the public, there should still be a formal process by which the details of the event, once fully understood, are communicated to all stakeholders who have the right to receive them in a form that they are capable of understanding.

There may be legal requirements in each Member State that require communication with the regulator following any major diversion from the agreed decommissioning programme, and these arrangements should still be respected.

The planning arrangements described above are very important in this area, as the need to change the decommissioning plan or divert funds from agreed projects may have socioeconomic impacts on the local, regional, national or even international communities.

4.8. MODIFICATIONS TO EXISTING PROGRAMMES

A comprehensive decommissioning plan will generally include a number of detailed programmes addressing specific aspects of decommissioning (e.g. waste management, health physics and quality assurance). Even though boundary conditions and other circumstances are not expected to change, it is good practice to include contingencies that would allow deviations to those programmes, including new methods and techniques, procedures and provisions that would be available, just in case. This publication considers unexpected events as the factors that determine anticipated modifications to existing programmes.

Examples of these contingencies are as follows:

— As the result of unexpected events, new waste streams may need handling, treatment, conditioning, storage, transport and disposal. It would be prudent to foresee the availability of methods and techniques (in-house, corporate, or provided by national or international companies) that could alleviate unexpected conditions. The unexpected appearance of mixed waste could be a case in question. Provisions may include, for example:

- Treatment of abnormal liquid and solid waste [39];
- Transport containers/vehicles that can accommodate large contaminated items or untreatable liquid waste;
- Segregated areas where high activity materials can be shielded and safely stored;
- A full range of facilities for the disposal of toxic/hazardous waste.

— Quality assurance programmes may be designed to allow deviations. Quality assurance programmes in place for decommissioning projects should incorporate ways in which they can be amended without undue delays following unexpected events.

— Unexpected events may prompt the need for new analytical resources, for example, to investigate unusual chemical and radiochemical compounds. While it can be unrealistic to purchase and maintain such resources in view of a low probability event, at least those responsible for decommissioning should know where such resources can be available at short notice.

5. HOW TO RESPOND TO UNEXPECTED EVENTS

When an unexpected event occurs, it is necessary to ensure that those who are managing the work appreciate the existence of the diversion from the expected and are empowered to take immediate action. In most cases, this will be to stop the job and carry out a review.

However, in some cases, the original scenario may change dramatically, so that, in addition to suspending the original tasks, new ones must be undertaken immediately. This would be the case when, say, a pipe containing active liquid is punctured, producing wholesale contamination of an area; the event would be more critical if the spread of contamination does not stop quickly.

Events such as these cannot be regulated/legislated for in detail, and are covered by the site emergency arrangements plan. Once the immediate emergency is dealt with, the revised actions to return to normal decommissioning are covered by the content of this publication.

One major issue that needs to be stressed is that, regardless of the severity of the unexpected event itself, changes to the decommissioning programme must always follow the approved change management process. This process should be designed to ensure that the impacts of changes to one element of the decommissioning plan do not adversely affect others. In engineering terms, this can often be managed; however, when it comes to finance, it may be that the need to mitigate the effects of an unexpected event are such that financial or other resources must be drawn from other parts of the programme. Even if this is the case, it is essential that the decommissioning programme is properly managed using the approved programme and project control methods. This is covered in more detail in the funding and planning sections below.

As a generic example, when an unexpected event occurs, the following activities may need to be undertaken. This checklist is typical, but the details will be determined on a case by case basis:

— The work should stop, pending a reappraisal of the way forward.

— The immediate workplace must be surveyed to ensure that it is safe and will remain so while a contingency plan is made and implemented.

— The previous item will include industrial safety, hazardous materials assessment, health physics reviews and any other reviews that are specific to the work in progress.

— Engineering staff will assess the extent of the problem and will seek information to support the production and implementation of a contingency plan.

— Where necessary, regulators and/or other statutory bodies will be informed/consulted.

— A stakeholder engagement plan will be prepared and implemented.

— A revised procedure will be created to address the unexpected event.

— A training plan will be produced, where necessary, to train staff in any new procedures.

— If necessary, the services of an external specialist contractor(s) may be engaged, and contractual arrangements must be in place to facilitate this.

— The decommissioning plan will be revised to include the new activity.

— An estimate of the cost of implementing the change will be prepared and included in the programme.
— Lessons learned from the event will be circulated within the corporate organization and to interested parties.

The structure of the sections here matches that of Section 4: the same components of a plan addressing unexpected events in Section 4 are given in Section 5 when taking action in cases where such events materialize.

5.1. ORGANIZATION

Section 4.1 described the arrangements that should be in place to ensure that staff are available to respond to unexpected events. These staff will normally be engaged in routine decommissioning and supporting activities, but will need to be redeployed to address the immediate issues associated with an unexpected event and also to look at its long term impacts, where appropriate.

In dealing with an unexpected event, the procedures that have been put in place will be carried out and staff deployed to form a team, or teams, responsible for dealing with the event. In minor cases, the immediate decommissioning team may be responsible for stopping the decommissioning, preparing a recovery plan and carrying it out. In more serious cases, additional staff and specialists, sometimes from external agencies, may be required. However, at all times, the responsibility for the safety of all staff and for the integrity of the plant remains vested in the plant operator as required by the IAEA Fundamental Safety Principles [40].

In addition to dealing with the immediate impact(s) of the event, enquiries will be undertaken to establish the root causes and lessons learned, and to prepare reports for circulation to other bodies, in case lessons are learned that are applicable to them. The organization described in Section 4.1 recommends individuals with the breadth of skills necessary to carry out such enquiries to be defined and made available to carry out the tasks as described above.

The enquiry teams will contain specialists in different areas and will work in association with, but separately from the teams who are recovering from the event. Typical issues to be addressed by these teams will include the:

— *Safety review team*: To determine whether any intervention action is necessary to assure ongoing safety.
— *Health physics review team*: To provide assurance that radiation and/or contamination levels are understood and contained.
— *Engineering review team*: To identify the nature of the problem and propose solutions.
— *Financial review team*: To begin to consider likely sources of finance to pay for the additional work.
— *Planning review team*: To review the impact of the cessation of the work on the remainder of the programme and, later, to build the revised activities from the discovery into the main decommissioning programme.
— *Legislation review team*: To decide the extent, if any, of regulatory or statutory activities that may be necessary to complete the revised scope of work.
— *Skills review team*: When the recovery plan has been prepared, a skills review team will be set up to consider the need for training of staff in new activities, where relevant.
— *Stakeholder engagement team*: To prepare a stakeholder engagement plan and implement this.

These teams will have been identified in the preparation of the contingency plan described in Section 4. They will be temporarily withdrawn from their other responsibilities to complete the assessment of the unexpected event, and when this is complete, they will return to their previous duties or to the recovery plan, as determined by the programme director.

5.2. FUNDING

For relatively minor unexpected events, it is possible that the overall decommissioning funding will not be affected significantly by an unexpected event (the case would be different for decommissioning following severe accidents) or contained within approved project contingencies; however, annual budgets may require adjustment for the current and potentially future years, depending upon the nature and severity of the event.

It would be ideal if, each year, a non-project specific contingency budget could be made available to be called upon as required; however, the extent to which this is likely is relatively small. It is more likely that funds to recover from the unexpected event will be made available by postponing other planned work or ceasing current work on other projects.

If this method is used to reallocate funds from elsewhere, it will have to be coordinated carefully by the programme controls team, to ensure that all of the impacts of the suspension of one job on the progress of others are taken into account.

In the case of Member States where decommissioning funding is derived externally from sources such as the World Bank or the European Bank for Reconstruction and Development, claims will need to be made to these institutions for additional funds; however, the procedure for this is well known to those involved and need not be expanded upon here.

To quote a few examples, the funding and cash flows related to specific activities may be affected by unexpected events such as discovery of soil and groundwater contamination, major ongoing leaks or the failure of support structures (stairs, gangways, etc.). In such cases, funds might be diverted from previously planned assignments towards the recovery from unexpected events. This, in turn, may imply a reduced productivity in other decommissioning activities and related delays. Whether the overall decommissioning schedule will be affected by these changes will depend on such factors as the extent of delays, whether delayed activities are on the critical path or the availability of funds from other parts of the overall decommissioning project.

Funding of unforeseen activities needed to recover from unexpected events can stem from a number of cost items such as engaging additional staff and/or contractors, procuring larger quantities of consumables, purchase of new equipment to tackle changed circumstances, etc.

5.3. PLANNING

The decommissioning plan in place is likely to be reviewed with respect to any significant unexpected event. The objective of this review would be twofold:

— To assess whether there was something in the current decommissioning plan that may have caused, or contributed to, the event;
— To make sure that the plan has no hidden, intrinsic faults, which might allow repetition of incidents or induce new incidents in the remaining parts of the decommissioning project.

As the result of this review, the decommissioning plan may be changed, to a major or minor extent, or it may not be. It is likely that the overall decommissioning strategy will not be affected by relatively minor incidents; however, it is possible that certain working procedures (or categories thereof) may be affected. This may include, but is not limited to, aspects such as:

— The use of more advanced PPE;
— The need for more characterization before first access to a contaminated environment is allowed;
— Preventive checks on materials of dubious nature, because they might contain asbestos or toxic chemicals, or be abandoned radiation sources;
— The need to perform a second survey before a decontaminated area is declared radiologically clean;
— The need to check or recheck the mechanical properties of SSCs that have been unused for a long time (e.g. pumps, drains, roofs, cranes, stairs), before using them within the decommissioning project;
— The reaching of a reasonable confidence that no embedded/buried components (pipes, live wires, etc.) will be hit before any intrusive action (excavations, drilling, etc.) is undertaken.

A decommissioning plan should be viewed as a living tool and be subject to modifications dictated by experience and feedback (not necessarily from the same project). Regulatory procedures should seek to ensure that acceptance of revised decommissioning procedures does not incur unnecessary delays to the decommissioning project (see Section 5.4). On the other hand, modifications should take into account economical factors and the capability of the workforce to understand reasons for a change to working practices and be trained for new procedures. Some procedures that seem acceptable in theory may prove to be unsuitable in practice.

Regardless of the changes to the decommissioning plan, it is important that a complete overview of the implications of the change be understood. This requires a programme management approach to the change rather than a project management approach, as what may expedite the problem at a project level could have significant programme implications, some of which may not become apparent for significant lengths of time (see Sections 6.5, 6.14 and 6.33).

5.4. LEGISLATION AND REGULATIONS

It is likely that the occurrence of some unexpected events will have legal or regulatory implications. The following highlights some typical legal/regulatory impacts.

Regulators may view an unexpected event as a sign of deficiencies in the decommissioning plan. They may then review the decommissioning plan and/or audit the decommissioning programme and possibly require modifications to prevent recurrences.

Depending upon the licensing regime of the Member State, there could be changes that are subject to an approval/licensing process. Decommissioning a plant is, in many ways, a series of major modifications, and implies constant change. Unlike routine operations where activities vary little from day to day, decommissioning results in activities that can differ significantly within short periods of time. In the IAEA Member States, decommissioning projects are subject to regulatory assessment and approval before they start. This may include the full decommissioning plan, including descriptions of room by room and component to component activities. However, events leading to modifications to the decommissioning plan occur all the time, and the procedures that are used to manage modifications, based on the safety significance of the proposal, can be followed using the due process that applies in that Member State.

Another legal/regulatory change may be imposed by unexpected events creating abnormal radiological conditions. In some cases, for the decommissioning work to proceed, there is a necessity for some workers to be exposed to doses higher than ALARA. Such cases are likely to be approached by the decommissioning organization as interventions rather than practices to allow adequate flexibility, and are subject to constant regulatory review.

Other legal/regulatory changes may also be required by unexpected events. Environmental regulators will have agreed site discharge limits for normal operations and also for decommissioning. Often, these are radionuclide specific and typically apply only to planned operations. Incidents/accidents may cause transient emissions that exceed authorized limits for 1 d or 1 month (e.g. the rupture of a high efficiency particulate air (HEPA) filter or the inadvertent discharge of a liquid waste tank).

5.5. INFORMATION

One of the first actions that will be undertaken following an unexpected occurrence will be to search for as much information on the event as possible, so that it is fully understood and analysed to identify the root causes and to prepare an optimum response.

Unexpected events can lead to significant searches of information databases and also to their revision when new information is found. In most cases, the decommissioning strategy and its associated plan would have been prepared based on the information available. When this is found to be in error or it is found that additional information is needed, additional searches of the database may reveal the presence of the missing information or it may be inferrable from other data. The extent of documentation management and configuration control employed in the 1950s and 1960s is significantly less than is the case today, so such discoveries are relatively common.

Regardless of the care that is taken in seeking information about a plant to be decommissioned, it is always likely that the information necessary to carry out a particular activity will be incorrect, inadequate or non-existent. In such cases, to increase knowledge of the plant being decommissioned, consultation of former staff is often useful, as described in Subsection 2.4.1; however, the validity of such information must be carefully checked, because different operatives can have widely differing recollections of the same event in a plant. This is particularly the case where the event was itself unusual, such as an accident that resulted in contamination. Once new information is added to the information database, it is essential that a trace be made on all other decommissioning projects that used the original information to ensure that their decommissioning plans can be checked, and if necessary, modified in light of the new findings. If this is actioned, it is possible that future decommissioning projects will encounter the same problems. It follows that if there is an engineering solution to the problem discovered, this should once again be communicated to all other decommissioning projects that may encounter similar difficulties, to ensure that a common solution to the whole series of problems is at least considered.

5.6. TRAINING

Following an unexpected event, consideration should be given to the cause, and in the context of training, if the event was caused or exacerbated by inadequate training. This is important, not only to identify the root cause, but if training represents a common mode failing, then there is a likelihood that it could happen again elsewhere in the programme. In this case, the training of the staff involved must be reviewed, new or additional training specified and delivered, and close scrutiny of future performance undertaken to be certain that it has been successful. In some cases, it may be more appropriate, more timely and more cost effective to engage a specialist contractor to undertake the work.

In many cases, the recovery from the discovery of an unexpected event may simply require different skills to be used. For example, if the decommissioning plan proposed manual scabbling of a wall and it was found that the radiation levels were too high, the job would change from manual scabbling to the operation of remotely operated machines. Most decommissioning teams will involve staff trained in both activities, so that there will be no need to carry out additional training unless the numbers of skilled staff are such that additional training is necessary. Even then, it will be repeat training, usually offered by the manufacturer of the equipment to be used.

If, however, the nature of the unexpected discovery is such that a completely new skill is necessary, then arrangements will have to be made either to engage the services of an external organization with the necessary skills, or to carry out in-house training of the staff to enable the work to be carried out internally. It is sometimes the case that external contractors have the necessary skills to operate the machines, but have not been trained to do so in a radioactive environment. In such cases, an assessment is necessary to decide if the in-house radiologically trained staff should be trained on the machine, or whether it may be better to train the experienced machine operators on working in controlled areas. Decisions of this kind must be taken on a case by case basis.

Often, the unexpected occurrence is associated with the discovery of a component that does not appear on the inventory of a plant or whose physical layout/location is not as per the drawing. This may require manual entry to areas of elevated radiation to remove the offending component. To minimize the time spent by the operatives in this process, it is often useful to make a mock-up of the plant in question and to use the same PPE — such as airline suits — to rehearse the detailed actions necessary. This reduces uncertainty, enables project specific tools and procedures to be developed and trialled, and results in a much reduced time in the facility, thus greatly reducing the dose uptake.

Creating a mock-up can be a time consuming and costly process. The design and construction of the mock-up and the rehearsal of the operation can take many months, and is then followed by a brief entry to the facility in question to remove the offending item. The impact on dose uptake is extremely advantageous, but the impact on cost and timescale can be very substantial. For this reason, it is important that when a team has been trained in such activities, this should be carefully flagged so that it may be available to be used again in the event that similar activities are necessary later.

5.7. STAKEHOLDER INVOLVEMENT

It is likely that an unexpected event will attract the attention of local communities and other stakeholders. Regardless of whether the event is associated with any (real or perceived) safety implications, any unexpected event is something that diverges from routine business, and as such, it may convey a threatening or warning message to the public and can also be seized upon by antinuclear parties.

Openness and transparency cannot begin when an unexpected event occurs. They must be instilled in the programme from the outset. Good communications must be in place at all times. If the only time that communication is used is when there is a problem, then it will be inferred that every time there is communication, there must be a problem.

A stakeholder management plan will have a policy organization identified to carry out the task and procedures and processes in place, and the performance of the plan will be subject to regular performance measurement and review (see Section 3 and Ref. [31]). Careful stakeholder management is important, and is often confused with public relations. Public relations is an element of stakeholder management, but it is only one element of it.

Regardless of the discovery of an unexpected event, there should be a competent stakeholder engagement plan available for all activities on the site. One of the key components of this will be the list of stakeholders. Examples include:

— Site workforce and labour unions;
— Regulators (safety, safeguards, environment, security, planning, etc.);
— National governments;
— Local general public;
— Wider general public;
— Local and national media;
— Supply chains (local and national);
— Local emergency services;
— The IAEA (in the case of major accidents).

Individual site representatives will be responsible for communicating with different stakeholders. In addition, the way in which information is passed and the timing will be markedly different between the different stakeholders. It is customary to alert the safety regulator in the event of the discovery of an unexpected event that has resulted in injury (conventional or radiological) or which could have had the potential to have caused injury. This will be carried out as soon as the details are known.

Such an approach is inappropriate in the case of the local general public (unless there is a major accident, resulting in danger to the local people, which is covered by the emergency arrangements). The key to managing the local public is to find a way to describe the discovery, the hazard (if any) that it represents, what is planned to be done about it and the consequences (if any). It takes significant time to prepare this type of statement, but it requires expert judgement to know when to release the information. If it is released too soon, the remediation plan will be incomplete, which simply worries the public. If too much time is left before releasing a statement, the fact that something has occurred will inevitably leak out, and again, may cause unnecessary concern. Getting the timing and content right is a task for professionals using a well considered and regularly exercised communications plan.

5.8. MODIFICATIONS TO EXISTING PROGRAMMES

After an unexpected event has occurred, modifications to existing programmes may be in order for one or more of the following reasons:

— The need to prevent and/or mitigate the recurrence of the event;
— The recognition that existing programmes had intrinsic, systematic flaws or the established presence of common mode failures;
— The convenience to establish safer, more practical or less expensive methods and techniques replacing those that have failed;
— The opportunity for surveying similar projects and importing new and better infrastructure, which has proven more successful elsewhere;
— The need to recruit new staff or specialist contractors to develop and implement such new infrastructure (or implement the old infrastructure more effectively).

It should be noted that modifications to existing programmes as the result of an unexpected event are not mandatory in all cases. Moreover, modifications to programmes may be more or less extensive. A trade-off may be needed, including the following factors:

- Cost of developing and implementing new programmes (including inter alia the recruitment of specialists, training, new equipment, any R&D or adaptation efforts, etc.);
- Probability that events occurred which may repeat themselves or are estimated to be unique occurrences;
- General conditions affecting entire programmes, for example, the lack of a safety culture or a sense of complacency;
- Reliable information that a given programme has or has not worked successfully in other projects.

Modifications to existing programmes may entail several consequences such as:

- The need to gain experience and expertise in new methods, techniques and procedures;
- A partly new workforce, which will call for amalgamation with the rest of the staff;
- Motivational issues, for example, staff become responsible for new or additional activities and are possibly promoted (or demoted) to new positions;
- The generic issue of digesting technical and organizational changes without confusion.

The following is an example of modifications to existing programmes resulting from unexpected events (not to be intended as recommendations that are valid in all cases):

- Modifications to liquid waste treatment systems (e.g. installation of reverse osmosis units against traditional filters);
- Use of telescopic radiation detectors or gamma cameras as a prerequisite to granting access to yet unexplored working areas;
- Full respiratory protection any time that a pipe is first cut open;
- Systematic in-field testing of gangways and scaffoldings before they are routinely used;
- Redefinition of reportable events and broader circulation among interested parties.

6. CASE STUDIES AND LESSONS LEARNED

The following examples of lessons learned outline the problems encountered at the nuclear facilities involved. The situations are typical of the difficulties that can arise when unexpected circumstances occur while planning or implementing a decommissioning project. Although the information is not intended to be exhaustive, the reader is encouraged to evaluate the applicability of the lessons learned to a specific decommissioning project. The general categories of problem and the relevant sections in which they are discussed are shown in Table 1.

The reader should also note that in almost all cases (more than those specifically mentioned in Table 1), the lack/inadequacy of construction or operational records contributed to the seriousness of the reported occurrences. Regardless of case histories specifically referring to missing or inadequate records in this section, it may be assumed that record deficiencies played a role in almost all cases quoted below.

6.1. UNEXPECTED CONTAMINATION FOUND DURING DECOMMISSIONING OF A THERAPEUTIC IRRADIATOR

Problem encountered

During refurbishment of a university building, the highest level of contamination was found on the walls of what was at the time an administrative office. The office was not part of the current decommissioning plan, owing

TABLE 1. CATEGORIES OF PROBLEMS AND SECTIONS IN WHICH THEY ARE DISCUSSED

Problem category	Sections
Unexpected radiological findings	6.1, 6.2, 6.4, 6.5, 6.7, 6.16, 6.19, 6.21, 6.26–6.29, 6.31, 6.40, 6.41
Unexpected items encountered	6.8, 6.9, 6.15, 6.17, 6.20–6.23, 6.30, 6.32, 6.35–6.37, 6.42
Waste management	6.7, 6.26–6.28
Organizational issues and changes	6.10, 6.15, 6.38, 6.39, 6.41
Missing or inadequate records	6.3, 6.6, 6.11–6.14, 6.18, 6.20, 6.25, 6.28, 6.33, 6.34, 6.39
Working conditions	6.24, 6.30, 6.31, 6.37
Potential public exposure	6.7, 6.10, 6.38
Training	6.29, 6.30, 6.37

to the only known use being as an office. A former use of the office as a radium laboratory had not been recorded, and the current authorization/licence listed only use of short lived radionuclides in the building. The contamination was found by accident during refurbishment of the office.

Analysis and solution found

Current design of radionuclide laboratories should ensure good containment of radioactivity, through use of hard, sealed, impervious surfaces. This has not always been the case. In the past, floors, pipe work and storage areas may have had poor containment from spills of liquid. Records for older sites are usually poor, and contamination of the building fabric beyond the immediate area of use is a common problem. There is also a risk that historical contamination has been managed by covering it over with shielding material, such as lead or concrete. Such remedies may only come to light during demolition or refurbishment, and can result in significant additional costs. Universities and hospitals dating back to the first half of the twentieth century often used radium in their work. The use of radium has now largely been phased out, but in many cases, records have not been kept of where and how it was used. Some old hospitals and clinics that used it have had very serious levels of contamination. Some hospitals had radium pits that were used for storage of sources. The cleanup of these old radium areas was often poorly conducted, and backfilling with concrete to cover up prior use was common. Such legacies could be difficult to detect if they have subsequently been built over, but are likely to come to light if the site is being redeveloped and foundations dug for new structures.

Lessons learned

Good planning and design of facilities need not be more costly, but can save huge expenses at the end of life when the facility is being considered for decommissioning. Prevention of migration of radioactive contamination to nearby areas (in particular, non-radiological areas) is essential. The preparation and safe archiving of records is essential to facilitate planning for decommissioning [41].

6.2. UNKNOWN MATERIAL ENCOUNTERED DURING DECOMMISSIONING

Problem encountered

During the assessment and subsequent characterization of a redundant fuel development laboratory, the source material was assumed to be uranium oxide and type S material. Early during decommissioning, glass bottles with uranium carbide were discovered. None of the personnel involved in the decommissioning project, nor anyone in the decommissioning department, had any knowledge and experience of the material. Uranium carbide is a pyrophoric compound that can oxidize and burn when exposed to air. The decommissioning plan did not provide for handling or disposal of pyrophoric materials. Uranium carbide in powder form needs to be handled in an inert atmosphere.

Analysis and solution found

Deferral of decommissioning after operations in the laboratory, as well as inadequate characterization, are causes of the problem. If decommissioning had been performed soon after closure of the laboratory, individuals with direct knowledge and experience in the handling of the specific material would have been involved. This specific cause relates to insufficient early decommissioning planning that would have provided appropriate arrangements and recordkeeping in support of deferred decommissioning. Adequate characterization could have ensured the identification of the specific uranium compound and ensured planning and arrangements that would have prevented the problem.

Lessons learned

Deferred dismantling does not generally apply to research and other small facilities. If deferral cannot be prevented, ensure that the source material is removed and that appropriate decommissioning plans are available. Special attention should be given to the presence of unknown materials and compounds during the characterization of abandoned facilities [41].

6.3. UNINVENTORIED RADIOACTIVE MATERIALS FOUND DURING DECOMMISSIONING

Problem encountered

When areas were prepared for dismantling, radioactive items, such as sources of calibration or flasks with solid and liquid samples, were spotted. There were also some obsolete neutron sources left behind.

Analysis and solution found

The radioactive sources were identified, characterized and conditioned for removal by the company responsible for handling radioactive waste. The solid and liquid samples were analysed and characterized to assess possible management routes: unconditional clearance or management as radioactive waste.

Lessons learned

In decommissioning, it is commonplace to encounter radioactive materials that are not shown in the inventory of the installation. Therefore, prior to decommissioning, it is desirable to assess all the documentation of the installation (reports, operation log books and records of incidents) and to speak with the operating staff. In this way, it should be possible to locate all radioactive material and select proper management routes [41].

6.4. UNINVENTORIED RADIOACTIVE LIQUID FOUND DURING DISMANTLING OF CIRCUIT

Problem encountered

While a valve was being dismantled, a liquid spill occurred, with resulting contamination of the worker and the area.

Analysis and solution found

The inventory of the installation did not show that the system in question contained some remaining liquid. There are several solutions to avoid these problems. One is to check the history of the system. In addition, it is necessary to assess the layout of circuits to check whether there are any drainage points. Work procedures should have clear instructions to ensure that the circuits are empty before they are opened.

Lessons learned

One of the most important procedures before dismantling a circuit is to make sure that the system does not possess internal liquids or gases. If there are fluids, it is necessary to find ways of emptying the circuits or sealing them so that no spills are possible [41].

6.5. SAFETY ANALYSIS FAILED TO IDENTIFY URANIUM IN TRAPS

Problem encountered

On 25 October 2010, a potential inadequacy of the documented safety analysis (DSA) (a potential positive unreviewed safety question) was identified. Preliminary non-destructive assay (NDA) readings indicated the presence of a significant amount of uranium on three sodium fluoride (NaF) traps in the K-25 building and six NaF traps in the K-27 building of ORNL. The form of uranium in the NaF traps was suspected to be uranium hexaflouride (UF_6). The inventory assumed in the DSA for UF_6 in buildings K-25 and K-27 did not account for the presence of UF_6 in these traps. Additionally, the NDA readings indicated a higher enrichment than that assumed in the DSA for the UF_6 inventory. Based on historical records and process knowledge, it previously had been assumed that the NaF traps had been desorbed, and that there was no UF_6 present in them.

Analysis and solution found

A root cause analysis was conducted. The team researched historical records (log books) and documentation relative to the NaF traps during the closing of the K-25 and K-27 facilities, conducted a series of interviews and reviewed similar occurrence reports. The analysis identified one causal factor: the UF_6 inventory assumed for the DSA did not account for UF_6 in the NaF traps. The causal factor was analysed to identify the root cause, so that corrective actions could be identified. The root cause for the causal factor was identified as a design/engineering problem.

Immediate/compensatory measures taken to render the facility to a safe condition included actions such as:

— No work that would allow the traps to be disconnected from the process gas lines was permitted.
— An evaluation of the safety of the situation and a justification for continued operation (JCO) were submitted to the US DOE.
— The total amount of uranium and the ^{235}U enrichment associated with each trap was determined through NDA.
— The K-25/K-27 DSA was revised to update the UF_6 inventories associated with the material contained within the NaF traps and to reflect the accident analysis to address potential activities and associated accidents affecting the material contained within the traps.

— The K-25/K-27 DSA was revised to reflect the application of appropriate controls to protect material contained within the NaF traps.
— The K-25 and K-27 emergency planning hazard assessments were revised to determine the impacts from the increased levels of UF_6.

Lessons learned

Determination of the quantities of uranium or other radioactive materials in a nuclear facility should be based on direct measurements/readings where possible. While historical documentation, process knowledge and procedures that were in place at the time of facility shutdown can be valuable resources, they are not always an accurate indication of the condition in which a facility was left [42].

6.6. INSUFFICIENT KNOWLEDGE OF SYSTEMS BEING DISMANTLED LED TO RELEASE OF HAZARDOUS MATERIALS

Problem encountered

During the investigation into recent releases of hazardous materials at C-340 and C-410 complexes at Paducah, Kentucky, USA, workers expressed concern that they had limited knowledge of the systems being deactivated and demolished. In the C-340 event, the workers did not understand that the insulated rectangular ducting surrounding a UF_6 pipe had instrument lines in it. This resulted in the instrument lines being accidently cut and a subsequent release of UF_6, resulting in UO_2F_2 and hydrofluoric acid (HF) being released into the containment.

Analysis and solution found

In decommissioning, there is often a lack of written knowledge about how a system is constructed or how it was used, and the information available may not provide a completely accurate description from which potential hazards can be identified. Field walks alone do not provide enough insight into potential hazards. Having access to a former system operator or designer enables the decommissioning team to ask questions that lead to a better understanding of the potential hazards that they may encounter during decommissioning. Often, the knowledgeable individual may be aware of alternative uses for the equipment that are not documented. One example is that nitrogen lines used to purge UF_6 systems may be contaminated with UF_6 owing to the use of the nitrogen line to bypass plugs in the UF_6 line. Knowing this enables the decommissioning team to be prepared for the potential off-gassing of HF when the nitrogen line is breached.

Lessons learned

When conducting decommissioning operations in buildings that have been shut down for several years, it is important to learn as much as possible about how the systems within the building were operated. In particular, it is advisable to:

— Involve former system designers and operators in the planning efforts for decommissioning of hazardous systems;
— Survey the workforce (existing and former employees) to determine who has system operational knowledge, and capture that knowledge on interview forms for use in decommissioning planning [43].

6.7. RADIOLOGICALLY CLEARED PROPERTY CONTAMINATED WHILE AWAITING DISPOSITION

Problem encountered

A metal laboratory cart that was being used as part of a laboratory cleanout effort at ORNL was surveyed by a radiological control technician (RCT), and then tagged and cleared for release to await final disposition to property management. The cart was not isolated from further use during the 30 d between when it was cleared for release and when it was retrieved by property management personnel for disposition. After the cart arrived at property management, it was found to be contaminated during a confirmatory survey. After confirming the contamination levels on the cart at property sales, the RCT examined the area of contamination more closely, and noticed that a transparent residue was visible. Where the small spots of contamination were identified, the residue was easily removed. The cart remained in government/contractor control at all times, and never entered the public domain.

Analysis and solution found

It is not certain whether the cart was contaminated prior to the first survey and missed by the RCT, or whether the cart was used during the 30 d in a manner that could have resulted in the contaminated surface. During its routine use, the cart had been stored in an area where access was limited; however, following the material clearance survey, the cart was moved to accessible locations within the building. A causal analysis identified contributing factors to help reduce the potential for recurrence. The analysis showed that the error rate for inadequate material releases is low. More than 70 000 items have been released to property sales by radiological survey over the past 5 years, with six instances of radiological contamination that were not detected during the survey (error rate of 0.009%), none of which were released to the public. The causal analysis identified opportunities for improvements in radiological survey techniques for material releases, staging of material cleared for release, roles and responsibilities for material releases and material lease documentation.

Lessons learned

Property that has been radiologically cleared for excess should be properly controlled while it is awaiting disposition to ensure that it is not used for another purpose or placed at risk of becoming contaminated [44].

6.8. HIDDEN STORAGE COMPARTMENTS CONTAINED UNKNOWN AND UNANTICIPATED MATERIALS AND HAZARDS

Problem encountered

The discovery of hidden compartments always represents a risk of unknown radiological conditions, hazards and radioactive material findings.

During the decontamination of horizontal surfaces in a surplus facility decontamination at ORNL, workers wiping down a storage shelf discovered hidden compartments and a lead storage array. Although the top of the shelf was empty, the workers discovered that the top shelf horizontal surface was ajar and moved when it was wiped. Their continued investigations revealed that the previously caulked and painted top surfaces were actually removable lids that concealed shielded storage areas. These contained lead components and other items, which were unexpected and not addressed by the safety analysis of the decommissioning operation. The revised safety analysis with the increased lead inventory resulted in a threefold increase in the lead exposure level to on-site workers and a doubling of the exposure to off-site receptors. This increase resulted in increasing the facility chemical hazard classification from low to high. However, the increase in the radiological inventory by the material found was contained within the 25% margin added to the known inventory, resulting in a very low increase in risk.

Lessons learned

This discovery highlights the very real potential of encountering unknown materials and hazards when performing decontamination and demolition of surplus facilities. Deactivation, decontamination and demolition should be conducted after interviews with personnel who are familiar with the past operations of the facility when available and after legacy documentation reviews are complete. However, if unknown or unanticipated hazards are encountered, compensatory measures such as stopping work, with inopportune schedule delays, must be taken. Facilities for heavy duty storage shelves (which could conceal lead shielding) similar to the ones discovered should be examined.

Legacy safety documentation and characterization for surplus facilities may not be accurate, true and complete. The creation of safety documentation that relies heavily upon prior documentation and diligent surveillance of observable facility contents and conditions will not completely eliminate the potential for unknown hazards to be identified when hands-on and/or intrusive decontamination work begins. Thus, appropriate conservatism in the development of work controls, combined with a questioning attitude during hands-on and/or intrusive decontamination work, is essential to complete work safety [45].

6.9. ELECTRICAL WIRE FOUND TO CONTAIN ASBESTOS

Problem encountered

The X-533 complex at Portsmouth, Ohio, USA, is a high voltage switchyard that was completed in 1956 and scheduled for demolition in 2010. The 70 000 m^2 facility (X-533A) included a two storey control room with two switch gear houses (X-533B), a general maintenance building (X-533C), an oil pump station (X-533D), two below-ground fire water head houses (X-533E and X-533F) and a gas circuit breaker maintenance building (X-533J).

While removing electrical wire from the X-533 control room, workers suspected a 10 gauge fibre coated wire might contain asbestos and called their safety/industrial hygiene representative. The wire, used as a relay or switch wire, was grey in colour and cloth coated. A sample of the wire was tested for asbestos. The outer grey layer was asbestos free, but the inner paper layer contained 50% chrysotile asbestos. The wire removal was suspended, and the wire was wetted and covered until an Ohio licensed asbestos abatement contractor removed the wire. Personal breathing zone air monitoring of the wire removal was in compliance with current fibre threshold limit values and permissible exposure levels.

The 10, 12 and 15 gauge wires were found in numerous switch cabinets in the X-533 and X-633 facilities. These wires were specified when a relay, switching or control function was necessary.

Analysis and solution found

Workers suspected a potential health hazard because the wire found while performing their assigned duties had a fibre outer layer. The workers voiced their concerns and contacted their safety/industrial hygiene representative. The work was quickly suspended pending the next day analysis of the wire for asbestos; the only work subsequently allowed was unscrewing or unbolting of the intact wire. The wire was ultimately removed by a state licensed asbestos abatement contractor.

A sample of the wire was submitted to a National Institute of Standards and Technology’s National Voluntary Laboratory Accreditation Program accredited laboratory for bulk asbestos fibre analysis. Using polarized light microscopy under method Environmental Protection Agency 600/R-93/116, asbestos fibres were identified in the inner paper layer (between the cloth layer and the copper wire).

Lessons learned

In old buildings, suspect fibrous building materials may contain asbestos, and the safety/industrial hygiene contact should be notified for further investigation [46].

If wires suspected of containing asbestos are intact and the inner layer not visible, then connections can be unscrewed or unbolted. Should the wires be found to contain asbestos, removal must be performed by a state licensed asbestos abatement company.

6.10. FAILURE TO REMOVE SIGNAGE AND CONTAINERS LED TO LACK OF CONFIDENCE THAT ALL RADIATION HAD BEEN REMOVED

Problem encountered

The Institute of Oncology at Ljubljana, Slovenia, had nuclear medicine and brachytherapy departments, which used a range of radioactive sources. As both departments were in a very old building, a decision was taken to construct a new building. The old building was to be reused by the University of Ljubljana's Faculty of Medicine. Once the new building was ready, the nuclear medicine and brachytherapy departments relocated to it. The University of Ljubljana was uncertain whether the rooms being allocated to them for reuse were safe, because they had previously been used for radioactive sources.

Analysis and solution found

The Institute of Oncology ordered a survey from an independent radiation protection expert, who was certified by the Ministry of Health. Dose rate and surface contamination measurements were performed. Air samples were taken for gamma spectrometry analyses. Some in situ gamma spectrometry measurements were also performed. All of the measurements showed that there was no remaining radiation or radioactive contamination in the rooms previously occupied by the nuclear medicine and brachytherapy departments. Some radiation warning signs had not been removed, and some empty non-contaminated shielding containers were found, as well as several historical spent sealed sources. After removal of all of these items, the building was handed over for reuse to the University of Ljubljana. The university ordered a further survey from another independent radiation protection expert, despite having received a copy of the report issued by the first independent expert, stating that the building was safe for further unrestricted use. The second independent survey confirmed the results of the first survey, so the university proceeded to refurbish all of these rooms, which were now to be used as offices.

Lessons learned

Independent checks from an outside expert are necessary whenever rooms or building where radioactive sources have been used are handed over to another user who has no knowledge of working with ionizing radiation. Reassurance is required that the former user has removed all of the sources, decontaminated all of the surfaces and has not overlooked any aspects, such as removal of radiation warning signs that are no longer applicable. The fact that the signs remained in place, as well as several other items bearing a radiation warning sign, caused concern to the intended new occupants, such that they felt compelled to order a second radiation survey [41].

6.11. UNEXPECTED ACCUMULATIONS OF CONTAMINATION IN SOIL AND AROUND ROADS

Problem encountered

During control measurements of soils, pavements and roads of the site of the superheated steam reactor (HDR) at Karlstein, Germany, contamination under the bitumen sealing between the road and pavement led to intense sampling at different depths. The gamma spectroscopy analysis of the samples revealed the potential for large contamination under the pavement and the road. The reason for the contamination was obviously a spill from a fuel cask used in the late 1970s for wet transportation of fuel rods. At that time, the limit for contamination was 3.7 Bq/cm^2. The contamination resulting from the spills was probably less than the 3.7 Bq/cm^2, and so the incident was not recorded. The release value for the final survey was reduced to 0.5 Bq/cm^2 and 0.03 Bq/g for ^{137}Cs and ^{60}Co, respectively.

Analysis and solution found

A large segmentation of the road and pavement over an area of 1000 m^2 and subsequent removal of soil up to 1.7 m depth was necessary. A total of 80 t of concrete and 450 t of soil had to be removed (see Figs 16–18), involving a total expenditure of EUR 2 million and creating a delay of 3 months.

Lessons learned

During the characterization of soil and roads of a site, special attention must be paid to areas where accumulations of contamination can occur, for example, the seals of roads and drains. In such areas, an intense sampling programme should be considered to prevent unforeseeable delays [47].

FIG. 16. Segmentation of the HDR superheated steam reactor road to remove contamination.

FIG. 17. View after remediation measures at the HDR superheated steam reactor.

FIG. 18. Control measurements of drains at the HDR superheated steam reactor.

6.12. PLANNED TOOLS FOUND TO BE INSUFFICIENT FOR DISMANTLING

Problem encountered

The first remote controlled dismantling step of the Niederaichbach nuclear power plant (KKN), Germany, reactor was the removal of the pressure tube internals. Following this, the side welds connecting the 351 pressure tubes with their respective shield sleeve at the lower neutron shield had to be opened. For this purpose, a tube grinder unit was used. The tool was lowered down inside the pressure tube by means of a purpose made lifting attachment and positioned at the vertical level of the side weld to be treated, approximately 6 m below the upper end of the pressure tube. The grinding process was performed as planned, followed by an inspection of the weld, which was meant to be removed. However, although extensive mock-up tests at the factory had demonstrated that the process was effective in removing the weld, the inspection showed that this was not the case in practice. Further investigations led to the conclusion that the side weld had not been carried out as indicated in the drawing (3 mm wide), but was, instead, a seam of width 9–16 mm.

Analysis and solution found

To remove the weld, a second cut had to be performed. This created additional problems with respect to further increases in the temperature at the cut position and schedule delays arising from the need to reduce the dust produced by cutting and the need to replace grinding wheels more frequently.

Lessons learned

The design of the pressure tube reactor was complicated, and the internals could not be readily viewed. Therefore, in spite of the mock-up tests, each remote controlled dismantling step had to be carefully planned, and the tools used had to be made as flexible as practicable so that modifications could be carried out in a simple and fast way [48].

6.13. SHIELDING SPHERES FOUND TO HAVE BEEN CONSTRUCTED DIFFERENTLY FROM DESIGN DRAWINGS

Problem encountered

The chambers that formed the neutron shield of the KKN reactor were filled with a large quantity of steel spheres, which had to be removed to allow decommissioning of the neutron shield to progress. To remove the spheres, the decision was taken to use a high velocity vacuum system to suck them into a transport/disposal container. The vacuum system had an oscillating suction tube and a small inlet orifice (maximum of 38 mm in diameter) through which individual spheres could be sucked. Development trials using mock-ups of the spheres led to the inclusion of an oscillating tandem suction tube, and proved that the system should perform adequately during actual operations on the reactor. When the system was deployed, problems were experienced for the following reasons:

— The spheres did not correspond to the design drawings and were, in fact, crude stampings that were unsymmetrical in shape and which had burred edges;
— The spheres had a resin like coating that caused them to stick together to form a solid structure (see Fig. 19).

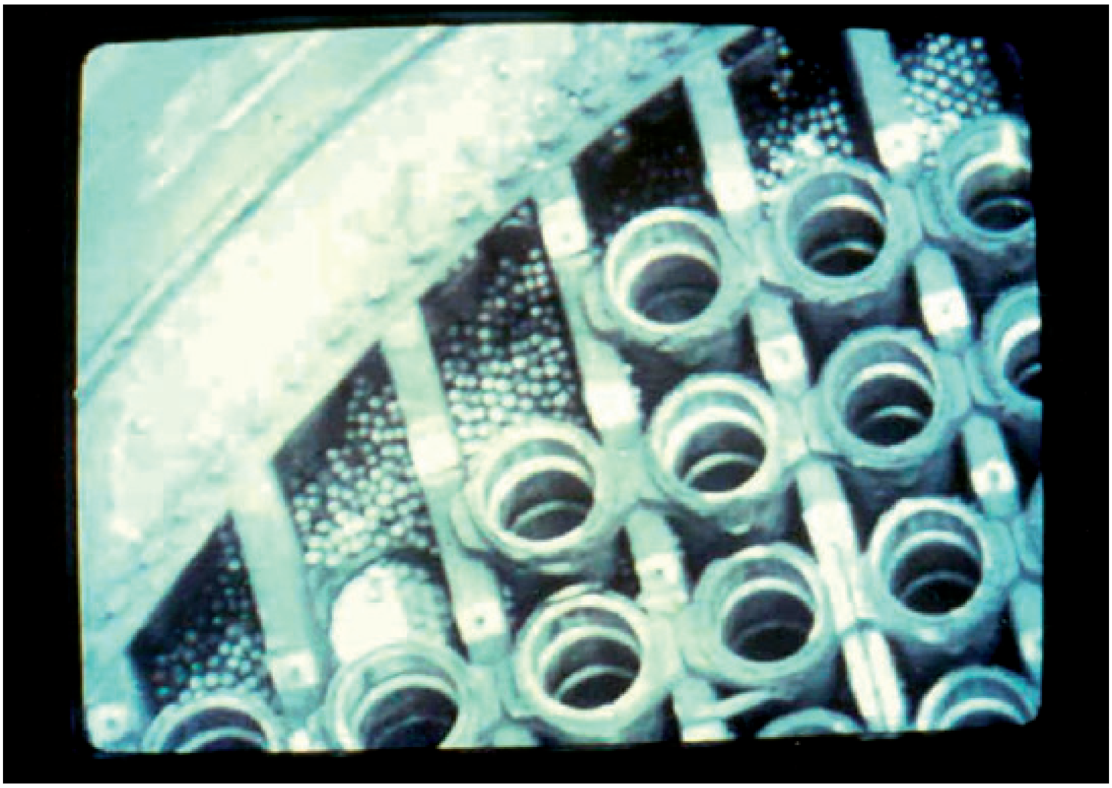

FIG. 19. View into a lower neutron shield showing sticky spheres with irregular shapes.

The consequence of the above problem was that removal rates dropped to one tenth of those achieved during mock-up trials, and a number of spheres could not be removed. These subsequently caused problems during removal of the shield girders as they tended to become trapped in moving parts.

Analysis and solution found

For removal of the lower neutron shield, the unit was modified to improve the suction capacity and the performance of the vibration device and suction tubes. These improved the efficiency of the operation such that the project schedule could be maintained.

Lessons learned

The lesson that can be drawn from this case is similar to that described in the previous example (Section 6.12), and emphasizes the need for visual inspection of components, especially in old plants where the design drawings are very often not reflected in the plant's as-built status [47].

6.14. OUTDATED DRAWINGS LED TO UNAPPROVED AREA BEING USED FOR STORAGE OF FISSILE MATERIAL

Problem encountered

In January 2006, personnel at ORNL realized that they were placing fissile material in an area of K-1420 that was not approved by the JCO they were working under.

Work was ongoing in an approved area of K-1420, classified as a hazard category 2 nuclear area within the facility, to ensure the absence of liquids. As workers ran out of room for arrays on the first floor in an approved area, and because space was limited for additional arrays on the first floor, approval was requested from the nuclear criticality safety organization to set up an array on the upper floor. Approval was given to use the upper floor. On 18 January 2006, posting for an array was established in what was thought to be an approved area on the upper floor, and bottles with fissile material were placed in the array. On 26 January 2006, an additional array was approved for this area. On 26 January 2006, at 14:30, questions were raised regarding whether or not this area was approved for storing arrays. It was pointed out that this was not actually an approved area. Work stopped at 15:00 in K-1420.

Analysis and solution found

Several issues arise from this event. However, the driving force that caused this event relates to drawing control during decommissioning. The problem with drawings during decommissioning is that because the building is planned to be removed, it is generally not considered economically sound to keep drawings updated as one would for buildings that are being constructed or operated. However, from a facility safety standpoint, one still needs the best set of drawings available as a starting point. These drawings need to be controlled. All documentation generated for this building needs to use this same set of controlled drawings as a basis.

Lessons learned

Develop project documentation based on the best available set of controlled drawings for a building or facility to maintain consistency and avoid confusion. Some issues to consider include the following:

- For the decommissioning, locate or obtain the best set of drawings available for a building or facility. Ensure these drawings are maintained in a formal drawing control programme.
- Consider using drawings that identify buildings by orientation, for example, by column and elevation or floor, as opposed to area or room. Whatever is selected, be consistent in all documentation to avoid confusion.

- Consider labelling sections of the building and/or equipment with paint or placards. The individuals performing the decommissioning are generally not the previous operators and are therefore not qualified on the equipment in the building and not as familiar with the building as previous operators. Labelling may avoid confusion.
- Ensure that all documentation generated for that building or facility uses the same set of controlled drawings as its basis.
- As equipment is removed, consider using a red line process rather than a formal as-built or drawing revision process.
- As drawings are no longer applicable owing to equipment having been removed, delete the drawings and retain as records that will show all equipment has been removed.
- As the building is removed, use the same red line process, particularly for large buildings, until the building has been taken down. Then, delete appropriate drawings and retain them as records to show what has been removed.
- Continue this process until there are no more active drawings for that building or facility [49].

6.15. UNDERGROUND UTILITY INFORMATION ON CONSTRUCTION DRAWINGS FOUND TO BE INCOMPLETE

Problem encountered

At the 200 East Areas at the Hanford Site, Washington, USA, Project W-519 provided underground raw and sanitary water, electric power utilities, roads and effluent drain piping for a vitrification facility to be constructed. During the design phase of the project, research of existing drawings was conducted to locate existing, buried utilities near the W-519 waterline routes. The results of that research were used to develop the plan and profile drawings for the new waterlines. Scanning for underground utilities was performed to provide the latest utility information and to verify the locations of known, existing utilities for a portion of the project. Because of schedule and project founding constraints, the project drawings were released for construction with only 75% of the ground penetrating scans for buried utilities complete. This resulted in the released construction drawings being issued with incomplete information regarding the existence and location of some buried utilities. When the scanning was completed in a highly congested underground tank area, additional utilities were discovered; however, the construction drawings used as part of the contract bid package were not updated to take these services into account.

Fortunately, the absence of scan data was noticed by the construction staff prior to the start of the work, and the drawings were updated. The work then proceeded without incident.

Lessons learned

This case demonstrates that construction drawings should include all underground utilities as determined by complete research of existing drawings, underground scans and, where appropriate, potholes (vacuum extraction/hand digging) [50].

6.16. HAZARD MITIGATION COMPONENTS NOT RECOGNIZED AS INDICATION OF PRESENCE OF RADIOACTIVE MATERIAL

Problem encountered

The presence of certain types of equipment, for example, HEPA filters installed on-site, can give some indication of the possible presence of radioactive material and potentially associated unknowns. For instance, building 211-42F (effluent pH control system) at the Savannah River Site, South Carolina, USA, was being prepared for removal. The exterior SSCs were not radiologically posted or labelled, and, as a result, the initial work package did not include radiological controls. However, based on process history and local knowledge, personnel provided health physics coverage during a job to disconnect a flange on the off-gas line, and low level contamination was found in the line's interior. The team failed to recognize the presence of HEPA filters in the tank vent path as an indication of the potential for radioactive contamination within the tank system served by the vent line. Discussions with area facility and radiological personnel (local knowledge) could have assisted in identifying the hazards and the need for radiological work controls. In this event, the HEPA filter was attached downstream of the line break, but was not recognized during the walk-downs.

Lessons learned

These include the following:

— Safe and effective work: decommissioning work is dependent upon thorough upfront planning. Specifically, engineering and work planning walk-downs must be conducted with a degree of thoroughness and attention to detail that leaves little to chance. If these are not properly accomplished, there could be radiological safety issues and work delays.
— All work package reviewers must conduct thorough initial and final reviews to ensure initial adequacy and to identify scope changes that may affect hazard mitigation and PPE requirements.
— Process components that could be involved in hazard mitigation (e.g. HEPA filters) should be looked for. In this event, an HEPA filter was attached downstream of the line break, but was not recognized during the walk-downs. The fact that the HEPA housing was not the typical one commonly used throughout the Savannah River Site may have influenced the misleading assessment [51].

6.17. PROMPT REACTION UPON DISCOVERY OF AN UNKNOWN SUBSTANCE PREVENTED EXPOSURE

Problem encountered

Potentially hazardous exposure was prevented by prompt action by a worker, when a bottle containing an unknown substance was found in a canyon at Los Alamos National Laboratory, New Mexico, USA. During a routine area survey in the Los Alamos Canyon, an environmental restoration employee observed a 250 mL bottle containing a yellowish substance on the ledge of the canyon. The employee photographed the bottle and showed it to the area operations manager. The operations manager notified emergency response and hazardous material personnel, who responded to investigate the scene. Upon arrival, they found the substance to be a moist, powdery material, with no visible crystal formation. The container had been breached, and the material exposed to water. Radiological and inhalation surveys were taken, and the results indicated no radiation levels above background or inhalation hazards. Samples of the material were taken, indicating the material to be picric acid.

The origin of the bottle could not be determined; however, it is suspected that the bottle may have been buried underground and released owing to significant erosion in the area resulting from a major potable water release (14 800 m^3) that had occurred a few days earlier. The area above the discovery location was investigated and remediated for decontamination and demolition.

Lessons learned

The employees responded in the appropriate manner, thus preventing any personnel exposure, spread of contamination or an environmental release of the unknown chemical [52].

6.18. FAILURE TO VERIFY HISTORICAL DATA AND DOCUMENTATION USING MODERN ANALYSIS APPROACHES

Problem encountered

During the performance of decommissioning work activities at K-1420 of the Oak Ridge Gaseous Diffusion Plant, East Tennessee Technology Park (ETTP), ORNL, liquid was discovered in pipes that were thought to have been previously drained. The liquid was collected and properly disposed of based upon prior documentation presented during the transition. The current nuclear criticality safety determination and safety basis documentation was developed based on the premise that all systems had been drained of all solutions, and thus by the nature of the process, criticality was incredible. With the discovery of liquid in the process piping, the criticality was no longer incredible.

Analysis and solution found

The historical documentation for the facility had been accepted from the previous contractor as adequate, with limited analysis to verify the credibility of this documentation. The previous contractor abandoned the facility in place after bankruptcy.

The piping system from which the liquid was drained had been air gapped by the previous contractor and left in place for several years. Historical documentation stated that any product material in columns/piping/equipment was assumed to have evaporated to sludge. Other historical documentation, 1 month later, stated that residual solution remained in the piping and tanks. Contemporary characterization did not include characterization of pipes. The authors of the contemporary safety basis documentation chose to rely most heavily on the historical documentation, which stated that any products in the columns/piping/equipment were assumed to have evaporated to sludge. Specific actions include:

— Analysis of the liquid collected to determine if any knowledge can be gained from knowing the identity of the liquid;
— Identification, through review of the work instructions, of the size/type of container used to collect liquids to avoid any hazardous situations in the future;
— Characterization of the piping and equipment associated with this system to gain a better view of what to expect;
— Revisitation of the assumptions made in the contemporary safety basis documentation and revision of documentation as appropriate.

Lessons learned

Historical data should be challenged and verified to the extent possible before relying on information to develop safety basis documentation. Modern analyses and inspections may yield results that are different from historical records as to what should be expected in SSCs abandoned in place for years [53].

6.19. CONTAMINATION IDENTIFIED IN A NON-RADIOLOGICAL AREA

Problem encountered

During a US DOE safety and health focused safety management evaluation of the ETTP, an auditor requested that an RCT survey a non-radiological area adjacent to a posted radiological area on the north side of building K-1015 laundry facility. During this survey, several spots of contamination were found along the building’s foundation and in cracks alongside a concrete pad. Background information indicated that the facility had been shut down for approximately 18 months. The particular area in question was previously posted as a contamination area, but had been downposted to a non-radiological area after being surveyed in November 1995. Between 1 August 1995 and 29 September 1995, all four lint collectors located on the north side of building K-1015 were within a contamination area. On 27 and 28 November 1995, the four lint collectors and surrounding area were surveyed for possible downposting. In addition, on 28 November 1995, lint collectors nos 3 and 4 and the area surrounding the collectors were downposted to a non-radiological area. Lint collectors nos 1 and 2 and the surrounding area were downposted from a contamination area to a fixed contamination area. On 12 June 1997, an auditor working with the focused safety management team requested that several areas around the two lint collectors in the non-radiological area be surveyed. Contamination was found in the area. Most of the contamination was found in the joint between the building and the asphalt.

Analysis and solution found

Three possible scenarios or a combination of events may have contributed to the contamination being outside of the posted radiological area. First, after a careful review of the downposting surveys, the contaminated spots may have been overlooked by the RCT. The survey does not specifically show readings taken in the exact locations where the contamination was discovered. The RCT who performed the downposting survey left the payroll in December 1996, so it could not be determined when the cracks in the asphalt appeared; the cracks may not have existed at the time of the downposting survey. Thus, the asphalt may have shielded the contamination from detection by the RCT's survey instruments. Second, based on where the contamination was discovered, possible leaching of radioactivity in the soil to a level that was detectable by the survey instruments was a possibility. Third, there had been almost continuous 20 d of rain prior to the discovery of the contamination. A fixed contamination area was adjacent to the area where the contamination was found. A survey of the lint inside the lint collectors within the fixed contamination area showed that the lint was contaminated above the limit for a fixed contamination area. Immediately, the open ports of the lint collectors were covered with plastic and secured with duct tape to contain the exposed lint (the use of plastic and duct tape was only a temporary fix). In addition, the fixed contamination area was up-posted to a contamination area. A few days later, water had collected in the plastic that had been placed over the exhaust ducts of the lint collectors. Outline surveys around the perimeter of the existing contamination area did not show the spread of contamination. Of these three possible causes, the third one has been verified through observations and survey data. Surveys of the soil, lint and vegetation (moss) in the area all showed elevated levels of radioactivity.

A comprehensive survey of this facility had been performed on the outside of the building. Results indicated that the building was correctly posted, except for a small section on the north side of the sludge pit which showed dose rates that exceeded twice the background rate. The posting (contamination area) in this area was extended by approximately 30 cm north of the pit to include the area exceeding twice the background rate. Postings around the four lint collectors on the north side of the building were modified to reflect the current conditions (contamination area). The lint collectors that were within the previously posted fixed contamination area (nos 1 and 2) were placarded with internal contamination stickers. Lint collectors that were previously in the non-radiological area (nos 3 and 4) were placarded with possible internal contamination stickers. The building operator of this facility was contacted, and efforts put in progress to prevent potential contamination from exiting the lint collection system. Routine surveillances were conducted after rain to ensure contamination had not spread from the contamination area. In addition, a barrier has been placed along perimeters to capture any lint that may possibly be washed out of the lint collection system.

Lessons learned

Areas that have been down posted to a non-radiological area should be periodically checked and resurveyed for radiological contamination if cracks or other physical changes are observed [54].

6.20. INADEQUATE AS-BUILT DRAWINGS LED TO CONTACT WITH AN UNDERGROUND ELECTRICAL LINE

Problem encountered

A Washington Closure Hanford (WCH) field remediation subcontractor at the Hanford Site, Washington, USA, was performing road maintenance on a gravel haul road with a motor grader. This was a work activity that had been performed routinely since the beginning of backfill operations. While grading the road, the motor grader caught the edge of a splice box/hand-hole enclosure buried under the haul road.

The tug on the enclosure caused the live line that ran from the enclosure to a junction box to disconnect from the junction box conduit. The act of pulling the cable out of the junction box placed tension on the fuse connection, pulling and breaking the lower fuse block from the main panel and dislodging a fuse in the panel. During the event, the wires melted the insulation and arced to the metal conduit.

The enclosure was not identified on any drawing, nor was it clearly marked in the field. There was another enclosure nearby that had been located during a field walk-down and which was marked with a construction candle. No one was injured, and there was no damage to the grader.

Analysis and solution found

The electrical system involved in this event was installed several years earlier by another remedial action subcontractor. As-built information was provided and filed upon completion of the job. As-built data were retrieved from the files and incorporated onto drawings provided to the WCH subcontractor. The original as-built information was not sufficient to accurately reflect the features installed. WCH and their subcontractor relied upon the data and did not verify and mark the physical location of the underground utilities — additional steps that could have prevented this incident.

An electrical subject matter expert was contacted, and the site was placed in a safe condition until electricians could perform a zero energy check. The main disconnection switch was placed in the off position, and a standing boundary was established for the exposed underground cable and disconnection switch.

Following the zero energy check, the fuses were removed from the main panel, and the panel was placed in an out of service mode until repairs could be carried out. Details of the incident were discussed with subcontractors at all other WCH field remediation sites, where drawings for electrical line locations were reviewed and active work locations walked down.

WCH reviewed as-built procedures and requirements to ensure information on future installations was accurately captured. However, project teams and subcontractors should consider utility information on site drawings to be approximate and incomplete, which should be physically verified in the field prior to initiating future activities.

Lessons learned

Utility information on drawings should be considered to be approximate or incomplete, and appropriate field verification should be performed when planning for activities that could interfere with utilities [55].

6.21. END-OF-LIFE FAILURE OF A BURIED WASTEWATER PIPE RELEASED RADIONUCLIDES

Problem encountered

On 9 October 2001 while excavating soil as part of a pipe replacement project at the Idaho National Laboratory advanced test reactor, a construction crew encountered wet soil in the vicinity of an underground 10 cm diameter radioactive warm wastewater transfer line. Tests revealed that the soil was radioactively contaminated. Further excavation revealed that the 10 cm pipe had broken subsequent to, and perhaps as a result of, an inspection excavation performed in 1997. The edges of the sheared pipe were corroded, indicating that the break had existed for some time. There was no incidence of personnel contamination or spread of contamination outside the posted soil contamination boundaries. The Occurrence Reporting and Processing System (ORPS) guidelines state that the soil could be contaminated to a depth greater than 3 m below the pipe break, and could remain so for an indefinite period of time.

Under carefully controlled conditions, the construction crew excavated approximately 1.8 m below grade, until the pipe was uncovered. The crew saw water seeping from around the pipe, and, as they continued to remove soil, a 12 L puddle of radioactively contaminated water formed in the hole around the pipe. It was evident from a half offset shear that four carbon steel pipes had broken. A survey of the excavated soil with a hand-held frisker confirmed that the soil was contaminated to 5000 Bq. The seepage was stopped by turning off system pumps, and a fibreglass patch was installed over the pipe break.

The warm wastewater in the pipe was normally pretreated to remove most radioactive constituents except tritium, which cannot be removed from water. It was not known how long the leak existed or how much leakage occurred from the pipe. The ORPS guidelines state that a calculated worst case scenario showed that no radioactive isotopes in the water would have exceeded 24 h release limits.

The direct cause and root cause of this event was an equipment/material problem (end-of-life failure). The failed pipe was about 50 years old, having been installed in the early 1950s. Engineers had identified the vulnerability for pipe failure and the need for replacing this underground piping in long range planning documentation many years ago. In order to obtain direct evidence of the deteriorated condition of the pipe and strengthen justification for replacement, this pipe was uncovered and inspected in 1997. No pipe breaks were observed at that time. However, the condition of the pipe was of concern because the inspection revealed heavy internal and external general surface corrosion and areas of pitting to a depth that approached half-wall thickness. It is likely that a combination of the deteriorated condition of the pipe and soil settling following this inspection excavation led to the pipe break.

A possible contributory cause is a legacy management problem (improper resource allocation). Based upon engineering judgement and funding issues, replacement was recommended within 5 years. The piping was on track for replacement within that time frame. The spill could have been avoided if the pipe had been taken out of service and replaced at the time of the 1997 inspection.

Analysis and solution found

The following corrective actions were implemented as a result of this event. The 10 cm pipe had been leak checked, repaired and placed back in service. The contaminated soil was removed to an approximate depth of 3 m below grade and replaced with clean soil. The soil was sampled to confirm that all contaminated soil resulting from the 10 cm line break had been removed to 3 m below grade. The contractor reviewed with US DOE the vulnerabilities and consequences of failure of other underground piping scheduled for replacement.

Lessons learned

This event illustrates the need for timely replacement of underground carbon steel piping that could fail and result in a spill of radioactive or hazardous materials. There are inherent risks in delaying replacement of such piping. Furthermore, managers and engineers need to consider that when soil around aged underground pipes is uncovered for inspection, the risk of a future pipe break in the affected area increases owing to soil settlement [56].

6.22. HANDLING MATERIALS BEFORE IDENTIFYING THEM COULD HAVE LED TO EXPOSURE

Problem encountered

At Lawrence Livermore National Laboratory (LLNL), California, USA, workers demolishing a wall unexpectedly discovered approximately half a kilogram of an unknown white powder that was inside a wall cavity. The work supervisors consulted the environmental analyst and waste technician, but did not contact the hygienist. The supervisors asked the waste technician to sweep up the material into a waste container. The worker doing the sweeping did not wear PPE and did not know what the material was. The next day, the supervisors directed the waste technician to vacuum up the residue left after the previous day's cleanup. The worker used a standard shop vacuum cleaner. A health and safety technician observed the vacuuming task being performed, but again, the industrial hygienist was not consulted. As the sweeping was done on dry material and the vacuum cleaner exhaust was not equipped with an HEPA filter, some of the white powder and dust were discharged into the air. As reported, two subcontracted workers were in the vicinity of the airborne material. Management directed all involved persons to seek medical attention as a precaution. There were no injuries or illnesses reported from this event.

A second event occurred on an on-site car park. A worker discovered a small plastic bag containing a few hundred grams of white powder. The bag had no labels or markings to indicate its contents. The worker picked it up, looked inside the bag, smelt the material, put it back down in the car park and went to the office. Later, upon reflection, the worker reported the discovery, due to concern that the material might have been hazardous. The material turned out to be non-hazardous; however, had it been hazardous, this employee and others could have been exposed.

In both cases, the workers involved handled the materials without a proper hazard analysis being performed, they did not wear appropriate PPE and they used inadequate technical equipment.

Analysis and solution found

Workers handled unknown materials without proper hazard analyses being performed. As a result, they created unnecessary risks to themselves and others from exposure to unknown materials, which could have been hazardous. The laboratory in question has trained personnel and effective procedures in place to deal with unknown materials and ideally the workers would have taken advantage of these resources.

Lessons learned

Not all unexpected events in decommissioning result in actual harm or increases to cost or schedule; nevertheless, they represent lessons that can be learned for future decommissioning planning and operations.

When encountering an unknown material, workers should not handle it without consulting with professional level health and safety personnel to analyse the hazards and to determine what controls are necessary to protect themselves and others in the work area [57].

6.23. INSUFFICIENT PREPARATION FOR BLIND PENETRATION LED TO A NUMBER OF INCIDENTS

Problems encountered

Event 1: Site/facility: Hanford Site Energy Research Programs; electrical near miss during core drilling

Workers were tasked with core drilling into a concrete floor. A scan performed before work began showed embedded material that was thought to be rebar, and the workers were given approval to cut into it. However, during the drilling, an embedded conduit housing an energized 110 V lighting circuit was cut through, which led to a circuit breaker tripping. Five metres away from the drill, cutting water was found dripping from a light fixture.

Event 2: Site/facility: Lawrence Livermore National Laboratory National Ignition Facility; near miss to electrical shock during wall penetration

During the installation of key boxes to a wall, a 7.5 cm screw made contact with a 277 V busbar in a 480/277 V panel mounted on the other side of the wall. This contact led to arcing inside the panel.

Although a prejob walk-down of the area had taken place, the electrical panel on the other side of the wall was not identified. The 7.5 cm sheet rock screw that the carpenter was using was longer than necessary for the task. When first noticing an obstruction (the electrical panel), the carpenter assumed it was a metal wall stud.

There were no proper work controls in place and the work was not adequately planned by management. No special permits or procedures were required for tasks that involved penetration into walls.

Event 3: Site/facility: Oak Ridge National Laboratory Central Complex; electrical near miss during concrete penetration

A construction worker was hand drilling into a concrete beam to install pipe hanger inserts and, after drilling approximately 2.5 cm, penetrated an embedded electrical conduit that contained an energized 120 V electrical line, which caused sparks to be seen from the drill hole.

In this case, there was no check of the drawings before the drilling and no lock-out/tag-out. It was assumed that, as in normal practice, the electric conduits embedded in concrete structures would be situated at a distance greater than 5 cm from the surface. As there is no need for an excavation/penetration permit when drilling 5 cm or less into concrete, this task was exempted from applying for a permit.

Event 4: Site/facility: North Las Vegas Pump House Facility; electrical near miss during wall penetration

Guardrails were being installed by construction workers. Permits for blind penetrations had been obtained in advance, and the locations for penetration were identified using a Hilti Ferroscan FS10 instrument in its Quickscan mode. While drilling holes, the hammer drill bit penetrated a 1.3 cm conduit, cutting into an energized 120 V lighting circuit.

Although it was required to mark the locations of utilities on the structure, this had not been done. The instrument used for the scan performed to identify drilling locations did not detect the presence of the wiring. This was because the wiring was 15 cm beneath the surface of the the wall, whereas a Quickscan has a depth limitation of 10 cm. The interior side of the wall was not scanned, and the workers were not aware of the Quickscan's depth limitations.

The construction personnel were relying completely on the instrument to identify all objects in the wall. However, the Ferroscan is for the identification of rebar only, and does not detect electrical cables or conduit unless they contain a sufficient amount of iron (i.e. ferromagnetic detection). The workers did not realize that the instrument had these limitations because there had been no previous case of wiring being encountered after the instrument had detected no obstruction.

The workers were assumed to be experienced enough in the use of the instrument and therefore no formal training was provided.

Event 5: Site/facility: Oak Ridge National Laboratory Nonreactor Nuclear Facilities; electrical near miss during concrete floor penetration

An anchor was to be placed to stabilize and support a condensate line, and a construction pipefitter was tasked with drilling into a concrete floor. The drill penetrated a 110 V electrical conduit and wiring to a nearby outlet, causing an arc and tripping a circuit breaker. The conduit was 2–3 cm from the surface of the floor and had not been identified because it was believed that any embedded conduits in concrete slabs and walls were more than 5 cm from the surface. The depth of the conduit was not identified from the as-built drawings of the facility as the drawings show electrical conduits in a schematic manner, rather than dimensionally.

Lessons learned

Deficiencies in work planning and hazards identification have resulted in electrical near misses when performing blind penetrations and core drilling. Before blind penetrations can be performed, the following tasks need to be completed [58]:

- Adequate inspection of the work areas and surfaces to be penetrated to identify potential hazards;
- Implementation of controls;
- Checking of the other side of a surface such as a floor, wall or ceiling, if it is to be fully penetrated;
- Review of all available construction and as-built drawings to identify hidden hazards;
- Use of survey equipment to check all surfaces for hazards, and recording of any hazards identified.
- Identifying the person responsible for de-energizing and locking out of any electrical hazards found, and ensuring that this task has been carried out;

— Establishing whether a penetration permit is required, and obtaining this permit if necessary;
— Ensuring that all workers are aware of the requirements of any permit, and in particular of any penetration limits it may contain;
— Identification and provision of appropriately rated PPE;
— Ensuring that an electrical drill stop is used if there is an expectation of encountering embedded rebar;
— Ensuring that workers are aware of the procedure to be followed if any obstruction is encountered during work and know whether they are expected to continue, or stop and investigate the obstruction.

6.24. DAMAGE TO STRUCTURES REQUIRED THEM TO BE DEMOLISHED EARLIER THAN PLANNED

Problem encountered

During the demolition of a former active handling building at Winfrith, UK, both brick transfer chambers associated with the cave lines were damaged such that they had to be demolished earlier than planned. However, by careful removal of the single skin brickwork, which was recovered into International Organization for Standardization (ISO) containers for disposal as low level waste, the cave line demolition was revised such that each line could be ventilated with an air mover protected from the elements by scaffolding supported enclosures. The ventilation plant had originally been intended to be located inside the transfer chambers and thus not require protection from the elements. This type of ingenuity was present throughout the project to assist with overcoming problems as they arose.

Lessons learned

The demolition of the two cave lines was achieved as planned, but the delays incurred by the construction of an enclosure over the North Cave Line at a late stage in the project might have been avoided by development of better means of dust control and by accepting delays when high winds were experienced. The demolition of the base slab of the building created major challenges, but the deployment of ventilated enclosures over identified hazardous areas was fully effective in maintaining radiological control without harm to operatives. The provision of a temporary enclosure around the North Cave Line to prevent the escape of debris took some time to implement. This delay could have been reduced had this problem been recognized at an earlier stage, allowing time to design the structure required to support the sheeting.

A second major lesson learned was the need to obtain better information on the decontamination state of the two cave line internal surfaces at a stage earlier than the start of demolition. Some concrete cores had been cut from the inner faces of both cave lines, and analyses revealed no evidence of fixed contamination on the internal surfaces or within the depth of the structure. There was thus reasonable confidence that the internal decontamination had been completed successfully, but events subsequently revealed areas where residual fixed contamination was still present, mainly in the foundations and below ground construction joints [59].

6.25. LACK OF DOCUMENT CONTROL DURING CONTRACTOR CHANGE LED TO DESTRUCTION OF RECORDS

Problem encountered

An example of inadequate storage and maintenance of records took place at ORNL. During removal of an office at ORNL while transitioning from one contractor to another, the record copy of an external assessment report of an ORNL programme was destroyed. The external assessor, who was reassigned to a different organization, discarded their copy of the record because it was an uncontrolled copy, but it turned out to be the only one remaining.

Lessons learned

The underlying cause of this unforeseen event was the lack of control of documentation; however, it is also a reminder that great care must be taken when the responsibility for decommissioning transfers from one contractor to another. All documentation in the possession of the outgoing contractor should be made available to the incoming contractor [60].

6.26. INCORRECT HISTORICAL ACCOUNTS MEANT THAT AREAS EXPECTED TO BE CLEAN WERE FOUND TO BE CONTAMINATED

Problem encountered

Some surprises appeared during decontamination and decommissioning of the New Brunswick Laboratory, Illinois, USA. The health physics section of Argonne National Laboratory (ANL), IL, was contracted to perform a very cursory spot check of the facilities and to certify that the designation and separation of contaminated areas and items were satisfactory. It was quickly noted that several areas designated to be clean were, in fact, contaminated above the prescribed levels for release for unrestricted use. In addition, office furniture that had been segregated as clean was, in fact, contaminated.

Analysis and solution found

When interviewed, past occupants of the facility could not recall the use of some of the radionuclides that were detected. The source of the contamination was therefore unclear. Possible reasons for this unforeseen event are that:

— Too much credence was placed on recollection of the past history of use of the facility in making the determination of what was contaminated.
— Interpretation of what was contaminated was based on the previous decontamination criteria and not on the American Nuclear Society standard valid at the time.
— Inadequate instrumentation was used in preparing the contamination survey.
— There was a lack of interest in the waste aspect on the part of the previous occupants, because they were moving to a new facility.

Following completion of this work and the preparation of a final survey report, the ANL health physics section was requested to verify that the remainder of the facility was, in fact, clean and could be demolished and disposed of in a landfill area. An extensive radiological assessment was made, and once again, it was found that the remaining facilities did not meet the criteria for release for unrestricted disposal in a landfill. It was later found that the experience of the decontamination contractor in monitoring mixed alpha and beta radiation emitters on surfaces and beneath them was lacking. Some specific findings were noted during the radiological assessment as follows:

— Transuranic levels of ^{241}Am in soil were present in the area where the drain pipes from the Pu facility had been removed.
— Several wall and floor junctions showed that the contamination had found its way into the floor plates, and as concrete was removed, the levels of radioactivity actually increased.
— Contamination in the area of a storm sewer inlet was identified to be ^{226}Ra and its daughters.
— There was an evidence of leaking drain lines under laboratory benches and in pipe races.
— Contaminated soil was found that cannot definitely be linked to burial of pitchblende from the Middlesex Sampling Plant, New Jersey, USA.

It was also found that decontamination of one area of concern often led to the discovery of another area of contamination that had been previously hidden. This is a common occurrence in research facilities.

Lessons learned

The following lessons learned are given in Ref. [61]:

- — Specialist experience in dealing with mixed alpha and beta contaminants is necessary for scoping the decommissioning effort and for providing the radiological assessment.
- — Historical accounts of past activities in old facilities are often incomplete and can be misleading.
- — Detailed understanding of the agreement of concerned parties on release and disposal criteria is essential, including for difficult cases.

6.27. UNEXPECTED CONTAMINATION LED TO SUBSTANTIAL INCREASE IN DECOMMISSIONING COSTS

Problem encountered

The cost of decommissioning of the research and training Saxton Reactor, Pennsylvania, USA, rose, in 2000, by US $17 million over the 1995 estimated US $22 million, mostly due to removal of low levels of radioactivity discovered in an underground steam discharge tunnel. The tunnel belonged to a coal fired power plant that was on-site before Saxton was built, and which runs into the Raystown branch of the Juanita River. The waste removed included around 75 m^3 of water and 28 m^3 of contaminated sediments. In addition, some of the added costs were attributed to extra scabbling needed to remove the contaminated surfaces of portions of the 1.5 m thick containment walls. The portions were from areas where the walls holding the reactor were submerged in water during operation.

Lessons learned

Unexpected contaminations found during decommissioning can be extremely expensive to remediate [62].

6.28. METALLIC PAINT SHIELDED CONTAMINATION AND PREVENTED DETECTION BY SURVEY

Problem encountered

A commonly found unexpected event is the discovery, during the final survey for release, of activity that has been shielded from detection during a normal survey by several coats of paint or other fixing material. An example was found during the decommissioning of the auxiliary reactor area (ARA) facility at INEEL. The ARA-II area housed the SL-1, a 200 kW reactor system and heat source intended for use at remote military bases. An accidental nuclear excursion and steam explosion occurred in 1961, and the initial cleanup and recovery operations were completed 18 months later. A radiological characterization of known or suspected contaminated areas was performed in 1983 to provide data for hazard evaluation and waste disposal. Radiation surveys of the interiors of the buildings and structures were performed, and smear samples for detecting removable contamination were taken. Surface and subsurface soil samples were gathered and analysed. Samples were also taken of building material such as insulation, lumber, metal siding and sheet rock to identify the severity of the hazards and help establish possible waste streams for conducting debris disposition. Radiation surveys from the 1983 characterization found that most of the buildings contained no contamination that was detectable by traditional smear tests. However, as the decommissioning was performed, it was discovered that most of the metal buildings had been painted with a heavy metallic paint after the SL-1 accident to cover and fix contamination in place. It was also discovered during decommissioning that concrete caps had been poured over the top of the original floors in two buildings to cover and fix contamination in place.

Additional surveys performed during the interior dismantling process confirmed that the contamination had concentrated behind the sheet rock walls and the attic spaces of the buildings. All of the building components in these spaces (lumber, insulation, sheet rock, ceiling tiles, electrical wiring and conduits) had to be manually disassembled, sized, containerized into waste boxes and disposed of at the INEEL low level waste burial grounds.

Lessons learned

The following lessons can be learned from this case:

— Records relevant to decommissioning, in particular, radiological and hazardous contaminant characterization, all require early preparation and sufficient time for extended review.
— The characterizations done before the decommissioning project, both physical and radiological, are not always a good indication of the levels of contamination that will be found at the site or the actual physical characteristics of the site.
— The process of characterizing waste streams for treatment or disposal options should be started as soon as the initial characterization data are available. Waste generator interfaces should be contacted on potential waste streams as early as possible to determine if additional sampling and analysis may be required to further characterize waste streams. This process can be very time consuming, and may lead to long delays in completing decommissioning projects [63].

6.29. HOT CELL PROCESS SYSTEM CONTAINED UNEXPECTED RADIOACTIVE MATERIAL

Problem encountered

This case is related to the Quehanna hot cell decommissioning project in central Pennsylvania, USA. During the dismantling of hot cell no. 4, it was determined that extremely high levels of very mobile ^{90}Sr, possibly more than 3.7 TBq, remained within the hot cell no. 4 process system. The severity and nature of the remaining strontium material was unexpectedly realized during dismantling activities in cell no. 4 annex in 1998. During these activities, about 3.7 GBq of ^{90}Sr was released from the cell no. 4 process system. Despite protective gear being worn, three decommissioning workers received skin contamination (the highest skin dose was about 20 mSv), and one of those received a small internal dose. The hot cell annex and adjacent isolation room became highly contaminated (up to 0.8 Gy/h per 100 cm^2) as a result of the release. The service area, the cell facing the operations area and the administrative areas were all slightly contaminated. The receptionist was also slightly contaminated. This discovery led to major changes in the original project, including enhanced personal protection, a modified dosimetry programme, extensive air containment and contamination control systems, and elevated levels of caution in all decommissioning processes. Subsequent work in hot cell no. 4 determined that the ^{90}Sr levels in parts of the equipment were at such high levels that personnel access presented undue risks. Measured contact radiation levels exceeded 400 Gy/h.

Lessons learned

Surprises can be found in construction areas where structures need to be removed to create space for new equipment [64].

6.30. SPENT FUEL POOL CONTAINED UNEXPECTED AND CONTAMINATED OBJECTS AND DEBRIS

Problem encountered

During the decommissioning of the Dresden, Ohio, USA, unit 1 spent fuel pool (SFP), unexpectedly high dose rates were measured during clean out and painting of the pool. One case happened when a radioactive particle became lodged in the ridges of the vacuuming hose that the diver used to clean the bottom. A smooth hose was substituted so that it would be less likely that particles would become lodged in the hose.

On a second occasion, the knee areas of the diver's suit became highly contaminated by kneeling in debris on the pool floor. To facilitate removal of this contamination in subsequent dives, the knees and shoes of the diver were covered with duct tape, which could be easily removed prior to leaving the area.

Another unexpected problem was instrumentation malfunction in the wet and high vibration conditions that were typical during this project. Condensation occurred within some of the radiation detection equipment (particularly the multiplexers). Some of the wires on the electronic dosimeters were fragile and did not stand up well to the vibrations and manipulations of the diver.

Lessons learned

During the Dresden unit 1 project, a number of lessons were learned, the most significant of which are listed below for the purposes of this publication:

— In the Dresden pool, the water turned brown after initial treatment, probably from high mineral and algae contents. High concentrations of minerals and algae are common with old spent fuel basins, especially if they have not been subject to rigorous water treatment pending decommissioning. Early preparations should be made to filter the residual mineral/algae that may come from initial water treatment (e.g. chemical shock treatments).
— Unusual and unexpected objects (probably highly contaminated) were found in SFPs. Work areas should be surveyed periodically using waterproof dosimeters. Some flexibility with special procedures and extended reach tools should be planned into the work. Simple tools such as inexpensive underwater cameras and vice grips can be effectively employed.
— After about 2 years of service, the coating at Dresden became loose on some wall areas. This may point to a lack of profile in preparing the wall using a hydrolaser. It is recommended that an abrasive technique, such as a hull scrubber, be employed in surface cleaning [65].

6.31. CORROSION LAYER LOCKED IN HIGH ACTIVITY THAT WAS RELEASED AND INHALED DURING CUTTING

Problem encountered

The experimental boiling water reactor (EBWR) at ANL ceased operations in 1967. Three characterizations of the facility were conducted between 1986 and 1992. Cobalt-60 was the only isotope detected.

During the decommissioning, bioassay results indicated that seven workers had detectable uptakes of ^{241}Am and minor uptakes of ^{60}Co, ^{137}Cs, ^{90}Sr and ^{3}H. Gamma and alpha spectroscopy of nearly 300 air sample filters provided dates when elevated levels of airborne particulate contamination were detected. The presence of alpha radiation in the air samples was not detectable at the job site. A matrix was developed to correlate the people who were exposed with the dates of elevated airborne contamination and the work in progress. Six of the seven affected workers were involved with plasma arc operations in or above the fuel pool. The uptake probably occurred over a particular 5 month period, with the greatest uptake in individuals working the longest with plasma arc cutting operations. Workers had been taken out of respiratory protection based on air sample results derived during the initial stages of the work. It is believed that radioactive particles, transported by the smoke and fumes rising from the pool, were inhaled by the workers, causing the uptake. Analysis of the corrosion layer present on the surfaces of the core internals revealed the presence of trace amounts of ^{241}Am and FPs. The corrosion layer was rusty in colour and extremely difficult to remove. A file was the only tool that could produce a sample of the material. Smears of the surfaces before the project started revealed only ^{60}Co in quantities of less than 100 Bq. It appears that the corrosion layer formed over time, and was very successful in locking in the activity present on the surface of the core at shutdown. This corrosion layer had 20×10^6 times more ^{60}Co than ^{241}Am. Speculation remains as to how ^{241}Am uptake was possible in the presence of such large quantities of ^{60}Co without detecting ^{60}Co during air sampling. Speculation also remains as to the source of the americium. Some believe it may have been a product of a ^{241}Pu foil documented as lost in the EBWR facility during experiments conducted in 1967.

Lessons learned

- — Conduct monitoring to detect radionuclides that can be reasonably expected based on past operations, even if they are not found during characterization.
- — Thorough knowledge of historic operations is a key factor in quality characterization, especially at experimental facilities.
- — Establish the PPE level conservatively.
- — Expand the use of scheduled bioassays.
- — Ensure bioassay data reach key managers in a timely fashion.
- — Use of good quality air monitoring and dosimetry equipment is desirable and cost effective.
- — If investigations committees are to be utilized, they should be preselected, trained and dedicated to the investigation function.
- — Improvement in recovery procedure roles is desirable.
- — Surge analytic capability is needed for sample analysis.
- — Clear consensus is needed on balancing internal exposure against other health and cost variables.
- — Entry and exit bioassay data are extremely valuable.
- — Archiving air samples is key to dose events and event reconstruction.
- — Excellent record keeping helps to understand and reconstruct events [66].

6.32. ASBSESTOS FOUND DURING DECOMMISSIONING

Problem encountered

During the decommissioning of the DR-1 reactor in Risoe, Denmark, it was unexpectedly found that asbestos was present in the insulation of the piping on the secondary side of the cooling circuits. However, no asbestos had been found in the insulation used for the pipes in the recombiner vault (these pipes were also parts of the cooling circuits). The asbestos resulted in additional expense and delayed the dismantling for some weeks.

It had been expected that the radiation level in the recombiner vault would decrease substantially once the recombiner had been removed. This turned out not to be the case because various pipes and valves belonging to the primary circuit still contained core solution — and probably also some activated material from the core. Therefore, a change of the sequence of removal of components was made, so that these active parts were taken out before proceeding with the reflector and core vessel.

Lessons learned

Unexpected events involving hazardous materials, such as asbestos, PCBs or mercury, are among the most challenging unexpected occurrences in nuclear decommissioning [67].

6.33. SAFETY ANALYSIS PROCESSES RELATED TO ENVIRONMENTAL RESTORATION AND DECOMMISSIONING PROJECTS WITH SIGNIFICANT UNKNOWNS

Problem encountered

A good example of restoration in which the records of materials deposited in the site were incomplete is the Kerr Hollow quarry restoration project, Tennessee, USA, for which disposal records and visual survey using an underwater remotely operated vehicle (ROV) were used to produce a safety assessment of the proposed operations. The safety assessment was based on a material inventory that was uncertain owing to incomplete records and the inability of the camera on the ROV to examine the details of silt covered materials and vessels. The safety authorization to proceed with the restoration process was granted based on the understanding that operations would be halted if any significant deviation from the assumed conditions was discovered.

Significant deviations did occur: some gas cylinders that were supposed to have been breached, and therefore vented of any gas, were found to be pressurized; substantial amounts of water reactive chemicals that were assumed to have been totally reacted due to their long residence under water in supposedly breached containers were found not to have reacted; and some very low level radioactive contamination was found, invalidating the belief that no radioactive materials had been disposed of in the quarry. Specifically for the quarry situation, the bases for the initial safety authorization were invalidated when a series of surprises occurred. Fish were killed owing to a chlorine release from an unbreached cylinder; unreacted NaK reacted violently with water when some containers were shredded, resulting in hydrogen releases and fires on the surface; pieces of NaK were expelled from the water into the surrounding woods, starting fires; and the shredder was damaged by an explosion.

Based on the new information following the surprises, with the agreement of plant experts regarding possible hazards, a worst case scenario was defined, based on a combination of the toxicity of the materials and their solubility in water. Calculations were performed to define the appropriate size hole that could be made in the cylinders such that if they contained toxic materials, the gas released would dissolve in water before reaching the surface, thus preventing a toxic gas release cloud. In addition, extensive emergency preparedness plans were made and exercised based on the potential hazards developed in the analysis.

Lessons learned

The decommissioning licensee and contractors should become comfortable with accepting some risk uncertainty if decommissioning activities are to continue when the hazards are not well known. This implies that full knowledge of the hazards is likely to be unachievable [68]. The actions of personnel when unexpected events occur are very important to prevent injuries, unnecessary exposures and contamination and to optimize the recovery position later.

6.34. RETRIEVAL AND CONDITIONING OF SOLID RADIOACTIVE WASTE FROM OLD FACILITIES

Problem encountered

In the 1960s, the then Soviet Union established a training centre for the safe operation of reactor systems for nuclear submarine crews at Paldiski, which is 45 km west of Tallinn, Estonia. Two full size nuclear reactors were built in two full scale submarine reactor compartments; the first went critical in 1968 and the second in 1983. Both reactors were of the pressurized water reactor type, with thermal powers of 70 and 90 MW, respectively. At the time of last criticality in 1989, the first reactor had been operated for about 21 000 h and the second for about 5000 h. Other nuclear facilities were located at Paldiski, including auxiliary systems, a liquid waste processing facility and stores where solid waste and liquid waste concentrates were placed. When Estonia proclaimed independence in 1991, it inherited the facility and the responsibility for its decommissioning. In September 1995, when the Russian Navy had transported the spent nuclear fuel to Mayak, the Estonian authorities took full control of the site. However, owing to political concerns, the handover of records was not ideal.

Initial characterization of the (inaccessible) waste compartments was made by visual inspection (a television camera was frequently used, owing to the high radiation level), dose rate measurements, in situ gamma spectroscopy and a gamma imaging camera. The initial characterization revealed that in addition to the expected unsorted waste from the operation and maintenance of the reactors, there were also 20 control rods in one of the compartments.

The retrieval was planned and initiated based on very limited information about the waste to be retrieved. Therefore, flexible techniques were used, and a tight follow-up of the situation was carried out. The waste in one of the cells could be retrieved manually, and consisted mainly of low level soft waste. This cell was decontaminated and used as an airlock to sluice material in and out of the facility. Most of the waste had to be retrieved using remote handling techniques with the help of two standard cranes: one small crane inside the cell and one larger crane on top. A number of unexpected difficulties and surprises were experienced during the work, for example, the control rods needed to be cut, but the information on where the absorbing material was located was not available. This was overcome by liaison with Russian experts and engineering estimates. Owing to the high activity of the control rods, a special control rod container had to be developed for the retrieval of the rods, for their transport to the on-site interim store and for their storage.

Another surprise was that the eight steam generators all contained about 500 L of water when they were taken up from the compartment. This water, which was slightly contaminated, was removed and used for making active grout for encapsulation of waste in the standard concrete waste packages used for certain types of waste. All the waste retrieved was transferred to a newly established interim storage facility on the site.

Lessons learned

Inadequate, unchecked transfers of records require extra contingencies to minimize and mitigate any unexpected events during decommissioning [69].

6.35. SUSPECT MATERIAL WAS NOT CHECKED FOR ASBESTOS BEFORE CUTTING

Problem encountered

In May 2004, a decommissioning worker in room 772-D at the Savannah River Site used a reciprocating saw to cut the corner of a laboratory bench top. The bench top was cut in order to provide access to process related components. A question was raised afterwards concerning the composition of the bench top material. An analysis of the material indicated that it contained 30% asbestos.

Lessons learned

During decommissioning work activities, ensure that you question working with suspect materials that may contain asbestos if the necessary asbestos work controls have not been established. A list of such materials should be notified to the workforce [70].

6.36. DEGRADATION OF SYSTEM LED TO UNEXPECTED WATER IN A PROCESS CELL SUMP

Problem encountered

An entry into 224-T process cell C at the Hanford Site was performed using a robotic platform for video inspection and NDA to determine radionuclide hold-up. During that entry, 200 Area Deactivation Project staff discovered that the sump pit contained about 3.7 m of water (an estimated 150 000 L), which was considerably more than expected.

Analysis and solution found

The 200 Area Deactivation Project assumed responsibility for the process cells at 224-T in 1999. No previous owner was identified, so minimal process and facility knowledge about the cells was available. The last surveillance of this sump pit, performed approximately 15 years ago, indicated approximately 0.7 m of water in the pit.

Evidence of sink holes in the ground nearby led staff to research site drawings, from which they identified a trench with pipes leading to the 224-T cells. A process sewer pipe ran perpendicular to and above this trench. A pipe encasement on the sewer line apparently failed, allowing rain and snowmelt to channel into the trench. Three tanks in the sump are now covered by water.

Routine surveillance programmes were established for monitoring all portions of facilities that could present hazards with degradation of systems. The leak was isolated and the water disposed of.

Lessons learned

Inactive facilities should have surveillance programmes in place to detect degradation that could present hazards to personnel, equipment, facilities or the environment [71].

6.37. INCORRECTLY DOCUMENTED ASBESTOS WRAPPING LED TO SIGNIFICANT CHANGES TO DECOMMISSIONING PLAN

Problem encountered

During the dismantling of the biological shield of the defunct research reactor DIORIT in Switzerland, it was recognized that tubing used to place samples near the reactor core had been wrapped in asbestos robes. A check of the records and drawings showed no indication of the use of asbestos for that tubing. In addition, it became clear that even the number of tubes in the drawings was incomplete. Contrary to this finding, the wrapping of the beamlines with asbestos was indicated in the drawings. However, at the time when asbestos was recognized around the sample tubing, the dismantling process had not yet reached the beamlines.

Analysis and solution found

After the asbestos issue was recognized, the work was interrupted, and the authority for conventional safety (Suva) was informed. The personnel involved were medically checked and their probable asbestos exposure was estimated by experts. The building was checked for asbestos and cleaned up by a specialized company. After cleanup, the building was rechecked for asbestos and proved to be clean. Having reached this status, facilities needed to work with non-fixed asbestos fibres (named black zone 5) were installed. A two chamber air log for the material and a four chamber log for the personnel were installed. Air ventilation flow was changed to separate the reactor hall from the other rooms in the building. The air filters had to be treated as asbestos containing waste. Once completed, improvements were assessed again by the authority for conventional safety. After receiving Suva's acceptance, the work was restarted. The personnel working in the asbestos zone wore whole body overalls with protection masks and electrically operated and filtered air supplies. In addition, the foreman and other responsible personnel were trained as asbestos specialists.

Lessons learned

Asbestos is ubiquitous in old installations and often not well reported in record databases. Recognition of asbestos may result in significant changes to the decommissioning plan. Dealing with asbestos contaminated materials requires specialist training.

6.38. CHERNOBYL NUCLEAR POWER PLANT DECOMMISSIONING

Problem encountered

The Chernobyl nuclear power plant was the first nuclear power plant in Ukraine to be under decommissioning. The last operating power unit was shut down on 15 December 2000 prior to the expiration of the design service life.

The main feature of the Chernobyl nuclear power plant decommissioning was the fact that it is located within the territory contaminated with long lived radionuclides as a result of the beyond design basis accident at unit 4 in 1986.

Analysis and solution found

The preparatory works for decommissioning at the Chernobyl nuclear power plant site started in 1998 with a comprehensive engineering and radiation survey (CERS). Taking into account the specific character of the Chernobyl nuclear power plant, great attention was paid to the radiation survey during the CERS. In total, more than 500 000 measurements of different parameters, including about 10 000 spectrometric analyses, were carried out. Calculations of the induced radioactivity of the reactor structures that were tested experimentally (including examination of surveillance specimens) were also performed. Under the CERS results, a specific database was created that was used during the development of basic documentation on decommissioning.

The Chernobyl nuclear power plant decommissioning concept was approved in 2004, and the Chernobyl nuclear power plant units 1, 2 and 3 decommissioning programme was approved in 2008.

In accordance with the concept, a strategy of deferred dismantling (SAFSTOR, a US term for safe enclosure and deferred dismantling as a decommissioning strategy) was accepted for the Chernobyl nuclear power plant. The end state after completion of the decommissioning work will be brown spot — the state of power units upon completion of activities on dismantling of equipment and decontamination of the remained building structures up to the radioactive contamination levels that are average for the surrounding area.

The Chernobyl nuclear power plant decommissioning is expected to be implemented in three stages:

— Final shutdown (completed) and preservation (to be completed by 2028);
— Safe enclosure (2029–2045);
— Dismantling (2045–2064).

The Chernobyl nuclear power plant decommissioning activities are planned to be finished by 2065. Dismantling of engineering structures of buildings and constructions is not envisaged during the Chernobyl nuclear power plant unit decommissioning. It is expected to be performed within the framework of activity on the exclusion zone remediation as a whole.

Transformation of the shelter object into an ecologically safe system is also planned to be implemented in three stages:

— Stabilization;
— Construction of new protection barriers to the methods of possible spread of radioactive substances (in the first place, new safe confinement) and reinforcement of existing barriers;
— Retrieval, conditioning and disposal in deep geological formations of fuel containing materials and high level waste (if, by the time of work start, another decision has not been made).

The main activities being implemented at the Chernobyl nuclear power plant site are as follows:

— Maintenance of power units in safe condition;
— Completion of construction and commissioning of infrastructure facilities for spent nuclear fuel and radioactive waste management;
— Removal of nuclear fuel from power units;
— Removal of working media and potentially hazardous substances from equipment;
— Final shutdown of process systems and equipment;
— Reconstruction of systems and equipment;
— Removal of liquid radioactive waste and partial removal of solid radioactive waste from power units;
— Development of decommissioning documentation;
— Shelter object transformation into an ecologically safe system.

A scope of work on putting equipment out of operation was performed at the power units in parallel with the construction of infrastructure facilities for spent nuclear fuel and radioactive waste management. All process systems and equipment were finally shut down and emptied (in total, 65% of the total amount of equipment and about 50% of electric assemblies). Only radioactive waste management systems and equipment, radiation monitoring systems and life support systems remain in operation.

The reconstruction of life support systems, which takes into account the changes of working parameters and reduction of needs in various media, was performed with the purpose of reducing operating costs.

Large scale work on dismantling, decontamination and release from regulatory control of the equipment external to the most contaminated parts of the facilities (reactors and primary circuits) has begun.

The activities on the first stage of the shelter object transformation into an ecologically safe system were completed in November 2008. Nine large scale activities on reinforcement of the most loaded structures of the object, as well as repair of a light roof, were implemented. Execution of the stabilization activities allowed extension of the design service life for 15 years.

Lessons Learned

Planning for decommissioning in a multi-reactor site where one of the reactors was severely damaged by a nuclear accident and contaminated the surrounding environment requires unique considerations.

6.39. INCOMPLETE DOCUMENTATION NECESSITATED THOROUGH DOCUMENTATION IN PREPARATION STAGE

6.39.1. Preparation for decommissioning

Problem encountered

The preparation for decommissioning of old nuclear facilities at the ÚJV Řež, a. s. (Nuclear Research Institute Řež) (ÚJV), Czech Republic, started in 1996. These old facilities were designed and installed in the 1950s and 1960s. Many of the facilities have been out of operation for a long time.

Collection of design and operational documentation, records, procedures, equipment and radioactive waste inventories was the first preparation step. During the preparation for decommissioning, the following unknowns were identified:

— Lack of documentation, working procedures and operational records;
— Design documentation that did not correspond to the actual state;
— Many upgrades were made without proper documentation;
— Lack of inventory of equipment, materials, radioactive waste, etc.

The preparation also included interviews with the actual and former or retired staff.

In the framework of the first stage, studying the existing data led to the identification of information that was lacking. Then, characterization of sources of ionizing radiation and radioactive contamination using dosimetric measurement and radiochemical analyses was performed. During characterization, many inaccessible environments were identified.

Analysis and solution found

According to the standard procedure valid at the ÚJV, all design documentation should have been archived in the central archive and in the respective buildings. Many documents had been lost or discarded in the central archive in the past. However, many documents have been found in the respective buildings. A thorough analysis has to be conducted to ascertain which documentation is relevant, because several versions or non-relevant documents exist.

The interviews with the actual and former or retired staff were important, but were sometimes not reliable. A thorough analysis of what information is relevant needs to be carried out. It was decided not to try to access inaccessible environments if there was a risk of release of radionuclides or loss of integrity.

Lessons learned

Unknowns are inevitable in decommissioning, as was demonstrated in the decommissioning of old facilities at ÚJV where many unknowns were identified. Collection of information, interviews with staff and extensive physical and radiological characterization are necessary during preparation and execution of decommissioning.

The approach for how to use the collected information must be well balanced. If not, the risk can be underestimated (impacts on safety) or overestimated (impacts on budget and time schedule). A proper documentation management system is necessary for the entire lifetime of the facility.

6.39.2. Decommissioning of a special sewage system

Problem encountered

A special sewage system was used for transfer of liquid radioactive waste from various facilities to a radioactive waste processing facility. The system consisted of a stainless steel pipe network, of total length 410 m, situated in an underground concrete corridor accessible through shafts. The decommissioning procedure started with removal of soil and opening of the corridor. During excavation works, it was discovered that the pipeline was partially laid in another location. This unknown had almost no impact on decommissioning, but in the case of excavation work in the past, the system could have been damaged.

Analysis and solution found

As this unknown had almost no impact on decommissioning, it was more important for the next decommissioning work at ÚJV.

Lessons learned

This was the first case where a major discrepancy with the documentation during decommissioning of old ÚJV facilities was found. It was taken into account during the preparation and execution of decommissioning of other facilities.

6.39.3. Decommissioning of technology for radioactive waste treatment

Problem encountered

The old radioactive waste treatment technology comprised the evaporation unit, storage tanks and a set of mixed bed filters. The technology started operation in 1962, and was shut down in 1992. The evaporation unit consisted of a heater heated by steam and a separator. With regard to the design documentation, the separator should have been simply put into an opening in the concrete floor during installation. Instead, the separator was captured in concrete. Two sedimentation tanks, each of volume 25 m^3, were used for sedimentation of liquid radioactive waste. The tanks were also captured in concrete, which was in contrast to the design documentation.

Analysis and solution found

As it was not removable in one piece, the described equipment was partially dismantled by oxyacetylene cutting and a nibbler prior to removal.

Lessons learned

The discrepancy between the design documentation and the real state is a frequent unknown during decommissioning, and must be taken into account at all times.

6.39.4. Decommissioning of gloveboxes

Problem encountered

Two laboratories, called Alpha halls, contained eight sets of wall boxes and a number of gloveboxes. The boxes were significantly contaminated by alpha particle emitting radionuclides (U, Np, Pu and Am). The total volume of the boxes was approximately 80 m^3.

The main unknown was the insufficient information about the equipment and contamination inside the boxes. Measurements and analyses were performed to obtain the information. As the boxes were contaminated by alpha particle emitting radionuclides, sampling was planned.

Analysis and solution found

The sampling was identified as a risk operation because of the possibility of the loss of box integrity after opening. The sampling will be done during decommissioning when tight confinement will be installed over the boxes.

Lessons learned

Sometimes, the sampling means the start of the real decommissioning activities. Then, it is better to perform it together with other decommissioning activities when all equipment and personnel are available and safety measures are of the necessary level.

6.39.5. Decommissioning of a hot cell

Problem encountered

A hot cell was used for experiments in the reprocessing of spent fuel during the period 1969–1974. The cell was heavily contaminated. The hot cell, made from cast iron of thickness 100 mm, had been partially decontaminated in the past and then its internal and external surfaces were coated to prevent the contamination from spreading.

The main unknowns were the lack of design documentation and almost no information on what was really inside the hot cell. In the late 1970s, the equipment was removed. In the early 1980s, the hot cell was partially decontaminated. The last record was: "Decontamination of the hot cell will be finished next year." Instead of this, the facility was abandoned.

Analysis and solution found

No one knew what was behind the door. That was why a survey had to be performed before decontamination. Decontamination of the hot cell started with removal of the fixative coating by a paint remover at first, and then dry ice blasting was applied for decontamination. Subsequently, the hot cell was removed from its mounting. During floor decontamination, contamination of subsurface layers was identified. Only a part of the contamination was removed to avoid breaching the integrity of the building that was still used. The range of the remaining contamination was recorded, and will be used for decommissioning of the building in the future.

Lessons learned

In this case, deferred and not properly planned decommissioning was the main problem. This was also accompanied by lack of design and operational documentation.

The decommissioning must be properly planned and performed as soon as possible after the shutdown. If this is not possible, all information about the facility (including the remaining contamination) must be collected and properly stored.

6.39.6. Release of waste into the environment

Problem encountered

In 2002, according to a change of legislation, the clearance criteria valid in the Czech Republic were changed. Before this date, there were five categories of radionuclides with clearance levels ranging from 0.3 to 3000 Bq either per cm^2 or per g. Since 2002, there have been four categories ranging from 0.3 to 300 Bq either per cm^2 or per g. This change decreased the amounts of wastes releasable into the environment and increased the cost of disposal.

Analysis and solution found

The only solution was to meet the legislative requirements and to increase the budget.

Lessons learned

There are some unknowns with impacts on decommissioning cost that are unavoidable. Change of legislation is one of them.

6.40. INCORRECT CONSTRUCTION LED TO UNEXPECTED ACTIVATION OF MATERIALS

Problem encountered

During the emptying of a pond, irradiation was detected on the top of Siloe research reactor, Grenoble, France [72].

Analysis and solution found

The discovery of hidden unforeseen irradiation around neutron beams stopped the emptying of the pond and resulted in a change of the dismantling scenario (from contact to remote operation). Decommissioning activities were halted to treat the problem. After the first investigation, it was found that the bottom part inside the pond was irradiated. In this case, the neutron beams had not been built correctly, and space existed between the neutron beam and the concrete. This gap allowed the neutrons, during operation, to activate the concrete and the iron bars. Levels of radiation related to this issue are illustrated in Fig. 20.

Lessons learned

This discovery highlights the very real potential of encountering unknown materials and hazards when performing decontamination and demolition of facilities.

Deactivation, decontamination and demolition should be conducted after interviews with personnel who have information on the erection and past operations of the facility, and after legacy documentation reviews are complete. However, if unknown or unanticipated hazards are encountered, compensatory measures, such as stopping work and additional shielding for radiological protection, with inopportune schedule delays, must be taken. Similar facilities should be examined and the information shared.

Legacy safety documentation and characterization for facilities may not be accurate, true or complete. The creation of safety documentation that relies heavily upon prior documentation and diligent surveillance of observable facility contents and conditions will not completely eliminate the potential for unknown hazards to be identified when hands-on and/or intrusive decontamination work begins.

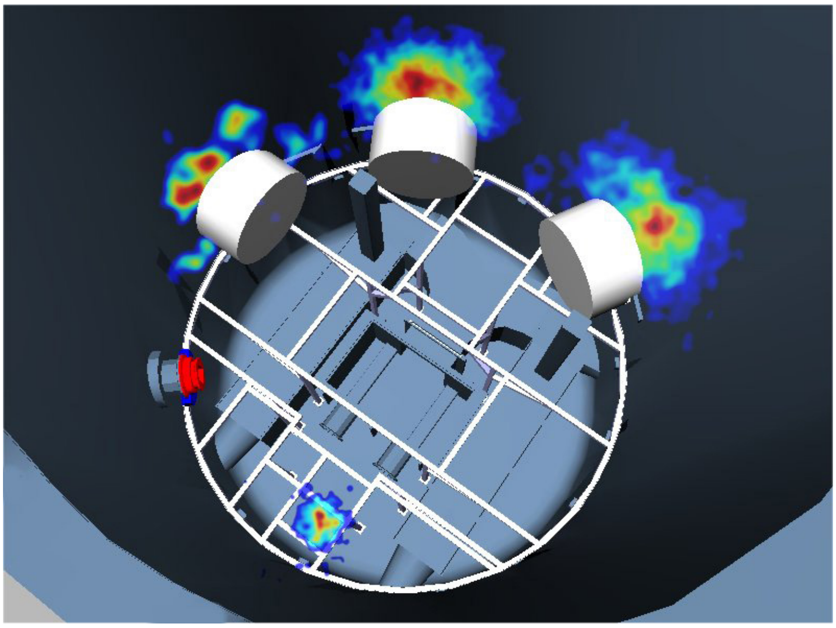

FIG. 20. Example of three dimensional modelling of activity distribution in the Siloe research reactor, France. Image courtesy of CEA.

6.41. CONTAMINATION MAY HAVE BEEN CAUSED BY DISMANTLING

Problem encountered

During the decommissioning of the former wet storage facility at the Greifswald decommissioning site, Germany, unexpected contaminated cable protection tubes (CPTs) were detected in the last control survey, just before the demolition work of the building was planned to start.

Analysis and solution found

Before the dismantling of the inventory started, a first radiological survey was executed in preparation for complete wet storage decommissioning.

It is not certain whether the protection tubes were already contaminated prior to the first survey, or whether during the dismantling, work could have resulted in the contamination of the tubes.

The task was to prove compliance with the release limit values at the inner surfaces of the CPTs as follows:

— All 105 CPTs were sampled (by pulling a wipe through the tubes).
— The 16 CPTs with the highest contamination were dismantled, decontaminated and measured in the free release measurement facility.
— At least 30% of the contamination was removed, proved by a wipe test.
— Mathematical proof of compliance of the CPTs with the release limit values.

Lessons learned

— A radiological survey should be planned in a detailed manner, also taking into account that unexpected contamination could occur.
— Touching any closed lines (pipe work, channels and tubes) before all equipment is completely dismantled should be avoided.
— The available techniques and administrative conditions are normally suitable to attain the goal to release a building under difficult conditions, but, mostly, additional time and money are required.

— Within a decommissioning project, contaminated concrete structures are the highest risk in terms of expenditure of time and money.

6.42. ASBESTOS FOUND IN UNEXPECTED PLACES SUCH AS AT OFF-SITE FACILITIES AND IN SEALS AND INSULATION

Problem encountered

During the practical dismantling work and the preparation work (planning and final characterization) for different dismantling objects at the Greifswald decommissioning site, unexpected asbestos contaminations were detected.

They occurred, for example, at:

— Different off-site facilities, such as smaller administration buildings (e.g. medical facilities);
— Seals in different facilities of the primary and secondary circuits;
— Insulation material parts (cohesive insulation belts).

Analysis and solution found

— In different, older radioactively uncontaminated off-site buildings, where no detailed survey had been conducted in the inventory phase, asbestos was not detected;
— Nobody expected asbestos contamination in the seals of the nuclear power plant facilities;
— It was unknown that insulation material belts consisted partly of asbestos.

All mentioned materials could be removed only under consideration of special health and safety measures (e.g. the wearing of protection clothing; before starting of dismantling activities, the erection of so called black areas with extraordinary air filtration measures; and the erection of a special treatment facility for contaminated seals).

Lessons learned

— A survey to analyse the existence of hazardous materials should be planned for all buildings, and also for all off-site facilities.
— Sometimes, insulation material that is not asbestos contaminated can have asbestos fix belts.
— All seals in the facilities should only be touched under the consideration that asbestos contamination could be possible. This means that they should not be cut in situ, only after removal to the special treatment and disposal facilities erected on-site.
— Unexpected hazardous material contamination, only detected during the dismantling phase — due to a decrease of survey activities — could lead to additional time consumption (project delays) and sometimes to extensive budget increases.

7. CONCLUSIONS

Unknowns in decommissioning cannot be eliminated, regardless of the efforts applied. This is especially the case in old facilities where documentation may have been lost or where modifications were carried out without updates to reports. As a result, when planning for decommissioning, it is prudent to assume that such problems will occur, and ensure that arrangements are in place to deal with them when they arise. This approach will not only improve the efficiency of the decommissioning project, but will also improve the safety of the operations.

In preparing this publication, it has become clear that opportunities exist at all stages of the lifetime of a facility to either increase or decrease the likelihood of unexpected events during the actual decommissioning. Care should therefore be taken at all stages of a plant's life to ensure that a decommissioning plan is produced, reviewed, used to inform routine modifications and kept up to date.

One of the most common root causes of unexpected events in decommissioning is the lack of detailed design information or missing records of modifications, maintenance issues and incidents during operation. It is therefore necessary to check the completeness of design information in existing plants and to ensure that CM techniques are applied at all stages of the lifetime of a plant. In the case of a new plant, archiving samples of materials can be a valuable source of information to support decommissioning planning.

Plants that were constructed to advance research in the area of nuclear engineering suffer particularly badly from unexpected events in decommissioning because they are generally older and also because the nature of their operations resulted in them being subject to regular and significant modifications as a routine part of their operation.

During the lifetime of plants, it is likely that modifications will be carried out involving the construction of new buildings. The opportunity should be taken in these circumstances to consider the layout, the physical size and other attributes of the plant to ensure that they do not make decommissioning of existing facilities more difficult and also to optimize the potential for reuse in support of the decommissioning of the whole site, later in the life of the facility.

Characterization of all aspects of a plant is essential to reduce the number of unknowns and the likelihood of unexpected events. This characterization should be extensive, but there is a limit to the level of detail that should be sought as the cost versus benefit gain may reduce.

Reducing unknowns by retrospectively obtaining physical data associated with a facility is a useful means of characterization, and there are many tools in existence that can be used to carry this out accurately and effectively.

There are also a number of organizational factors that may induce unexpected events. These generally include:

— Inadequate planning and inadequate work packages;
— Communications issues;
— Insufficient learning from operating experiences and lessons learned.

However, regardless of the efforts that are employed in decommissioning planning, unexpected events should be anticipated and contingency plans prepared. Although the details of the event itself may not be anticipated, its impact may affect safety and environmental discharge, and may or may not involve radiological impacts. Regardless of more serious impacts, unexpected events are likely to result in modifications to the decommissioning plan, incur delays and cost money.

The experiences identified in this publication can be used to help specify tools, equipment, training and actions that can be prepared and which are available for immediate use as contingency measures when unexpected events occur.

Finally, regardless of the status of a facility, whether at the concept stage or at the decommissioning stage of its life cycle, it is never too early to begin thinking and planning for decommissioning.

Appendix I

EXPECT THE UNEXPECTED IN DECOMMISSIONING AFTER A SEVERE ACCIDENT

I.1. INTRODUCTION

Most decommissioning related publications by the IAEA (e.g. Refs [28, 73, 74]) and other organizations such as the OECD Nuclear Energy Agency or the European Commission clearly specify that their scope applies to the decommissioning of nuclear facilities under planned conditions. It is generally specified that decommissioning of facilities that have been subject to a severe accident is excluded from the scope of these publications. This is due to the peculiar, generally unpredictable, circumstances resulting from a severe accident, including inter alia high radiation and contamination fields, abnormal waste and unexpected configuration changes.

Based on the literature, there is no unique definition of a severe accident. All definitions include various consequence (damage) types (evacuees, injured persons, fatalities or costs) and a minimum level for each damage type. The differences between the definitions concern both the set of specific consequence types considered and the damage threshold.

For our purposes, the scope of this study encompasses only facilities that have been seriously contaminated and physically damaged to the point that planned routine decommissioning strategies and techniques are unusable or impractical.

It should be noted that there is a large grey area between planned and accidental closure of a nuclear facility. In fact, there are facilities that have been permanently shut down as the result of a relatively minor accident (at least in radiological terms), but the prohibitive costs of restoring the facility to a safe, profitable status have made decommissioning the obvious practical strategy. Therefore, some of these facilities have been decommissioned subject to routine decommissioning practices (e.g. Vandéllos gas cooled reactor, Spain [75]), because end-of-life radiological conditions were not significantly different from normal, expected conditions.

One factor affecting the decommissioning of nuclear facilities after a severe accident is the uncertainties/unknowns (UUs) caused by the incontrollable generation and spread of radioactive substances (often of unpredictable physical/chemical/radiological nature), and the damage to SSCs produced by the release of high pressures and temperatures previously confined within safe barriers. Actually, it is generally the breech of containment barriers that causes the major impacts of a severe accident and determines the course of subsequent decommissioning.

It should be noted that there are three phases typically associated with a post-accident phase: (i) stabilization, (ii) recovery and (iii) decommissioning. Stabilization refers to the immediate aftermath of a nuclear accident, and it implies control of conditions so that impacts to the environment and the general public are minimized. Recovery entails the planning and implementation of activities to control and subsequently reduce the extent of abnormal conditions, and to prepare the plant for achieving a longer term, safer configuration. Recovery can be viewed as a precursor to decommissioning. The study in this appendix addresses the management of UUs resulting from a severe accident as a key factor affecting strategies, methods and techniques of subsequent decommissioning. However, there is no clear cut line between the three above mentioned phases; in fact, UUs are generated by the accident and its evolution, and may be recognized, faced and dealt with during the stabilization, recovery or decommissioning phases. As far as activities are concerned, treatment of liquid waste, initiated during the recovery phase, may continue well into the decommissioning phase. It is only in planning for or implementing decommissioning when access to plant SSCs is re-established that the full extent of and the actual/potential issues are identified and tackled as necessary.

I.2. UNCERTAINTIES/UNKNOWNS

Owing to the unpredictable conditions and evolution of a severe accident, it is hard to define specific UUs that can be expected during decommissioning of a facility after a severe accident. In other words, you cannot expect the unexpected. The best that can be done to analyse UUs is to try to define categories and provide specific examples based on the experience of severe accidents such as those at the A1 nuclear power plant, TMI-2, Chernobyl and Fukushima Daiichi in Japan.

This study defines the following categories of UUs, which are described in more detail later on:

— Physical state of SSCs;
— Radiation and contamination levels;
— Abnormal wastes and their management;
— Safeguards;
— Implementation and regulatory responsibilities;
— End states, including decontamination and dismantling techniques;
— Records and data management;
— Resources;
— Organization and management, including stakeholders.

I.2.1. Physical state of structures, systems and components

It is quite possible that a severe accident results in extensive damage to SSCs owing to the release of thermal and mechanical forces. It is also likely that the long period of time between the accident and the implementation of the decommissioning strategy will result in extensive corrosion of metal SSCs (e.g. due to vapours) and more damage. Piping may become clogged owing to uncontrolled transport of sludge and debris, which can happen in inaccessible spots. These circumstances may, in turn, alter the configuration of the plant beyond reconnaissance and may require ad hoc characterization. Owing to these uncertainties, physical and radiological characterization of unknown environments will take much longer and will be more hazardous to the workers engaged in a characterization campaign.

Post-accident planning for decommissioning will face uncertainties linked to the mechanical properties of SSCs bound to have a role in decommissioning. This may concern the assurance of proper functioning of stairs, elevators, cranes, pumps, floor drains, floor bearings, etc.

One example of difficult characterization was posed by Windscale pile 1, where fire broke out in the reactor core in October 1957. The fire led to a release of radioactive contamination into the environment and represented a major nuclear accident for the UK nuclear industry, which was in the early stages of its development. Pile 1 and its sister plant, pile 2 were quickly closed down. Attempts were made to defuel pile 1, but these were only partially successful, and an estimated 15 t of uranium metal fuel remained within the reactor core. Since then, the pile has been in a quiescent state and has been subject to surveillance and maintenance. The preparation to decommission the reactor is in progress, but the state of the core internals has remained mostly unknown during the shutdown. The lack of adequate characterization has led to a hiatus in the decommissioning programme. Hence, the initial step prior to dismantling was to better understand the status of the pile. Safety related issues that presented a number of technical challenges had to be addressed to enable the selection of a safe and cost effective option for decommissioning. Many of these challenges were addressed by research based studies and characterization work. It was feared that intrusive inspection into the fire affected zone of the pile could alter its structure, leading to serious accidents. Following clarification of these concerns, intrusive inspections were possible [76].

Experience at accident damaged plants suggests ways to overcome such difficulties. For example, at A1 nuclear power plant, laser scanning was extensively employed to characterize room layouts in inaccessible areas (see Fig. 21). The laser range finder system consisted of a laser, a receiver (such as a camera) and data processing equipment. For the structured light system, the position and direction of propagation of the laser beam were known and controlled. The camera showed the two dimensional projected position of the beam on the surface to be mapped. Knowing that this position was the intersection of the laser beam with the object, simple trigonometric calculations could be performed to determine the position of the point in space [2]. At A1, laser scanning was used because:

— High levels of contamination made rooms dangerous for employees to spend time in.
— Access was dangerous due to structural deterioration.
— As-built engineering drawings did not exist, or were unreliable.

FIG. 21. Laser scanners used to support characterization for the decommissioning of the A1 nuclear power plant, Slovakia. Image courtesy of VÚJE.

A comprehensive description of A1 decommissioning activities, with a focus on radiation protection aspects, is given in Ref. [77].

At Fukushima Daiichi, the soundness of fuels stored in SFPs was investigated. Corrosion of the vessels and components was a concern because of seawater injection into the fuel pools. Appearance checks for unused fuel removed from the unit 4 SFP were implemented, and it was confirmed that there was no significant damage or corrosion on the surface of the removed fuel.

Dropped debris collision tests were conducted to address the concern of deformation of fuel in a situation where debris falls from above. As a result, although there were handle deformations and bends in the fuel, elevation performance and the safety of fuel sealing performance was ensured [78]. After debris on top of the fuel racks was removed, fuel removal from unit 4 SFP to the on-site common pool started on 18 November 2013, and was completed without accident by 22 December 2014.

I.2.2. Radiation and contamination levels

TMI-2 experience shows that access to an accident damaged reactor is problematic owing to unknown radiation and contamination levels and their distribution within the plant. Typically, the accident-generated disruption of ordinary fluid collection routes (e.g. ventilation, liquid drainage) will imply the deposition of contaminated solids, liquids and gases in unexpected spots. It is also possible that the accident resulted in the seepage of contaminants out of controlled areas to sewage, trenches, rainwater collection points and ultimately to the environment, leaving a contaminated pathway all over the route. A scoping survey will then have many more uncertainties than in planned decommissioning.

Accessing areas contaminated by an accident will be restricted to shorter times owing to the need to control exposures to the workers. In addition, high contamination levels will dictate the use of heavy, clumsy, fully equipped PPE. The productivity of workers will be further impaired by environmental constraints. The need to become familiar with unusual PPE will impose strict training programmes, but it may also potentially open a gateway to various incidents. Technology offers ways to offset environmental concerns; for example, there is PPE available that reduces heat stress through the adoption of refrigerated tubes or other means [79]. To prevent hazards to workers, the use of robots is described in Appendix II.

In the context of the Fukushima Daiichi accident, a portable gamma camera was developed that allowed radiation hot spots to be found easily. Field tests took place in December 2011.

The portable gamma camera combines gamma ray data measured by its radiation sensor with an image taken by its camcorder using a signal processing device. It also uses different colours to quantify the radiation. It uses red for high levels of radiation and yellow, green and blue to indicate lower radiation levels.

The portable gamma camera was developed by Toshiba, who improved the performance and reduced the size of one of their former gamma camera models. The sensitivity and measurement capability was improved by about 30 times by embedding semiconductor detection elements and process signals and data. As a result, it became possible to detect a hot spot with a relatively low dose rate of 0.1 μSv/h (1 mSv/a). Furthermore, Toshiba reduced the weight of the camera by about half by using smaller electronic circuits and redesigning the shield used to take images of radiation while blocking off radiation around the camera [80].

At Windscale pile 1, the control and limitation of dose uptake to the operators has been achieved through careful planning, the use of inactive trials, thoughtful use of remote handling techniques (e.g. ROVs) and review and feedback of information. Detailed information is given in Ref. [81].

The following examples during the recovery phase of Fukushima Daiichi highlight unexpected events that are also quite possible during the decommissioning phase [82].

I.2.2.1. Hot spot identification

At the beginning of August 2011, two localized very high radiation fields were identified at a dose rate of 10 Sv/h. One high dose area was situated at the main exhaust tower between units 1 and 2, which was the location of the stack drain pipe. At the bottom of the stack drain pipe, the dose rate was measured by a telescopic detector to be 3.6 Sv/h. Another hot spot was detected in unit 1. The dose rate around the entrance to the train room for the standby gas treatment system on the second floor of the turbine building was determined to be greater than 5 Sv/h.

I.2.2.2. Management of on-site contamination

The accumulated water in the trench of the turbine building of unit 2 was transferred to the radioactive waste treatment facilities. The Fukushima Daiichi operator, Tokyo Electric Power Company (TEPCO), installed a second caesium removal system, called a simplified active water retrieve and recovery (SARRY) system, within the water treatment and waste removal system. The system uses a combination of absorption towers and oil separators. On 23 August 2011, it was announced that a dose rate of 3 Sv/h had been measured at an isolated point within the operating SARRY system. At this location, there was an air vent with a float. During the exchange of vessels, radioactive material passed the float and accumulated in the piping. After dissolving this material back to the vessel, the system was activated again.

I.2.3. Abnormal wastes and their management

I.2.3.1. Fuel and fuel debris

Damaged fuel and fuel debris are unlike any customary waste form. The content and shape of debris can vary significantly. It can be a mixture of ceramics, metals and possibly eutectics. The shapes vary from fine particles, to lumps of materials, to partially recognizable shapes. There is a possibility of relatively large amorphous masses of glass-like corium. The Chernobyl lava [83] offers another example of unusual fuel containing materials (FCMs).

Retrieval and packaging of FCMs may take several years. However, criteria are needed because they will affect design and operations.

The state of the art research into Chernobyl accident generated materials is quoted in the following as an example of activities required to reduce UUs in decommissioning after a severe accident [84]. More than 6000 available data of molten nuclear fuel and FCMs, measured at Chernobyl nuclear power plant site just after the accident and then during the subsequent 20 years, were analysed and systematized.

The following achievements are important to mention:

— Creation of a database on nuclear fuel state and activity at various stages of the active phase of the accident at Chernobyl nuclear power plant unit 4, including the formation of melt material and the spread of corium over the whole building;
— Determination of the uranium and zirconium concentrations in metallic melts in the compartments below the reactor;
— Computer evaluation of the FCM state.

The database and developed models are useful for the prediction of further behaviour of the reactor fuel and components, for assessment of doses over the site, for redesigning the Chernobyl shelter, for further on-site operation planning and also as a basis for designing the core catcher for new nuclear power plants.

Materials and technologies that are capable of producing stable matrices for immobilization of high level waste for retaining radionuclides at high temperatures, radiation and under dissolution have also been developed by the Interdisciplinary Scientific and Technical Centre (ISTC), including:

— Immobilization in basalt and basalt like matrices;
— Immobilization in porous matrices;
— Immobilization in glass, aluminium silicate glass ceramic and metal ceramic matrices;
— Development of technologies for partitioning of waste;
— Solidification technologies: solidification in an induction smelter with a cold crucible;
— Solidification using microwave heating;
— Development of technology for induction slag melting of zirconium alloys and stainless steel waste (the ISMW-CC process) and its validation using simulation materials in pilot and demonstration facilities;
— Development of technologies for recovery of palladium and promethium from spent nuclear fuel.

Finally, the ISTC have developed a number of corium studies, including:

— In-depth studies and theoretical modelling for understanding the physical–chemical processes taking place at the core melt interaction with the catcher and reactor vessel (experiments with 5–10–50–100–1200 kg of corium);
— Assessment of FP release to the reactor containment atmosphere.

The results improved the understanding of severe accident management, improved the accuracy of models for melt formation, corium phase diagrams, corium component interactions and the thermodynamics of corium behaviour inside the reactor vessel (with reactor core melting), and for corium interactions outside the vessel (with traps, shafts, concrete, sacrificial materials, etc.).

I.2.3.2. Processing of contaminated water

The processing of accident generated water starts during the recovery phase, and extends well into the decommissioning period. Contaminated water presents new features that are typically unsuited to existing waste treatment plants. Therefore, a testing campaign prior to operation of any new system is imperative. The Fukushima Daiichi case discussed below is exemplary: the need to cool the reactors forced the operator TEPCO to inject sea water into the reactor. Caesium contaminated sea water was untreatable by on-site systems [85].

One special problem in accident generated water is the presence of oil, which is a serious complication to waste treatment options [86]. Needless to say, the distribution of oil contaminated waste is a priori unknown under the circumstances.

The water treatment involved private companies working with TEPCO to set up cleanup systems to separate oil and then decontaminate and desalinate the basement water ready for reinjection. An example of this is the multinuclide removal equipment (advanced liquid processing system). Its purpose is to remove radionuclides from the contaminated water and reduce risks. It aims to reduce the levels of 62 nuclides in contaminated water to the legal release limit or lower (tritium cannot be removed). At the time of writing, water treatment remained a pressing issue after the Fukushima Daiichi accident. In 2014, about 400 m^3/d of water was circulated to keep cooling the cores of the three reactors. In addition, about 400 m^3/d of groundwater flowed into the buildings. Therefore, in total, about 800 m^3/d of accumulated contaminated water in the buildings had to be treated. After the treatment, 400 m^3/d of treated water were stored in on-site tanks. TEPCO had planned to install tanks with 800 000 t capacity by March 2015 [87].

In order to reduce the volume of accumulated contaminated water to be treated in the buildings, TEPCO pumps groundwater for bypassing before it flows into the buildings.

In addition, TEPCO has constructed land side impermeable walls with frozen soil. The walls surround the buildings with frozen soil and reduce groundwater inflow into the buildings. On-site tests have been conducted and completed successfully. Construction work started in June 2014 and tests of the frozen soil wall began in May 2015 [87].

I.2.3.3. Seawater challenges

The high radioactivity of the wastewater and the use of sea water to keep the Fukushima Daiichi cores cooled present particular challenges. Organic ion exchange material, traditionally used to remove radioactive elements from water, does not work in salt water.

However, testing by Kurion and an independent laboratory in Japan showed that inorganic material used by Kurion would be effective. The Kurion material focuses on a specific element and removes it, although it is not able to distinguish between radioactive and non-radioactive isotopes of caesium. The effect of the inability to separate just radioisotopes is minimal because of the overall capacity of the media to remove specific elements. Kurion's material is a modified herschelite, similar to that used to decontaminate fluids at TMI-2.

Areva have developed a decontamination system using chemical reagents and based on technology used at Areva's La Hague and Marcoule reprocessing facilities. The system removes caesium as well as strontium. The process includes mixing the wastewater with chemical reagents designed to capture radioactive elements, then passing it through a series of tanks for mixing with coagulants, micro sand and a polymer. In the next stage, radioactive material that has precipitated out or formed a colloidal solution is separated from the water, leaving a sludge that will be stored in an interim sludge waste storage facility.

The final stage of the water processing system is two desalination systems: one using reverse osmosis and the other using evaporative concentration. The desalination capacity will start at 480 t/d and increase in stages.

An overview of the water treatment system filtration/sorption modules for wastewater treatment that are transportable (skid mounted or mobile) is given below. The list is not intended to be exhaustive nor is preference intended for any of the systems mentioned below:

— The mobile modular system Aqua-Express was designed by MosNPO Radon, Russian Federation, for the treatment of liquid low and intermediate level waste (LILW), and can be optimized to address different needs. Treatment is achieved through a technological chain including filtration, sorption and ultrafiltration processes, and is designed to release non-radioactive salts together with the cleaned water. The system consists of three autonomous wastewater purifying modules and a sampling system. The system can be transported by road, rail or air. It can be installed in a standard ISO transport container. Its basic capacity is 300–500 L/h, and it is commercially available at short notice.
— A mobile nuclide removal system (NURES) was constructed and operated by Fortum Nuclear Services, Finland. NURES can be tailored to different needs, either as a fixed or as a mobile system. Owing to its flexibility, the mobile units can differ from case to case. NURES can be used for treatment of different liquids, including liquids with high salt concentrations. The system has been used for liquids with total salt concentrations up to 300 g/L. The first step in the process is an efficient filtering unit, which removes suspended radioactive particles. The next step removes target radionuclides as ionic radioactivity by highly selective ion exchange materials. The basic capacity with a standard 12 L column gives a processing flow rate of 120–240 L/h. Parallel use of columns or use of powdered material in cartridges can increase the capacity, and it is commercially available.
— A mobile filtration and ion exchange treatment system was utilized by Bhabha Atomic Research Centre, India, for treatment of alkaline intermediate level waste streams. The process involves passing the aqueous waste through a disposable filter cartridge for removal of suspended solids after on-line pH adjustment and then through a series of ion exchange columns for removal of ^{137}Cs and ^{90}Sr. The basic capacity with 100 L columns is 400–500 L/h. Note that this mobile system has not been offered on a commercial basis so far.
— A mobile multimodule facility, ECO-3, for the treatment and utilization of low mineralized low level wastewater was developed by MosNPO Radon, Russian Federation. The operation of the facility is based on sorption membrane purification technology and concentration of low level waste followed by conditioning of concentrate in the standard 200 L drums. It is a variant of Aqua-Express, but includes a waste conditioning module and is installed inside ISO shipping containers. It is commercially available.

— The floating waste processing facility Landysh belongs to the Zvezda shipyard in the Russian Far East (near Vladivostok). It processes low level liquid waste from submarines (evaporation technology), and its maximum capacity is 7000 m^3/a. The maximum salt content is 35 g/L. The facility was funded by the Japanese Government, designed by the USA, and built and commissioned in the Russian Federation in 2001. The facility can be transported by a heavy lifting ship. Note that this facility has always been used at one shipyard and has never been offered on a commercial basis to other companies.
— Potok-2 is a membrane sorption mobile facility for processing LILW with complex chemical compositions and salt contents up to 27 g/L. It can process LILW with an activity up to 109 Bq/L of beta particle emitters, and its capacity is 1 m^3/h. The facilities are provided by Ecoatom, located in Sosnovyi Bor (near St. Petersburg, Russian Federation). They have had good experience in the processing of waste from nuclear submarines and naval bases. One such facility is located in the Russian Far East at DalRAO Company.
— The submerged demineralizer system processed nearly 2500 m^3 of high activity contaminated water from the TMI-2 accident. The system was designed by Chem-Nuclear (now Energy Solutions) in collaboration with the US DOE (Savannah River Site and ORNL) [88].

It should be noted that nearly all commercial systems need to be optimized and configured for particular applications. System components and basic designs are available from many commercial vendors.

I.2.3.4. Concentrates from water processing

There will be ion exchange and filtration media resulting from processing accident contaminated water. Radiological and physical–chemical forms will be generally unknown a priori and in need of careful characterization. Much of them will contain high concentrations of ^{137}Cs. If evaporators are used, the concentrates will need to be collected and solidified. Highly radioactive isotopes such as ^{60}Co will also be captured, and the concentrates may also contain traces of uranium and plutonium. There can be highly radioactive sludge that includes foreign materials such as silt and organics.

There will be substantial volumes of processing concentrates that will be too radioactive for acceptance within low or intermediate level waste disposal facilities. Stabilization may be by solidification or within high integrity containers.

How to store, package and transport this material can all be affected by where it will be sent, or whether it will be on-site indefinitely. Some will be impossible to qualify for waste acceptance criteria for established disposal grounds.

It is desirable that criteria be established for these abnormal waste types for long term on-site storage and eventual disposal. The need for disposing of this material may be several years away, or longer. Therefore, there is a need to first develop criteria for long term storage on-site or off-site.

As one example of these uncertainties, Ref. [89] illustrates an application of a severe accident analysis code, MAAP, to the uncertainty analysis of FP behaviour in severe reactor accidents. The code employs many user options that support sensitivity and uncertainty analyses. The application described in Ref. [89] is focused on estimating the FPs in release and transport processes, and the relative importance of the dominant contributors to the predicted FPs. Key modelling parameters and phenomenological models employed for the uncertainty analysis described in Ref. [89] are closely related to FP release correlations, vapour–aerosol equilibrium, vapour–surface equilibrium for a revaporization calculation and aerosol decontamination factors. The Korean standardized nuclear power plant, OPR-1000, was used as a reference plant for the analysis [89].

I.2.4. Safeguards

It is impossible to accurately account for the special nuclear material in a core that has been melted or otherwise massively destroyed. The Fukushima Daiichi cleanup will need relief from normal standards for accountability just as was the case for TMI-2. The TMI-2 experience provides an example from which to formulate this relief. In that case, the approach was to measure what remained following fuel removal, as well as the weight of material removed. Accounting on an isotopic basis was not required.

There may be other standards that apply in normal situations from which relief will be needed for the Fukushima Daiichi cleanup. Initial identification should be carried out as soon as possible after an accident. Periodic follow-up should be conducted as the cleanup progresses. The timing for development of an approach for each identified requirements or standard, and for implementing the changes, should be decided on a case by case basis.

I.2.5. Implementation and regulatory responsibilities

Planning and implementation of decommissioning after a severe accident need to contain the following upper level policy attributes:

- Which organization will be responsible for implementing the decommissioning plan?
- Which organization will be responsible for independent regulation of the implementation of the plan?
- Additional social and political policy considerations should be addressed such as:
  - Governmental involvement;
  - Public involvement;
  - Safety standards;
  - Environmental protection standards.

The plan should address the fact that post-accident decommissioning implementation is very different to reactor construction or reactor operation. Therefore, it is likely that the implementing organization will be defined as a variation of a normal utility organization with changes to incorporate nuclear industry companies with decommissioning and decontamination expertise, along with the management ability to incorporate various necessary state of the art advanced sciences, such as robotics and advanced diagnostics.

The plan should clearly state the implementing organization's responsibility, as well as specify its authorities and ensure that resources are made available to achieve success [90].

The plan should specify the role of the independent regulatory authority. The regulatory authority and implementing organization should establish appropriate working relationships and processes to provide prompt regulatory decisions to support cleanup progress while providing assurance to the public that the decommissioning and remediation programme does not create inappropriate risks to the public and workers.

Both the regulator and the implementing organization need to recognize that traditional national reactor regulatory practices are not likely to be appropriate for post-accident decommissioning. Modifications will need to be made to incorporate risk based engineering judgement in consideration that post-accident conditions are uncertain and that timely decommissioning progress is important to reduce overall risk. Cost–benefit–risk reduction evaluations may be appropriate for some situations [90].

It is likely that a regulator forced to tackle the decommissioning of an accident damaged reactor will be exposed to some tough decisions. In a case of force majeure, decisions can be dictated by the need to prevent greater impacts to the public and the environment.

For example, this may concern the disposal of such large amounts of radioactive waste (or those having unusual properties) that preclude the use of ordinary, available waste disposal facilities. As is likely to be selected at Fukushima Daiichi, temporary storage of waste may be provided by municipal landfills, at least initially. Towns near Fukushima have responded cautiously to plans to build temporary storage sites for massive quantities of radioactive waste generated during the post-accident remediation activities.

Almost 8 months after the accident at the Fukushima Daiichi nuclear power plant, the Government said the facilities will not be ready for at least another 3 years. In the meantime, towns will have to store the contaminated waste locally, despite health concerns. Once completed, the storage facilities would hold soil and other contaminated waste for up to 30 years.

In general, it is expected that the application of the ALARA principle under accident conditions will be different from that under a planned practice, because urgency, higher costs, de facto constraints and societal concerns may play a major role.

At TMI-2, the operator encountered worker situations that were not fully appreciated at the outset. Examples included the following:

— From a radiological protection standpoint, the FP mix from uncontained damaged fuel was different from the familiar radiation sources at operating nuclear plants. Therefore, conventional radiological assumptions and rules of thumb were not valid.
— The combination of severe industrial and radiological threats can be particularly vexing. As a prime example, the combination of heat stress risks (e.g. for workers wearing multiple layers of protective clothing in high contamination areas), egress challenges (e.g. in congested, multistorey buildings without functioning elevators) and dangerously high radiation fields required new approaches to the planning and implementation of activities in radiation areas.

I.2.6. End state, including decontamination and dismantling strategies and techniques

Strategies for decommissioning after a severe accident can be conceptually different from planned decommissioning. Guidance should be developed to address the following, which would be some time prior to conducting final decommissioning:

— At what point does the accident cleanup end with the facility either in a monitored storage mode or ready to proceed to the next phase of decommissioning?
— How would this be applied to part of the overall facility or areas being cleaned up?
— How would this apply to events of lesser severity than that involving fuel damage?
— For final decommissioning, guidance should be developed that addresses the following:
  • What are the options for the ultimate end state and conditions for the site and facility, including residual radioactivity? What safety and pathways analyses are needed to evaluate options?
  • Should part of the facility be permanently entombed or must all of it be removed and transported elsewhere?

The decommissioning plan should specify the general end point of the project. Following early stabilization work, initial TMI-2 activities, such as auxiliary building decontamination work, were undertaken without clear understanding of how these activities contributed to the desired plant end state — simple questions such as 'how clean is clean enough?' were unanswerable. As a result, significant effort was expended on tasks that were either unnecessary or would have to be repeated later. In summary, it is pivotally important to define both the ultimate condition for the plant and the interim milestone conditions to be achieved on an orderly path to that final end state. These need to be reduced further to specific end states for all plant systems, spaces and components, each based on clear need, defined in quantitative and practically achievable terms, and prioritized and sequenced. At TMI, eventually the end point was defined as the damaged reactor being defuelled and in a physical condition that was not (radiologically) very different to that of a normal end-of-life reactor plant (named postdefuelling monitored storage). This end point allowed the damaged TMI-2 reactor to be kept in a safe store until its companion operating reactor, TMI unit 1, was ready for its end-of-life decommissioning. At that point, both reactors could undergo a cost effective normal joint reactor decommissioning project.

It should be noted that decommissioning strategies uncommon in a planned shutdown may be adopted if the radiological and physical consequences of a severe accident make it hard to access the remaining SSCs for dismantling purposes. In such cases, grouting the structure in concrete could be a way to reach a safer state, pending decisions on future dismantling. This approach is likely to be decided on a case by case basis. For example, construction of the sarcophagus covering the destroyed Chernobyl unit 4 was started soon after the accident in May 1986 and completed by the Soviet authorities in an extremely challenging environment 6 months later in November. It was quickly built as a temporary fix to channel the remaining radiation from the reactor through air filters before being released to the environment. After several years, uncertainties about the actual condition of the sarcophagus, primarily due to the high radiation environment, began to emerge.

In 1997, the countries of the G7, the European Commission and Ukraine agreed that a multilateral funding mechanism should be established to help Ukraine transform the existing sarcophagus into a stable and environmentally safe system through the Chernobyl shelter implementation plan. The Chernobyl Shelter Fund was established to finance the plan. The European Bank for Reconstruction and Development was entrusted with managing the fund. The plan is intended to protect the personnel, population and environment from the threat of the very large inventory of radioactive material contained within the existing sarcophagus, for many decades. First, the existing sarcophagus will be stabilized, and then, eventually, it will be replaced with a new safe shelter (confinement). New shelter construction started in the late 2000s, with a design to include an arch shaped steel structure, which will slide across the existing sarcophagus via rails. This new structure is designed to remain functional for 100 years.

In terms of decontamination and dismantling technology, one should start with Ref. [91], which best serves as an idea generator for engineers faced with similar problems. However, many of the detection systems, remotely operated devices and video systems it describes have been surpassed by technology. Others are specific to the problems of TMI-2 and Chernobyl. The publication was generated by the experience of a limited number of individuals plus a questionnaire for which responses were dependent on companies that wished to submit their product descriptions. Its purpose was to provide information about methods and equipment to manage a nuclear fuel damage event.

Reference [91] is organized into six categories: (i) defuelling, (ii) data acquisition, (iii) personnel protection, (iv) safety, (v) waste management and (vi) decontamination. Note that the four entries in the safety category could well have been placed elsewhere.

With today's ability to search the Internet, it is much easier to find tools and equipment for all but one category of the activities. The exception is defuelling, which describes removal of damaged fuel and debris. Therefore, it is desirable to address that information which may not be readily available via the Internet. It also considers events that are less significant than the ones involving fuel meltdown. In particular:

— Specific effort should not be expended on any of the categories except for defuelling.
— Consideration should be given to creating descriptions of methods and tools for removing and packaging damaged nuclear fuel. The initial population would be taken from Ref. [91]. It could be expanded based on experience gained since the 1990s, and further expanded to include that developed in the future for the Fukushima Daiichi cleanup.
— Additional consideration should be given to expanding the scope beyond damaged fuel to include special methods and tools used in high radiation situations or other highly radioactive material and contamination cleanup.

Extensive experience from the TMI-2 cleanup is collected in Ref. [92]. The whole series of TMI-2 related reports under Ref. [92] includes:

— Volume 1: reactor coolant system and systems decontamination;
— Volume 2: reactor building decontamination;
— Volume 3: reactor defuelling and disassembly;
— Volume 4: auxiliary and fuel handling building decontamination;
— Volume 5: common support facilities and systems operations;
— Volume 6: plant stability and safety activities;
— Volume 7: liquid waste handling;
— Volume 8: solid waste handling;
— Volume 9: radioactive waste and laundry shipments.

At TMI-2, the operator encountered defuelling surprises at every turn, particularly in the form of wide variations in the characteristics, location and configuration of damaged fuel — variations that dictated near constant adaptation of defuelling tools, including development over time of more than 100 end effectors for gripping and retrieval of fuel material. The operator employed a full dimensional mock-up of the defuelling system in a non-radioactive area for trial and error and operator training on tool revisions. Fortunately, the base system was simple and adaptable enough to accommodate this ongoing evolution.

I.2.7. Records and data management

It is noteworthy that an adequate record management system should be in place during decommissioning to minimize planning and operational mistakes. This is particularly true for accidents, as any (presumably scarce, owing to UUs) information collected should be adequately processed and shared in real time to aid in planning for and implementing decommissioning. It is expected that acquisition and processing of records will be much more difficult after an accident than in normal circumstances; this is due not only to the access difficulties in garnering data, but also to the irregular, unpredictable dispersion of contamination following an accident, which can make statistical assumptions arbitrary. Yet an accidental situation will require as many reliable data as possible to reduce UUs during subsequent activities. A potentially conflicting situation is thus possible, where on one side, more contingencies are needed to cope with UUs during post-accident decommissioning, and on the other side, the hazards associated with UUs are higher.

The record keeping will benefit not only the decommissioning workers, but also the decommissioning community at large. The experience of the TMI-2 cleanup was well recorded during and at the end of the cleanup. The report EPRI-NP-6931 [93] and three companion reports give a comprehensive record of the TMI-2 cleanup. In particular, they focus on decisions, options, what went wrong, what was successful, why certain choices were made, etc. The current IAEA guidance (see Bibliography below) is much more generalized than these reports, which is why they were published.

Although these reports were written towards the end of the TMI-2 project, there were many smaller topically focused reports that were written as the cleanup progressed. These provided valuable inputs to the final reports.

Recording the Fukushima Daiichi recovery and cleanup should be carried out. The conditions are very different to either TMI-2 or Chernobyl, and there will be many decisions not previously faced, with different outcomes. Much of the cleanup will provide new lessons. Reference [94] describes the salient features of a record management system being developed for the aftermath of the Fukushima Daiichi accident.

I.2.8. Resources

The unpredictable nature of severe accidents makes it difficult to assess the human, scientific, technical and financial resources needed for decommissioning. The lack of resources of any type may determine the UUs to be tackled less efficiently. Post-accident cleanup involves a large number of individuals and skills. At TMI-2, there were approximately 1000 persons working on the cleanup during the project’s 10 year duration. As fuel removal was completed, a technical approach was developed to reduce the effort while placing the facilities in conditions that would be safe, stable and able to be monitored over a long period of time.

Resources needed for a major cleanup include personnel, equipment and examination facilities that have past use and experience with high radiation materials and damaged fuel. In countries where severe accidents have occurred to date, the technical resources to deal with the cleanup have generally been available. This may not always be the case. The results can be based on activities required to respond to a range of accident scenarios:

— Beyond design basis accidents such as at Windscale, TMI-2, Chernobyl and Fukushima Daiichi;
— Less serious events such as at A1 in Slovakia;
— Research reactors.

The recommendation is to describe in detail the requirements for cleanup after an accident that has involved significant damage to nuclear fuel. This would be conducted at a functional level combined with detailed capability descriptions for personnel, equipment and examination facilities that would be needed, for what they would be used and the time frame of the requirements.

During this effort, it is very important to involve individuals with direct experience in past events that are representative of the first two scenarios listed above. Extending the results to research reactors will require individuals who can realistically postulate corresponding events at these types of facilities.

I.2.9. Organization and management, including stakeholders

Decommissioning after a severe accident is likely to require different organization and management than following planned shutdown. Aspects such as those listed below will be different, and will affect organizational and managerial decisions:

— Technical competences, contractors and specialists;
— Planning;
— Stakeholders;
— Timing;
— Expenses.

A brief comment on the above items follows. For a typical case, the reader is encouraged to read Ref. [95]. As an introductory note, it may happen that UUs dictate more organizational flexibility than in normal circumstances. Following a severe accident, the expertise required will go far beyond that required under routine decommissioning conditions. This is due, for example, to the need to deploy and be trained in novel (unproven) technologies. One such technical area could be robotics for use in hazardous environments. Another could be the management of abnormal, unique waste. The pool of contractors and specialists in these technologies is necessarily more limited than for routine circumstances; in some cases, there might be very few companies that have enough experience/expertise in certain technologies. If so, the identification and selection of these companies may not follow the usual tender and bid process. The deployment of US robots in the Fukushima Daiichi accident, as mentioned in Appendix II–3, is a case in question.

In post-accident decommissioning, the planning process will be necessarily slower than after planned shutdown, taking into account the numerous UUs to be expected. It is inevitable that any such decommissioning plan will be less detailed and include more contingencies and more flexibility than in more normal circumstances. Deviations from a preliminary plan will be common in the course of the work. A plan of this kind may be hard to digest for the regulators, who will have to establish new approval and inspection procedures. On either the decommissioner's or the regulator's side, the decision making process should be adaptable to changes in real time.

While participation of a wide range of stakeholders is a desirable component of any decommissioning project, it is likely that post-accident decommissioning will see the active, even anxious, involvement of many more stakeholders. These may include: delegations from segments of the general public, either locals or public opinion groups; the media; international bodies; shareholders; funding bodies; etc. In turn, the decommissioner's organization (and the regulatory body, the government, etc.) will have to set up dedicated structures in charge of communicating information and responding to the concerns of all stakeholders. Whereas, in principle, planned decommissioning is well received by most stakeholders, decommissioning after an accident is likely to face a rebellious attitude on the part of many stakeholders, and they may feel reluctant to cooperate with those perceived to be responsible for their situation.

Public distrust after an accident translates to understandable public and political opposition and non-constructive intrusion to the recovery work. The overriding lesson here is that people do not trust (or distrust) a technology, they trust (or distrust) those who implement it. This perception is likely to inject more UUs into the decommissioning project.

The presumably long times of a decommissioning project after a severe accident (either at Chernobyl or at Fukushima Daiichi, the expected duration of decommissioning spans several decades) will strongly affect the organization and management of the project. It can be expected that considerations that are applicable to deferred dismantling will be in order, including staff turnover, regulatory changes, etc. In addition, unlike situations in which deferred dismantling of a plant shutdown takes place under planned circumstances, the high radiation/contamination levels and the UUs expected to remain permanent in a post-accident state will mean that organization(s) responsible for the plant will need to be strictly supervised and periodically restructured over long time spans.

One organizational aspect of decommissioning, the flow of expenses expected in a post-decommissioning scenario for a long time, is worth a specific mention. The costs of decommissioning a reactor after a severe accident are hard to estimate and are subject to a number of UUs. They will ultimately be much higher than after a planned shutdown (according to some estimates, even an order of magnitude higher). To ensure a regular cash flow, it will be crucial that funding bodies guarantee the funding availability throughout the entire decommissioning project.

If there is a lack of such assurance, it is likely that post-accident decommissioning will last even longer, ultimately resulting in higher costs, if spread over a longer time horizon. The inevitability of UUs during decommissioning is likely to add unforeseen expenses (e.g. the discovery of hidden or underground contamination), and cause further delays.

I.2.10. Further IAEA information and guidance related to severe accidents involving damaged nuclear fuel

Management of Severely Damaged Nuclear Fuel and Related Waste, Technical Reports Series No. 321 (1991) [39]. This publication addressed a broad spectrum of activities for post-accident management leading to an end state in which the potential for uncontrolled release to the environment no longer existed. The contents were derived primarily from experiences at Chernobyl, TMI-2 and studies conducted in Sweden.

Cleanup and Decommissioning of a Nuclear Reactor after a Severe Accident, IAEA Technical Reports Series No. 346 (1992) [96]. The purpose of this publication was to provide an overview of factors relevant to the identification of cleanup requirements and to the choice of a decommissioning option for a severely damaged nuclear power plant.

Issues and Decisions for Nuclear Power Plant Management after Fuel Damage Events, IAEA-TECDOC-935 (1997) [97]. This publication addressed fuel damage events that were less serious than the Fukushima Daiichi/TMI-2 accidents. Its purpose was to serve as a management checklist for on-site activities associated with in-plant systems, processes and fuels.

Experiences and Lessons Learned Worldwide in the Cleanup and Decommissioning of Nuclear Facilities in the Aftermath of Accidents, IAEA Nuclear Energy Series NW-T-2.7 (2014) [98]. This publication reviewed experiences that were relevant to the cleanup and decommissioning of nuclear facilities in the aftermath of accidents, and provided an overview of lessons learned worldwide. It also updated information from earlier publications on this topic, according to the different phases of activity after the accident had been declared ended (site stabilization, post-accident cleanup and safe enclosure) and, in the longer term, final decommissioning and site remediation. The focus of the publications mentioned above is mainly on on-site activities. There are other publications related to off-site remediation that are not listed above.

The IAEA report on Fukushima Daiichi accident [99] was published in September 2015, following three years of preparation involving some 180 experts from 42 IAEA Member States and several international bodies. The report and its five technical volumes distill and assemble lessons learned from the accident and provide a knowledge base for the future. They consider the accident itself, emergency preparedness and response, radiological consequences of the accident, post-accident recovery and the activities of the IAEA since the accident.

Appendix II

REMOTE OPERATION AND ROBOTICS

II.1. INTRODUCTION

While in almost all decommissioning situations, hands-on operation by workers is acceptable, in certain conditions, it is not. For example, when a work area contains a hazardous environment, such as a high radiation field or a chemically contaminated atmosphere, human presence should be limited to maintaining safe operating conditions. For a manually operated system, limiting human presence means limiting operating time and thus productivity. Therefore, it is often desirable to provide equipment that can be operated from outside the hazardous environment in order to overcome these limits. This is the primary reason for using remotely operated equipment. Some other reasons include reutilization of facility resources, improved safety environment, cost reduction and accessibility to hard to reach work areas. In decommissioning projects where remote equipment must enter hazardous environments, it is important to remember that the equipment should be kept simple or be proven under a variety of similar circumstances. This is done to ensure the success of the equipment's intervention, to prevent loss of time and effort, and to minimize exposure to hazardous environments caused by retrieving a failed piece of remotely operated equipment [96].

Developing remote equipment for any one of the decommissioning tasks can be considered a project, or part of a project, that will develop equipment for multiple functions. Each task may take weeks or months, depending on its complexity and what components are already available that can be adapted to the situation; in many situations, complete development will be required.

The challenges for each project are twofold. One is dealing with the complexity of each unique application above. The second is how to tap into the insights for what is needed that are best known by operators, engineers and the technician that will be responsible for the ultimate application of the technologies and who will be gaining experience as the cleanup proceeds [93].

Current decommissioning systems utilize virtually all advanced approaches used in other nuclear and non-nuclear industries. These include not only advanced electronics and the design of robots, but also virtual reality and software that make robots intelligent and adaptable to a variety of tasks. Positive experiences have been had with industrial robots and remotely operated equipment in non-nuclear sectors, especially those that deal with hazardous materials (e.g. the chemical industry) or with special and difficult tasks (e.g. the defence or space industries).

In general, two main categories of remote operation/robotics can be identified:

— To characterize a high radiation/contamination environment in view of anticipated work;
— To conduct decontamination and dismantling work remotely instead of using a hands-on method.

For the purposes of this publication, remote operation/robotics are intended as a means to prevent unexpected events and related impacts on workers. While this objective is typical of characterization efforts, there are some decommissioning activities that could be prone to unexpected events by their very nature; for example, clearing the working environment of concrete debris and other miscellaneous waste would determine a cleaner environment, with fewer unexpected events

The decision to adopt remote operation or robotics systems needs to be, in many cases, supported by a cost–benefit analysis comparing manual, semiremote and remote implementation of decommissioning tasks. The costs of the remote operation and robotics equipment should be compared with the benefits in dose and decommissioning time reduction resulting from the use of this technology. Prevention or mitigation of unexpected events introduces a probability factor that should be factored in. Semi-remote operation can be viewed as a trade-off between the manual and fully remote alternatives.

II.2. REMOTE PHYSICAL AND RADIOLOGICAL CHARACTERIZATION FOR DECOMMISSIONING

Physical and radiological characterization is a necessary prerequisite for the planning of decommissioning tasks. Characterization is especially important in cases when available information (e.g. operational records, drawings) is obsolete and inaccurate. Various techniques have been developed and used for physical characterization in decommissioning, for example, standard photography, photogrammetry, laser scanning, etc. Radiological characterization includes measurements of surface contamination and radiation doses, gamma imaging, taking of samples for analysis, core drilling, etc.

Remotely operated and robotics technologies used for the physical and radiological characterization in decommissioning are rather small tools with high flexibility and mobility. Many small mobile ROVs and robots that can carry tools for physical and radiological characterization have been developed. Horizontal, inclined or even vertical movement or movement through and/or around barriers must be ensured, if necessary. The equipment can move autonomously (i.e. without an operator’s direct control) based on preprogrammed internal algorithms; however, in most cases, the equipment is controlled by an operator (cable or wireless control). In some special cases (e.g. underground, difficult-to-access structures, vessels or pipes), long reach manipulator arm(s) or other special equipment need to be used for characterization. The reach of a snake arm can be about 15 m. In telescopic tubes, the reach can be up to 25 m.

The requirements for flexibility and mobility of the remotely operated and robotics technologies for physical and radiological characterization can significantly affect the design of these systems. Their dimensions must be sufficiently small to allow access to any part of the area to be characterized. The carrier must be sufficiently robust to allow the carrying of all characterization tools, for example, a digital camera, radiation detectors, an infrared camera, sampling probes or tools for measurement of hazardous substances. An independent lighting system is usually carried along with the characterization tools.

Limited dimensions and loads of this equipment usually limit further utilization for subsequent decommissioning activities, although this is not a rule, and the equipment can be designed and used for repeated applications. The same equipment can be used, for example, for the retrieval of liquid and solid radioactive waste, and later on for the spreading of decontamination agents.

II.3. EXAMPLES OF REMOTELY OPERATED AND ROBOTICS TECHNOLOGIES USED FOR PHYSICAL AND RADIOLOGICAL CHARACTERIZATION

The following examples of remotely operated and robotics technologies for physical and radiological characterization do not represent a full list of worldwide applications. This is only basic information on technologies that can serve as examples of successful implementation.

Many other mobile robots for characterization purposes have been developed worldwide (e.g. in Belgium, Canada, Germany, France, Japan, Russian Federation, the UK and the USA). For example, the mobile automated characterization system, designed to autonomously characterize large floor areas, was developed at ORNL and used for the floor radiation survey of the Chicago pile 5 facility (CP-5) at ANL. The mobile robot ANDROS Mark IV was used for characterization and inspection of tunnels at the U plant on the Hanford Site. A very flexible snake arm robot SAFIRE with 18 degrees of freedom was used to perform outage inspections in a Candu reactor, and it also had very wide utilization for characterization for decommissioning needs. Several vehicles for remote underwater characterization have also been developed.

Another small mobile robot (ROV) is used for monitoring and characterization tasks. This mobile robot can also be used for light duty tasks such as vacuuming of sludge or spent ion exchange resins, and removal of small pieces of solid radioactive waste. The electrically powered mobile robot consists of a remote vehicle platform, which bears a small robotics arm with various end tools (e.g. grip jaws, wire loop, permanent magnet), a box for storing smear samples or small objects, lighting and a camera. Some other examples of mobile robots that can be used for characterization, and also for other decommissioning tasks, are given in the following.

As an example of non-vehicle remotely operated technology, one can quote the pipe explorer surveying system, which has been demonstrated at the CP-5 research reactor. This system transports characterization tools into pipes and ducts (see Fig. 22).

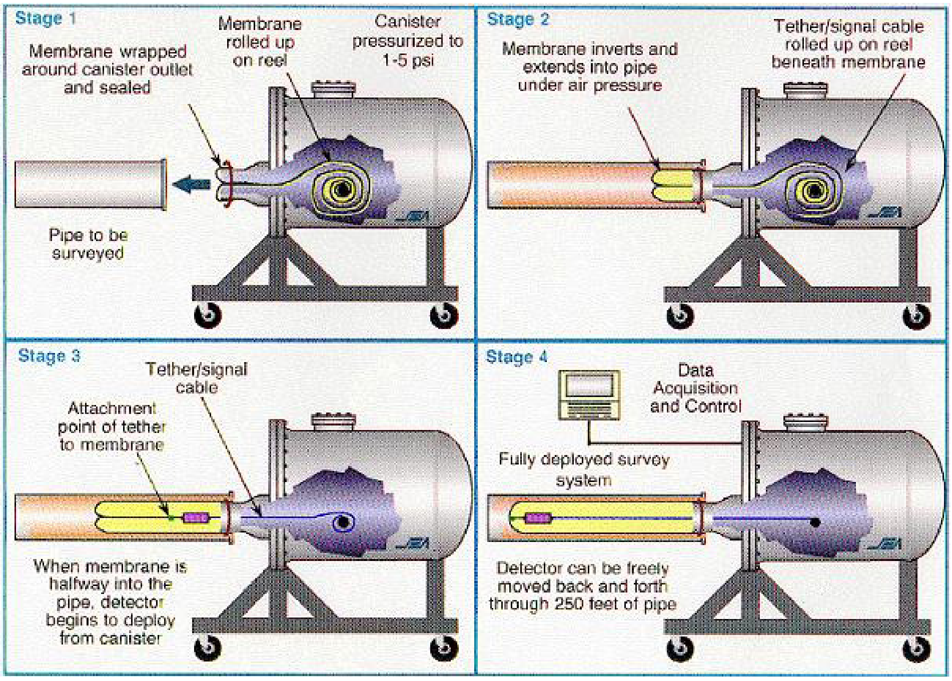

FIG. 22. Deployment of the pipe explorer system. Image courtesy of US DOE.

Robots from the USA were used to enter the Fukushima Daiichi buildings and provide initial views inside. Two Packbot robots were used in early efforts to ascertain the full extent of the wreckage inside the units (see Fig. 23).

FIG. 23. A Packbot robot at work inside Fukushima Daiichi Unit 3, Japan. Image courtesy of TEPCO.

The first Japanese robot used at Fukushima Daiichi nuclear power plant site was the Monirobo (monitoring robot) that was deployed during the second week following the accident. Monirobo was designed to operate at radiation levels that are too high for humans. The 1.5 m robot runs on a pair of caterpillar tracks and has a manipulator arm for removing obstacles and collecting samples. Sensors include a radiation detector, a 3-D camera system, and temperature and humidity sensors.

Another Japanese robot used at Fukushima Daiichi was the robot Quince, developed by scientists at the Chiba Institute of Technology and other universities. The robot had been reinforced with new radiation protection features to make it suitable for use at Fukushima Daiichi, and was used in six missions between 24 June and 20 October 2011. An example image taken by the robot is shown in Fig. 24.

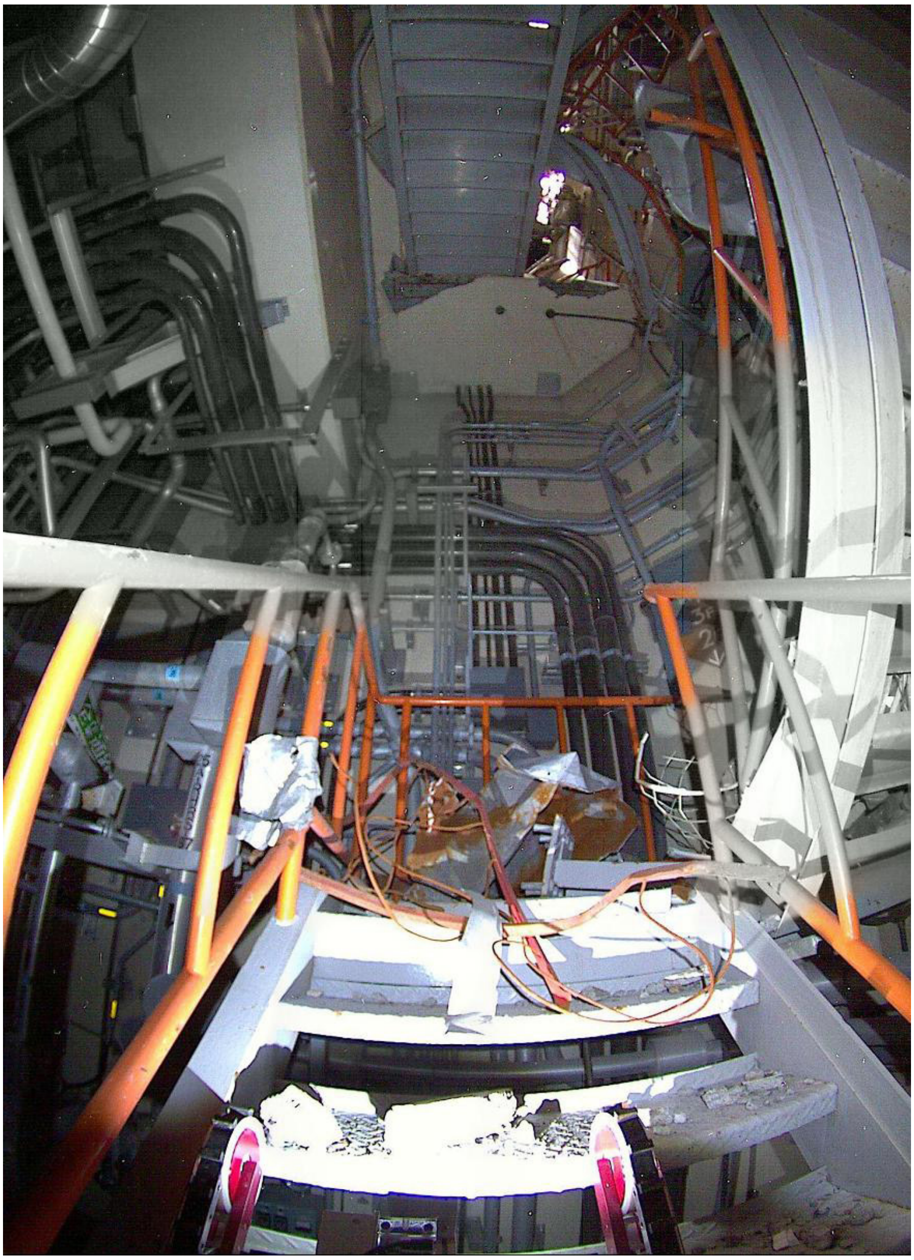

FIG. 24. Image of Fukushima Daiichi Unit 3, staircase from second to third floor, taken by the robot Quince on 26 July 2011. Photograph courtesy of TEPCO.

The first adaption made was to shield the robot from extreme radiation. A 13 mm thick lead cover was used to protect Quince's controller, increasing the robot's weight by 21 kg to 47 kg.

Secondly, it was necessary to devise a way of operating Quince remotely from distant locations, because the robot's existing wireless system would have malfunctioned inside the fortified reactor buildings. A 450 m cable was used to link Quince and the engineers operating it, which introduced new problems as the cable is in danger of snapping when the robot is moving among or on top of debris, and it also has to be retracted automatically to prevent the robot itself from damaging the cable.

Quince has some advantages over the Packbots: the quality of the photographs it takes is higher and it is better at navigating stairs. Quince can easily be reprogramed when TEPCO workers submit new specifications, as it does not contain confidential defence technology, unlike the Packbots. However, Quince became stuck inside the unit 2 reactor building when its cable snapped in October 2012 [100].

The latest examples of advanced robots developed for difficult tasks of the Fukushima Daiichi decommissioning are shown in Figs 25 and 26. Several decontamination robots are to be used to apply various decontamination techniques [101].

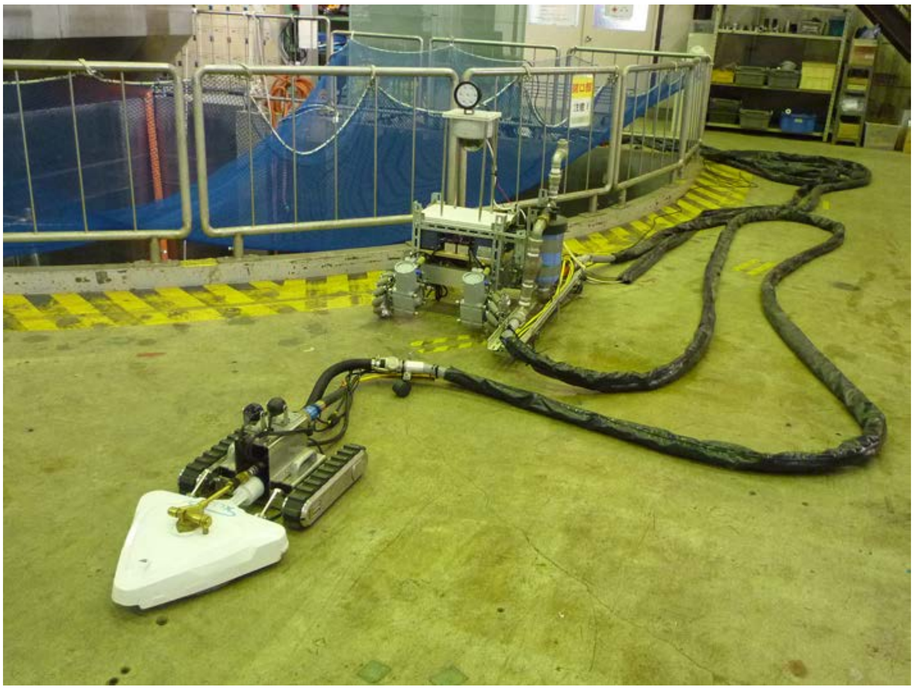

FIG. 25. Travelling and relay units used for decontamination work on the first floor of Unit 2 of Fukushima Daiichi. Photograph courtesy of TEPCO.

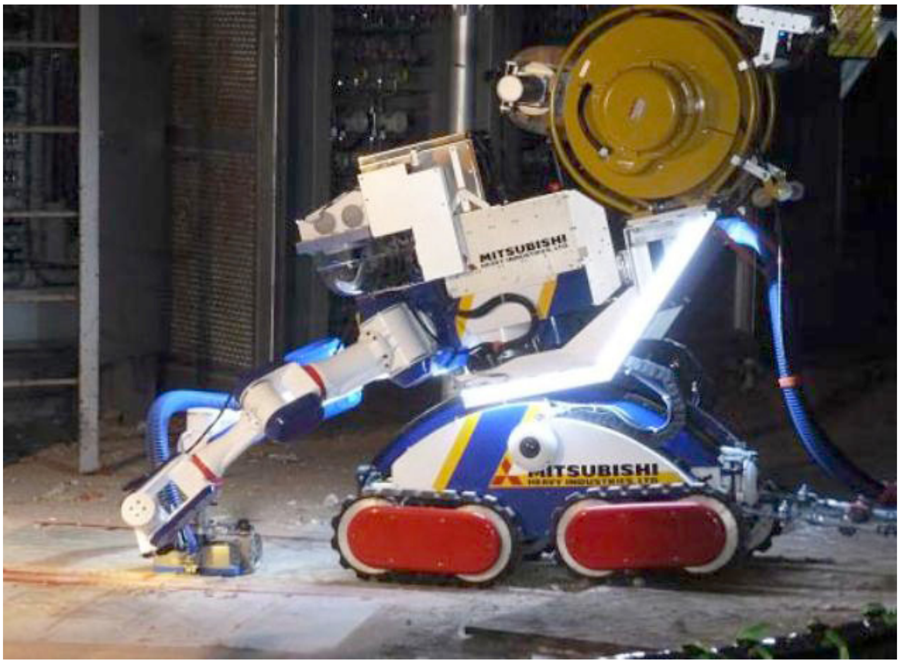

FIG. 26. Remote controlled decontamination device. Photograph courtesy of TEPCO and Mitsubishi Heavy Industries.

II.4. GENERAL PURPOSE ROBOTS

General purpose robots, such as the Remotec ANDROS or Rovtech Scarab, can be used for a number of different tasks. They can navigate in unstructured environments, they have an efficient vision system and a mechanical arm that allows for a wide range of actions. The first robots that were sent to Chernobyl failed because of a lack of radiation hardness or because their tethers became stuck in the rubble. The then USSR was the first to design a robot especially for the site of the Chernobyl accident. The Mobot-ChHV was on-site as soon as August 1986, and successfully cleaned the roof. It was equipped with electromechanical actuators, but did not have any on-board electronics. In the following years, many robots have been developed and have accomplished a wide variety of tasks at Chernobyl. These include a video inspection robot, a boring and drilling robot, a dust and air cleaning robot and a few dismantling robots.

An example of a robot designed to explore the inside of the Chernobyl sarcophagus is the result of USA–USSR collaboration. This robot is called Pioneer, and it uses many features of the successful Redzone Houdini vehicle. Pioneer uses a fully electric track based platform, and the modularity of the vehicle means that each separate module can be transported into the Chernobyl building separately; final assembly takes place close to the work location. Pioneer carries a remote viewing system, a concrete sampling drill, a manipulator arm, a sensor package and a plough bucket at the front of the vehicle [102].

II.5. CONCLUSIONS

Development and deployment of remotely operated and robotics technologies for decommissioning have created much relevant experience. Although the general experience is mostly positive, some challenges for the future still remain.

Technical improvements of the remotely operated and robotics technologies are still needed. These include increasing the equipment flexibility and reliability, and the optimization of other operational factors.

The improvement of human–machine interfaces is another challenge. This includes advanced development of all hardware devices and software tools necessary for effective control of remote operations. In the broader sense, it also includes the improvement of training procedures and hands-on skills of operators.

The economical challenge to decrease costs for development, manufacturing and operation of remotely operated and robotics technologies seems to be in contradiction with the previous challenges. However, technical and operational feedback may result in the decreasing of costs while the technical and operational parameters are being improved.

The most common lessons learned can be summarized as follows:

— Already available equipment and tools should be considered before the planning and design phase of the decommissioning.
— Innovative technologies should be evaluated with caution.
— The design of equipment must be as simple as possible, but it must also ensure performance of all required functions.
— The human–machine interface should be user friendly.
— Certain technical aspects could be improved, for example, less vibration during cutting, cable (tether) management.
— Maintenance of equipment and tools should be performed regularly to avoid technical difficulties and failures.
— If commercially available tools are used, it is recommended to purchase spare parts of the most important modules (e.g. cutting tools or robotics arm). This will save time for decontamination or repair of damaged module(s).
— Utilization of mock-up models and software simulation tools improves training of operators and allows testing of various operational modes.
— Managers and operators should have a plan for contingencies. Decommissioning projects may vary, and unexpected situations occur frequently.

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Annexes

EXPERIENCES FROM INTERNATIONAL PROJECTS

The examples provided in these annexes cover experiences from international projects on the decommissioning of both large and small facilities. The annexes contain a number of project examples where events took place that were not expected and which caused an impact on the decommissioning programme.

Although the information presented is not intended to be exhaustive, the reader is encouraged to evaluate the applicability of these examples to a specific decommissioning project. These international annexes reflect the experience and views of their contributors, and, although generally consistent with the main text, they are not intended as specific guidance.

Annex I

CZECH REPUBLIC

I–1. INTRODUCTION

After more than 55 years of activities at the ÚJV Řež, a. s. (Řež Nuclear Research Institute) (ÚJV) in the nuclear field, there were some obsolete nuclear facilities that needed to be decommissioned. Decommissioning of nuclear facilities at the ÚJV is the only ongoing decommissioning project in the Czech Republic. Decommissioning started in 2003, and will be finished in 2016. Some facilities have already been successfully decommissioned. During the decommissioning, many unknowns were identified.

I–2. PREPARATION FOR DECOMMISSIONING

The first step in the preparation for decommissioning started in 1996, with the collection of design and operational documentation, records, procedures, equipment and radioactive waste inventories. It also included interviews with current and former, or retired, staff. The interviews were very important; however, they needed to be treated with caution, because it is likely that many of the recollections of the staff will be unreliable.

The first stage of the analysis of the information collected identified the extent of the information that was missing. This was followed by detailed characterization of sources of radiation and contamination using radiometric and chemical analyses.

During the characterization process, many areas were found to be inaccessible without significant intrusive engineering such as cutting holes in walls. It was decided not to attempt to access these locations, if there was a risk of release of radionuclides or loss of integrity.

A safety analysis report [I–1] was prepared. This included the identification and characterization of potential sources of risk, individuals who could potentially be exposed and exposure pathways. It also included potential chemical compounds, radionuclides and other hazardous materials. The safety analysis report was approved in 2000.

Based on the results of the safety analysis report, the priorities of the decommissioning were identified, the decommissioning procedures prepared, and the decommissioning and waste management costs estimated.

The decommissioning programme was then divided into two phases based on the level of risk and the availability of funding. The decommissioning project [I–2] was then commenced, and both the programme and the procedures updated as necessary during the implementation [I–3].

I–3. GENERAL UNKNOWNS

There were several unknowns identified during preparation and execution of decommissioning, mainly connected with the facts that:

- Facilities were designed and installed in the 1950s and 1960s.
- Operational procedures were less stringent than those used today.
- Some facilities were not shut down properly (their operation was only intended to be interrupted, but they were never restarted or fully shut down).
- Many facilities had been out of operation for a long time.
- There was almost no regular maintenance or service of facilities that were out of operation.

During preparation for decommissioning, further unknowns were identified:

- Design documentation did not correspond to the actual state.
- Many modifications or upgrades were made without adequate documentation.
- There was a lack of documentation, working procedures and operational records.

— There was a lack of inventory of equipment, materials, radioactive waste, etc..
— There was a lack of limited radiation survey information.

The use of information gathered about the decommissioning must be used with care in order to minimize the risks while not overemphasizing potential difficulties, as both will have impacts on cost and schedule.

Competent decommissioning requires engagement with stakeholders. It includes identification of the stakeholders and implementation of a proper means of communication with each of them. Accurate information has to be delivered to them, on time, and also in a form that is easy to understand without risks of being either under or overestimated.

I–4. DECOMMISSIONING OF A SPECIAL SEWAGE SYSTEM

The special sewage system was used for transfer of liquid radioactive waste from various facilities to a radioactive waste processing facility. The system consisted of a stainless steel pipe network of a total length of 410 m situated in an underground concrete corridor that was accessible through shafts (see Fig. I–1) [I–4]. The integrity of the system had never been tested.

The decommissioning procedure started with the removal of soil and opening of the corridor. During excavation works, it was discovered that the pipeline was partially laid in another location (see Fig. I–2). This unknown has practically almost no impact on decommissioning, but in the case of excavation work in the past, the system could have been damaged.

FIG. I–1. Special sewage system shaft.

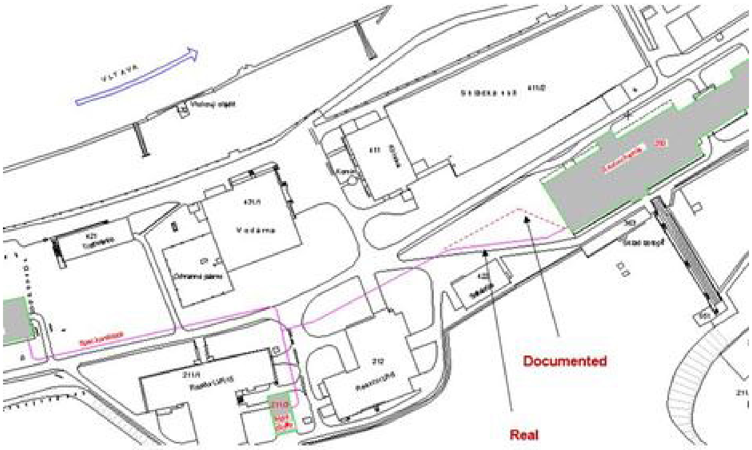

FIG. I–2. Map of the special sewage system: documented and actual (marked 'real').

As part of the decommissioning process, pipes and other steel components (valves, fittings, etc.) were removed. During removal, it was found that the material quality of the installed pipes was lower than had been specified by the design, resulting in leaks in the past and in partial contamination of the concrete corridor. The concrete surfaces were therefore removed, and the resulting waste disposed of as radioactive waste. This decommissioning began in 2004, was finished in 2005 [I–5], and a new sewage system has since been installed. The old concrete corridor was renovated and used for installation of the new system, which was also equipped with a leakage monitoring system.

I–5. DECOMMISSIONING OF THE FACILITY FOR RADIOACTIVE WASTE TREATMENT

The old radioactive waste treatment facility comprised an evaporation unit, storage tanks and a set of mixed bed filters. The plant started operation in 1962, and was shut down in 1992. The material inventory contains approximately 50 t of steel. The decommissioning of this facility started in 2004 and was finished in 2011.

An old evaporation system used for the treatment of liquid waste consisted of a steam based heater (diameter 1.4 m, height 4.2 m) and a separator (diameter 1.4 m, height 4.2 m) (see Fig. I–3). The separator was partially dismantled by oxyacetylene cutting before removal (see Fig. I–4), because it was too large to be removed as a single item. It was encased in concrete, which was not as per the original design documentation. The heater was removed in one piece.

FIG. I–3. Old evaporator (heater and separator).

FIG. I–4. Removing the separator after partial segmentation.

Two sedimentation tanks, each of volume 25 m^3, were used for sedimentation of liquid radioactive waste during chemical pretreatment (see Fig. I–5). After sludge removal, the tanks underwent preliminary decontamination by high pressure water jetting before being partially dismantled by a nibbler and using oxyacetylene cutting. This was necessary because it was not possible to remove them in one piece owing to their encapsulation in concrete, which was in contrast to the design documentation (see Fig. I–6).

FIG. I–5. Sedimentation tank before dismantling.

FIG. I–6. Removal of the rest of the sedimentation tank.

I–6. DECOMMISSIONING OF GLOVEBOXES

Two laboratories, called Alpha halls, contained eight sets of wall boxes (see Fig. I–7) and a number of gloveboxes (see Fig. I–8) [I–6]. These were used for handling alpha particle emitting radionuclides (U, Np, Pu and Am), and were significantly contaminated. The total volume of the boxes was approximately 80 m^3.

FIG. I–7. Alpha boxes.

FIG. I–8. Gloveboxes.

There was a lack of information about the gloveboxes, which needed to be obtained in order to plan the decommissioning and to prepare a disposition route for the resulting waste material. The gloveboxes had been used to handle alpha particle emitting materials, and so it was essential that their interiors should be sampled. The sampling process was identified as a risk owing to the possibility of loss of containment.

A tent was planned to be constructed over the gloveboxes to manage contamination during the decommissioning process. The sampling was planned to be carried out at the same time in order to make use of this containment improvement and thus reduce the contamination risk. The decommissioning will consist of the dismantling of the equipment and the processing of the resulting alpha contaminated radioactive waste. The dismantling of the equipment started in 2013 and will be finished in 2016.

I–7. DECONTAMINATION OF THE HOT CELL

The hot cell was used for experiments in the reprocessing of spent fuel from 1969 to 1974. The cell was heavily contaminated. The hot cell, made from cast iron with a thickness of 100 mm, was partially decontaminated in the past, and its internal and external surfaces coated to fix the contamination, in order to prevent it from spreading.

The main unknowns were the design documentation and information about what had been placed inside the hot cell. In the late 1970s, the equipment in the cell was removed, and in the early 1980s, the hot cell was partially decontaminated. The last record was: “The decontamination of the hot cell will be finished next year.” Instead of this, the facility was abandoned. The state before decontamination is shown in Fig. I–9. There was no reliable record of what was actually behind the door of the cell, and it was therefore necessary to carry out a survey prior to decontamination.

Decontamination of the hot cell started with removal of the fixative coating, initially using paint remover and then by dry ice blasting. Then, the hot cell was dismantled (see Fig. I–10). Dry ice blasting was also used for decontaminating the wall surfaces.

During cell floor decontamination, contamination of subsurface layers was identified. This was only partly removed in order to maintain the integrity of the cell to enable it to be used again for another purpose. The range of the contamination was recorded, and will be used for decommissioning of the building in the future.

FIG. I–9. Transfer box: entrance to the hot cell.

FIG. I–10. Dismantling of the hot cell.

I–8. DECOMMISSIONING OF DECAY TANKS

The decay tanks, which had been in use since 1961, were designed for storage and decay of concentrated short lived radioactive waste. In addition, radioactive waste containing long lived radionuclides was also shipped there. Two cylindrical tanks (length 9.5 m, diameter 3 m, weight approximately 10 t), each with a capacity of 63 m^3 (see Fig. I–11), were contained inside a building submerged in the terrain on three sides (see Fig. I–12). The decay tanks were made from structural steel, and were jacketed inside the vessel in stainless steel. They were located in two separate concrete bunkers that were located partially below ground. Above the bunkers, there was a building with tank inlet pipes and ventilation equipment.

The tanks contained liquid radioactive waste, but tank B also contained solid radioactive waste. The main identified radioisotopes were ^{60}Co and ^{137}Cs; however, the presence of ^{239}Pu was also assumed. The solid radioactive waste consisted of tins with irradiated metallic samples and residues of spent fuel. The maximum dose rate was found above the pile of solid radioactive waste (hundreds of mGy/h).

The following main unknowns were identified:

- Lack of design documentation, and reports that did not correspond to the actual state (a survey with the assistance of ground penetrating radar was performed);
- Insufficient information about the radioactive waste inside the tanks.

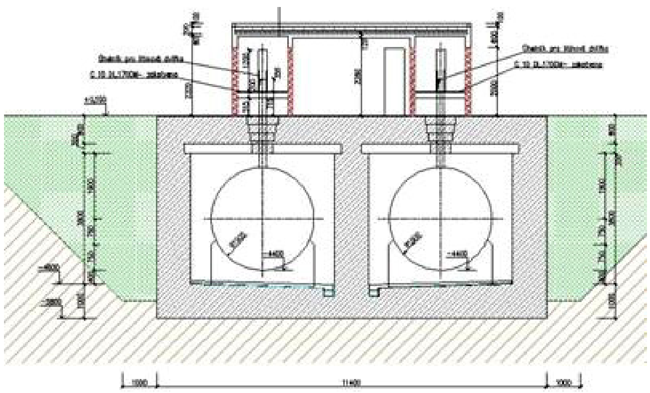

FIG. I–11. Decay tanks (section).

FIG. I–12. Uncovered bunkers.

Available information about the waste was collected and analysed. Measurement and analysis were performed, including sampling. A radiation resistant camera was used for a survey of the stored radioactive waste.

To obtain some of the design information, ground penetrating radar was used. In the case of the unknowns of the waste inventory, samples were taken and analyses performed. Radiation resistant cameras were used to obtain detailed pictures of the location and nature of the waste.

In 2007, a hall was built above the decay tanks, and the old building located above the tanks demolished. It was found that the construction details of the building were different to those in the design documentation, as a result of which, concrete monoliths had been used in place of the bricks and mortar shown in the design. An industrial concrete cutting saw was used for segmentation of the concrete inlets, and the demolition of the concrete structure was completed by hydraulic cutters (see Fig. I–13). The liquid radioactive waste from the tanks was then removed, and a special remote controlled manipulator was installed in the tank inlet (see Fig. I–14) to remove the solid radioactive waste. The activities finished in 2014. The tanks were not segmented, only decontaminated and may be reused.

FIG. I–13. Demolition of tank inlets.

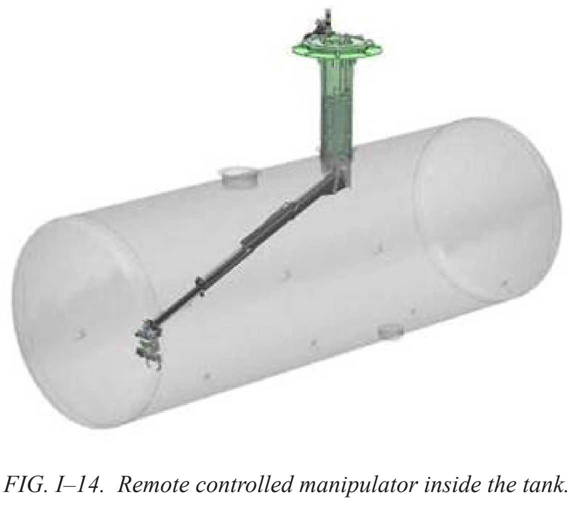

FIG. I–14. Remote controlled manipulator inside the tank.

I–9. PROCESSING OF RADIOACTIVE WASTE STORED IN THE RELOADING SITE

The reloading site was initially constructed as a temporary storage site to handle conditioned radioactive waste, but was later also used for storage of miscellaneous radioactive waste before treatment. The waste was stored in eight concrete boxes, each of dimensions 5.5 m × 8 m × 4 m (approximately 1400 m^3 total capacity). The bases of the boxes were 4 m below ground level and were drained to four closed sumps. The building had a steel roof (see Fig. I–15).

The total volume of stored radioactive waste was approximately 600 m^3. An incomplete inventory was available, which gave only a very general description of the radioactive waste contained in the boxes. A preliminary radiation characterization had already been performed using a gamma camera for visualization of hot spots (see Fig. I–16). The maximum dose rate was approximately 5 mGy/h.

The hall above the reloading site contained a crane and ancillary equipment, and was constructed in 2004 (see Fig. I–17). Radioactive waste will be sorted and transported for processing (segmentation, decontamination and conditioning). The radioactive waste will then be disposed of or released into the environment. The waste is being removed and processed, a task that will be completed in 2016. The reuse plan is still current. The building will then be decontaminated, and after reconstruction, it will be used as a new radioactive waste store.

FIG. I–15. Reloading site before reconstruction.

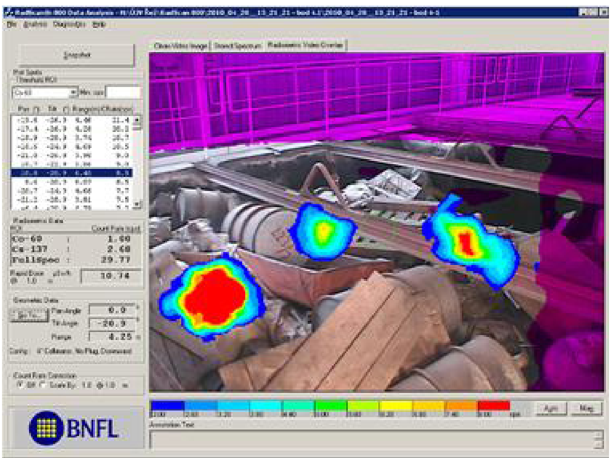

FIG. I–16. Stored radioactive waste in one box (approximately 180 m^3) with visualization of hot spots.

FIG. I–17. Reloading site with a new hall.

I–10. RELEASE OF WASTE INTO THE ENVIRONMENT

The following amounts of radioactive waste are estimated to be generated at the completion of these activities. The total amount of radioactive waste resulting from decommissioning to be processed will be approximately 1500 m^3. About 240 t of radioactive waste is expected to be released into the environment after decontamination. Czech Republic legislation requires: (i) measurement of average mass and activities of particular radionuclides in each kilogram of material and (ii) average surface activities of particular radionuclides on each 100 cm^2.

To meet the first requirement, special equipment for measurement was developed by an external contractor (a measuring chamber equipped with several semiconductor high purity germanium detectors), and has been successfully used.

In 2002, according to the change of legislation, the clearance criteria valid in the Czech Republic were changed. Before this date, there were five categories of radionuclides with clearance levels from 0.3 to 3000 Bq per cm^2 or g. Since 2002, there have been four categories from 0.3 to 300 Bq per cm^2 or g. This change decreased the amount of wastes releasable into the environment, and increased the cost of disposal.

I–11. SECOND PHASE OF DECOMMISSIONING

Preparation for the second phase of decommissioning has already started. It includes new items discovered during the first phase of decommissioning. The safety analysis report and the feasibility study have already been prepared and approved.

I–12. FINANCING DECOMMISSIONING AND THE TIME SCHEDULE

The Ministry of Finance of the Czech Republic finances the decommissioning as part of a special ecological project on old environmental liabilities. When ÚJV was privatized in 1992, the Ministry guaranteed to finance the decommissioning activities, but no funds have so far been allocated.

For this reason, the decommissioning started in 2003, when the budget was allocated to ÚJV, with the original execution of decommissioning to be completed by 2010. The total cost of decommissioning of obsolete facilities in the ÚJV was approximately EUR 18 million.

During execution of decommissioning, the budget was increased because new contingencies had been discovered and because the value added tax rate was changed several times.

The total budget is now estimated at approximately EUR 26 million, and completion has been postponed until 2016. The funding of the last phase of decommissioning was being negotiated with the Government at the time of writing.

I–13. CONCLUSIONS

Unknowns are inevitable in decommissioning, and this was the case at ÚJV in the Czech Republic. The experiences involving unknowns may be generally summarized as follows:

— Collection of information, interviews with staff, and extensive physical and radiological characterization during preparation and execution of decommissioning.
— The approach to the collection of information must be well balanced. If not, the risk can be underestimated (impact on safety) or overestimated (impact on budget and time schedule).
— The unknowns affect the budget and time schedule of decommissioning activities. It is necessary to have adequate contingencies in both the budget and the time schedule.

Engagement with stakeholders is an essential element of decommissioning. All unexpected events, problems and risks must be communicated in a way that recognizes the specific needs of the stakeholder. This information must also be delivered on time, to ensure that it is not received from a different, uncontrolled source. To support the stakeholders in understanding the facts about decommissioning, regular presentations and workshops outlining the work are essential.

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Annex II

FRANCE

II–1. ORIS CELLS 22–24, SACLAY

A separate subdivision of the Commissariat à l’energie atomique et aux energies alternatives (CEA) for radiopharmaceutical production named ORIS was formed within the CEA in the 1950s. Three shielded cells were used for production of ^{137}Ce and ^{90}Sr sources for medical purposes. This was stopped in 1972, the cells were taken out of service in 1973, and remained in disuse until 1987, when a first cleaning campaign was launched for a few months. Decommissioning work started in 1990 and reached the total dismantling stage in 1994. These activities are illustrated in Figs II–1, II–2 and II–3.

As the plant was quite old, plans were not necessarily perfectly up to date (as-built), and the engineers in charge of the dismantling did not have information on what happened when the cells were in use. Operating reports were not available, and reliable records were missing.

The details were not all documented, so sometimes contamination was found in places where there should not have been any. Moreover, objects were discovered that were not assembled as indicated on the plans.

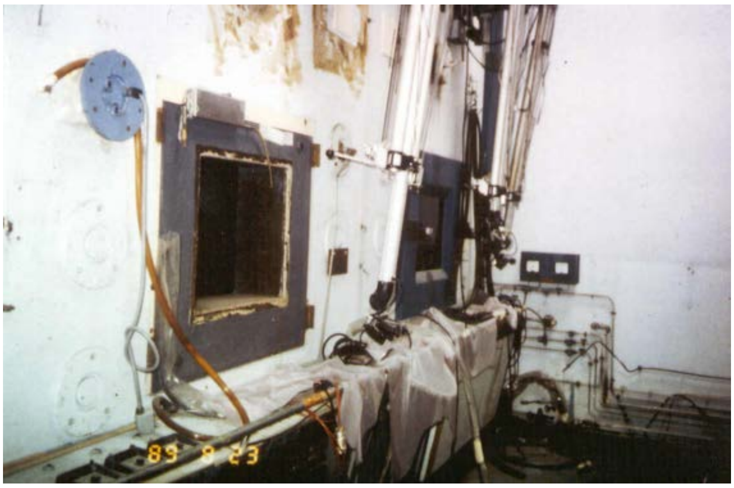

FIG. II–1. Cells in 1989 before dismantling.

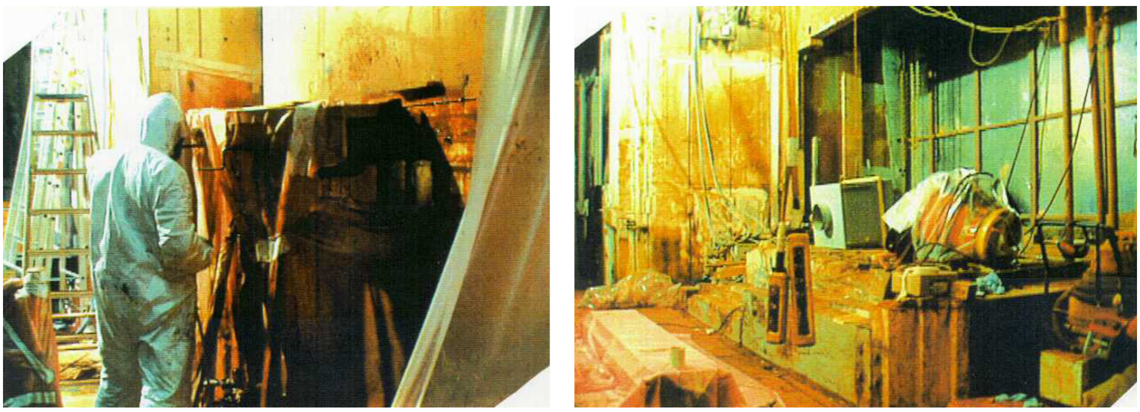

FIG. II–2. Cells during dismantling.

FIG. II–3. After cleaning, walls were cut into blocks (of weight 2–3 t), radiologically checked and sent to ANDRA for disposal.

Several drawings showed pits inside the cells, but they were not at the expected locations.

During concrete decontamination and removal of the floor concrete layer (3–5 cm) in April/May 1994, water suddenly emerged from under the cells. Decommissioning operations were stopped, and after investigation, it was found that the cells were built above small water pipes (a few centimetres in diameter) that were used by the central heating system at a temperature of 180°C and under pressure. Fortunately, the heating system was closed at that time. If this had not been the case, the decommissioners would have probably been faced with a severe accident. Drawings showing these pipes were never found.

Lessons learned from this example are that drawings, when they exist, do not always accurately represent the reality. Necessary precautions should be taken regarding these problems. Such unknowns are common in the dismantling of old facilities with unreliable records and lack of data.

II–2. AT1 FAST BREEDER FUEL REPROCESSING PILOT FACILITY, LA HAGUE

The AT1 facility (see Fig. II–4) started operation in 1969, and since its shutdown in 1979, has reprocessed 1100 kg of uranium and plutonium fuel from fast breeder reactors (up to 150 000 MW·d/t).

Preliminary cleaning of the AT1 facility took place from 1979 to 1981, and dismantling began in January 1982, after 1 year of analyses The selected dismantling strategy was the total and unconditional release of the premises, followed by reuse. Decommissioning started in 1985 after post-operational activities (cleaning and decontamination), with a relatively good knowledge of record keeping and radiological mapping. This involved the following major steps.

II–2.1. Between 1985 and 1990

- Dismantling of the alpha radiation contaminated cells and the unshielded gloveboxes (non-irradiating). This work was conducted by direct access (in contact) with a modular shop.
- Dismantling of the irradiating cells to allow easier access to the high level radioactive cells. This work was conducted by direct access (in contact) with biological protective shielding.
- Dismantling of the storage cells (wastes, fission products (FPs), etc.). This work was conducted by direct access with biological protective shielding.

FIG. II–4. AT1 facility during operation.

II–2.2. Between 1990 and 1994

- Dismantling of the high level radioactive cells, requiring the use of specific remotely operated equipment. This work was conducted remotely (see Fig. II–5).
- Removal of all equipment, and cells left bare.

II–2.3. In 1995

- Video inspections, mapping, sampling and preparation of the scenario on how to reach the set objective (zero labile contamination, radioprotection limited to continuous atmospheric control with deferred measurements, simplified low level ventilation).

II–2.4. Between 1996 and 2001

- General cleansing of the building and related monitoring.

FIG. II–5. Scraping walls in hot cells.

From an overall perspective, there were two major periods: 1989–1995 and 1996–2001 [II–1]. Between 1989 and 1995, work was focused on the following dismantling operations:

- Remotely operated dismantling, using the ATENA machine (which was entirely designed, built and tested for this type of operation), of the equipment in cells 903 (dissolution), 904 and 905, corresponding to the first extraction cycles.
- Measurement of the radioactivity and conditioning of the wastes from the high level radioactive cells. This required the installation of a counting station and the construction of a modular panel cell.
- Dismantling of the FP storage tanks using explosive charges.
- Development of specific data on the AT1 dismantling, and key in the EC DB-Tool and the DB-Cost databases from the Commission of the European Communities.
- Remotely operated cutting of the cross wall between cells 903 and 904, using the ATENA machine equipped with a diamond wheel saw.
- Decontamination, measurement and monitoring of the radioactivity in the floors and the concrete walls using a semiautomatic process.

Between 1996 and 2001, the work essentially consisted of cleansing the cells and freeing them of all radiological restrictions. Here, a Brokk machine was widely used, equipped with a stone crusher and a scraper. The calculation of the residual radioactivity in the civil engineering works, based on a theoretical approach, was reported, which resulted in the decommissioning of the facility (mapping and sample taking). This approach contributed to the total and unconditional release of the premises.

In 1999, during the removal of a concrete floor (5 cm), coated resin was found; under the resin, there was alpha radiation contamination. This unexpected event was found outside of a hot cell, in a controlled area.

After investigation, interviews with retired staff revealed that inside the ventilation system (containing a high activity ventilation duct from the cells), there were small pots to recover condensation water, which unfortunately were contaminated, and sometimes they overflowed. Nothing was written about this in the operational note book.

Lessons learned from this example are that in old facilities, personnel have not worked with accurate quality assurance. The operator should record all incidents and deal with them.

Operators should be tasked, after each contamination, to decontaminate the place. A specific procedure for this has to be set up at the facility. It is very important for old facilities to obtain as much information as possible (even oral) from existing and retired staff. It is also important to have a staff debriefing and to record it.

REFERENCES TO ANNEX II

[II–1] COMMISSARIAT A L’ENERGIE ATOMIQUE, Reprocessing Fuel Facility Decommissioning Feedback Experience, Technical Rep. CEA/DEN/DPA/JGN 01-507, Commissariat a l’energie atomique, Siege, France (2001).

Annex III

UKRAINE

III–1. SHELTER CONSTRUCTION

Unit 4 of the Chernobyl nuclear power plant was damaged, as the result of a beyond design basis accident, on 26 April 1986. Most of the reactor unit constructions were either damaged or destroyed. The reactor core was completely destroyed. Constructions of the central hall collapsed and scattered, including the metal constructions of columns above the level +53.0 m, trusses and wall infilling. The floors and walls of the drum separator premises were also destroyed. Floorings above the northern premise of the main circulation pumps and southern floorings above the level +35.5 m were completely destroyed.

The central hall of the reactor building was filled with former core elements (fuel assemblies, graphite blocks, etc.), destroyed constructions of the former central hall hipped roof and materials dumped from helicopters during containment efforts following the accident. In some places, the height of these blockages reached 15 m.

Two upper floors of the deaerator stack in axes 41–51 above the level +38.6 m were completely destroyed; the columns of the frame configuration between the levels +24.27 m and +38.6 m were deviated from the vertical in the direction of the turbine hall, in the range 0.6–1.1 m.

As a result of the fire and falling debris, the turbine hall roof was destroyed in many places, and the columns of the frame configuration on row A in axes 42–51 were displaced by the blast wave. The emergency reactor cooling system from the northern side was completely destroyed, and was filled with building construction debris.

The top slab of the reactor biological protection (scheme E), weighing approximately 2750 t, together with steam and water pipelines and fragments of the fuel channels, was torn from its regular location by the explosion, and was left in an upside down position, standing at an angle of about 15° to the vertical, based on scheme D (bioshielding tank).

The metal construction of the reactor base scheme after the explosion was displaced about 4.0 m vertically down, crushing the supporting construction and displacing lower water pipes. The south-east quadrant of the reactor base scheme was destroyed.

The building construction of the main circulation pump blocks, the downcomer pipeline ducts and the monolithic reinforced concrete constructions below the level of +9.0 m survived. The destroyed constructions of unit 4 can, in general, be characterized by:

— Spatial distributions and the presence of critical zones within the construction close to the limit state in terms of the bearing capacity and deformability;
— Inaccessibility of most parts of the constructions;
— Absence of the necessary design and as-built documentation;
— Ongoing degradation processes of the materials (corrosion, foundation settlement, etc.) giving a short term durability (in comparison with the normal for these types of facilities).

The existing shelter, formally referred to as the shelter and often called the sarcophagus, was constructed between May and November 1986 as an emergency measure to contain the radioactive materials within unit 4 (see Fig. III–1). The shelter was constructed under extreme conditions, with very high levels of radiation, under extreme time constraints. The shelter object was moderately successful in containing radioactive contamination and providing for post-accident monitoring of the destroyed nuclear reactor unit. However, the shelter cannot ensure full reliability, stability and durability of the facility due to the following reasons:

— During installation of the facility, it was not possible to control the quality of the installation. It is essential that the supporting nodes of the constructions are made without welding and/or bolted connections. Taking into account the fact that the installation of constructions was performed remotely (as a rule), the quality of supporting construction fittings was not controlled.

FIG. III–1. Shelter construction.

— The main supporting constructions of the facility are based on the pre-accident constructions that remained after the explosion.
— The constructions are not protected against weather and temperature impacts.

Based on these facts, the shelter object can be considered as a temporary interim solution to ensure the safety of the destroyed Chernobyl unit 4 for the preservation period. The shelter building construction does not meet the requirements of safety regulations in terms of mechanical durability, structural integrity and structural reliability, and has an undefined lifetime.

As a result of a study performed within the shelter implementation plan (SIP) in 1998–2000, urgent measures to stabilize the shelter object building constructions were identified. The volume of stabilization measures were selected based on the following key factors:

— The necessity to reinforce the most unreliable and dangerous building constructions to mitigate the consequences of a collapse;
— The minimization of doses for personnel performing the construction work;
— The construction of a new safe confinement within several years after stabilization.

Stabilization of the shelter construction was performed in two stages:

— In 1998–1999, the repair of ventilation stack 2 foundation and bracings and the reinforcement of B1 and B2 beam supports were carried out.
— The project to stabilize the following structures and components was implemented in 2004–2008. This included:
  • The shelter object western fragment;
  • The upper tier of the frame and emergency covering slabs of the deaerator stack;
  • The western and eastern supports of the mammoth beam;
  • The junction nodes of the southern shields and southern shields sticks;
  • The northern buttress wall and components of its junction with northern shields sticks;
  • Light roof repair (unquantified).

Implementation of urgent stabilization measures (see example in Fig. III–2) has improved the safety of the confining construction of the shelter, on the basis of a limited lifetime of the stabilized constructions, by up to 15 years. It is stipulated to complete the construction of the new, safe, confinement (see Fig. III–3) within this time frame.

FIG. III–2. Example of stabilization measures.

FIG. III–3. New safe confinement.

In the future, the problem of unstable shelter constructions should be resolved by their dismantling or reinforcement inside the localized encasement.

An example of an unexpected event that occurred in February 2013 is the collapse of a portion of the roof over unit 4 turbine hall [III–1]. Some 600 m^2 of wall panels and roof sections caved into the building. The shelter itself was unaffected, and there was no release of radioactivity from the incident (see Fig. III–4).

FIG. III–4. Collapse of part of the roof over Chernobyl nuclear power plant unit 4 turbine hall.

The IAEA expert team completed a mission in June 2013 to review the causes and effects of the partial roof collapse, and to assess any radiological consequences of the incident and the plant's response to the event. The IAEA team credited plant personnel for their timely response to the incident, their investigation into the causes of the event and their rapid reporting to the public. In addition, the experts offered recommendations for implementing organizational and technical measures to enhance the monitoring of the building structures, thus improving general industrial and radiation safety at the site [III–2].

III–2. SITE FOR TEMPORARY STORAGE OF TECHNOLOGICAL MATERIALS

During the realization of the SIP, a significant volume of soil and other materials needed to be excavated and removed. According to preliminary estimates, the volume of such technological materials (TMs) was approximately 50 000–70 000 m^3 (consisting of soils and other solid radioactive waste). It was stipulated to use part of these TMs for backfilling during facility construction.

In 2003, it was decided to transport the soil removed during facility construction at the temporary storage site for possible use for backfilling during construction works. This is a part of the 'Classification of soils and others materials, generated during excavation works performance within the Shelter Implementation Plan' official initiative. Further work has been done on the site arrangement, including development of the necessary operational and technical documentation and commissioning work.

The site for temporary storage of TMs was commissioned in October 2006. The expected lifetime of the site was 10 years. The site was divided into storage areas for soil, metal constructions and reinforced concrete constructions. The area for soil storage was subdivided, depending on the exposure dose rate from stored material (soil suitable for backfilling and soil unsuitable for backfilling).

Transportation of TMs to the site for temporary storage began in November 2006, with the implementation of the physical work on SIP projects.

Radiation monitoring of TMs before delivery to the storage site was performed in stages, as specified in the work performance programme and in the programme of safe performance of work:

— Before the removal of each layer of soil, or before some other TM loading (e.g. metals or reinforced concrete structures);
— During the soil loading into the lorry body (using a ladle dosimeter on the excavator);
— Upon completion of the car loading (directly into the lorry body).

During work, a health physicist performed dose rate measurements before removing each layer of soil. Radiation monitoring of loose TMs during loading into the special lorry body was performed by a ladle dosimeter.

In the future, soil will be used as backfill during construction works within the SIP. A decision about the management of the remaining soil should be taken after the SIP construction activities have been completed. Characterization of the material determines the suitability for backfilling according to dose rates.

REFERENCES TO ANNEX III

[III–1] WORLD NUCLEAR NEWS, Experts Study Chernobyl Roof Collapse (2013), http://www.world-nuclear-news.org/RS_Experts_study_Chernobyl_roof_collapse_1007131.html

[III–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report, IAEA Mission on Partial Collapse of Turbine Hall Roof of Unit 4 (3–7 June 2013), https://www.iaea.org/sites/default/files/missionreport130613.pdf

Annex IV

UNITED KINGDOM

IV–1. DOUNREAY NUCLEAR POWER STATION

In the UK, early reactor developments were centred on graphite moderated Windscale piles, which were constructed for the manufacture of plutonium for the UK weapons programme. In those days, it was anticipated that nuclear power would become the universal means of providing electrical power, and the need to obtain massive quantities of uranium, of which only 0.71% is fissile, was considered to be a strategic matter for the nation. One of the solutions proposed by the UK was the development of fast reactors that could initially burn uranium, but which could also breed plutonium, which could then be used as a fuel. This provided the opportunity for use of all of the uranium, not just the 0.71% of ^{235}U.

The site chosen for this very new and not well understood technology was at the extreme far north of Scotland at Dounreay. Since the 1990s, it has been undergoing decommissioning and waste management operations. There are many relevant examples of unexpected events at the site, owing to its operational history and age. Some typical examples are included here.

IV–1.1. Discovery of an irradiated fuel fragment

Two reactors were constructed at the Dounreay site in the 1950s: one materials test thermal reactor and one liquid metal cooled fast breeder reactor. Associated with the thermal reactor was a fuel cooling pond and other laboratories used for post-irradiation examination of different fuel types. In keeping with most research reactors, the fuel for the Dounreay materials test reactor was in the form of aluminium plates with uranium pressed into depressions made on the plate surface.

When the fuel had been irradiated, the plates were cut up under water in the pond, and the uranium material exposed. A variety of post-irradiation examination tests were performed on the fuel, from which its performance could be derived and different types designed, tested and further analysed.

Over the years of this programme, a great deal of fuel passed through the pond, and corrosion products from the fuel, principally aluminium hydroxide, built up on the floor of the pond in the form of a sludge. One of the consequences of this buildup was that the water clarity degenerated to the point where it was difficult to see the operation of the milling machine.

Several campaigns were conducted to clean the sludge from the pond, and it is thought that during one of these, a quantity of sludge containing fuel fragments from the cutting process was discharged to the sea, resulting in the radioactive particles that are found from time to time along the north coast of Scotland in the vicinity of the Dounreay site [IV–1 to IV–3].

As part of the decommissioning of the Dounreay materials test reactor complex, it was planned that the pond would be drained of water, the sludge removed and the pond decommissioned and demolished. The expectation was that the specific activity of the sludge would be relatively low, enabling it to be dealt with by one or more of the existing waste treatment plants on the site, following which, the pond could be decontaminated and demolished.

However, during previous decommissioning work at the Dounreay site, operators had found unexpected problems, and over the years, had “hoped for the best but planned for the worst”. A risk assessment showed that the worst that could happen would be the discovery of a piece of fuel, because this was the most hazardous material to be consigned to the pond. While this was not anticipated, the method statement for the work required that the water level be reduced slowly and the radiation levels all around the pond measured regularly on the basis that if a higher than expected reading was detected, the process would be stopped and investigated. A contingency plan for how to deal with such an eventuality was also prepared.

As work proceeded and the water level was reduced, the radiation levels did indeed rise very rapidly, and it was suspected that there was an item of high specific activity buried in the sludge. It was suspected that this might be a fragment of fuel.

Work stopped, and the regulator was informed, while an investigation was carried out to determine the nature of the high activity source. In the meantime, a contingency plan for dealing with the item was enacted. Again planning for the worst, the site director, who was scheduled to make a number of presentations on the decommissioning plan of the site, chose the project as one to use to describe the decommissioning work of the site. He described the process that was under way and the precautions that were being taken in the event of discovery of fuel.

These presentations, over a period of time, moved away from “what we might do if we found something” to “the procedures we developed to deal with the finding of an item of high activity are in place and working well”. In effect, the announcement of the discovery of the fuel was used as a success story to demonstrate the competence of the management systems and the adequacy of the risk assessment and method statement.

By the time that the fuel fragment, the contact dose from which was 10 Sv/h, was located and the disposition route for it deployed, both the public and regulator were aware of the event, and there was little negative reaction.

IV–1.2. Increasing the inventory of fissile material

As Dounreay’s decommissioning progressed, tiny amounts of fissile material caught up in areas of inaccessible pipework and equipment were identified. This material had previously been given up as lost, and described as material unaccounted for in Dounreay’s fissile material balance, undertaken as a component of the UK State System of Accounting and Control [IV–4 to IV–8].

With the clean out and demolition of reprocessing plants progressing, the site is showing an apparent gain in material, counterbalancing past years where it has shown an apparent loss.

A 5 year drum repacking project in the billet production plant detected some of this lost nuclear material. Over 200 waste drums that were full of material produced during historic operations were inspected, assayed and repacked for safe long term storage. During the work, operators opened up the old packaging and confirmed that there was more uranium trapped in the waste than had previously been measured. The site has recovered approximately 1.5 kg of ^{235}U [IV–8].

Some reasons for the deviations are:

- The equipment now used to assay the waste is far more accurate than that available when the drums were originally packaged;
- The figures from the repackaging work show that material previously considered lost was, in fact, safely packaged as waste.

IV–1.3. Disturbance of an 11 kV cable

In 1998, while excavations were under way for a possible extension to a waste disposal facility, an excavator disturbed a power cable for the site. The cable was not penetrated, but the electrical protection equipment operated and tripped the power supply. However, it was found that the electrical protection equipment was not properly configured, resulting in power being cut off to a large part of the site.

The fault could have been isolated and power to the affected part of the site restored very quickly; however, an error by the engineer investigating the fault resulted in the diagnosis that there was a more significant fault than was actually the case. The effect of this was that power was not restored to the site until the following day.

The main safety implication of the event was that the ventilation systems in the fuel processing area of the site were shut down. In fact, the updraught to the exhaust stack was sufficient to maintain adequate depression in the caves and gloveboxes to prevent contamination; however, no formal safety case to support this had been made.

This event was considered by the regulator to be indicative of severe underlying management problems at the site, and, as a consequence, a formal direction was issued to cease all operations on the site other than those essential to safety. This included all of the decommissioning work.

The regulator conducted a formal audit of the site and published a major report with 124 recommendations for improvements.

The impact of this on the site was very significant, and it took a period of 2 years and many millions in pounds sterling to restructure the management and recruit additional suitable staff, before the formal direction was lifted and decommissioning was allowed to restart.

The situation has since continually improved to the point where the Dounreay site is now considered to be among the best managed facilities in the UK. Public perception of the site and its operations, which had been at a very low level before and during the cable episode, recovered, and it is now rare for adverse publicity to emerge, although the radioactive particles will remain a constant concern until they are recovered or are destroyed and diluted naturally by the sea. That said, the efforts of the current management to recognize and accept the problem and seek to deal with it have been recognized by the regulator and the general public.

The difference between the two events — the discovery of the fuel in the pond and the disruption of the power supply — was that the fuel discovery, by the time it became known, was perceived to be under the control of the site management, while the excavation problem served to suggest that the management had lost control of the site. The public and the regulator generally do not like surprises. They expect the management of the site to be in control and to predict potential problems before they occur. When this does not happen, the regulator, who represents the best interests of public safety, is forced to take action; the impact of this can be as dramatic as any contamination incident or, as was the case at Dounreay, even more so.

This example is different to the usual unexpected events during decommissioning in that the initiating event — the disturbance of the cable — was not, itself, very significant, but the combination of the perceptions of the public and the regulator amplified it to the point where a 2 year delay to the programme occurred, and additional expenditure of millions of pounds sterling was needed to recover the situation.

IV–2. WINDSCALE PILE 1

Windscale pile 1 was a plutonium producing plant with a graphite air cooled core built in the north-west of the UK. It was in operation in the 1950s. In October 1957, fire broke out in the reactor core, and radioactive contamination was released into the environment; this was a major nuclear accident for the developing nuclear industry in the UK. Pile 1 was closed down, as was pile 2. It was not possible to defuel pile 1 completely, and approximately 15 t of uranium metal fuel was estimated to still be in the reactor core. The pile has been subject to a regime of surveillance and maintenance since that time. There was no new information on the state of the core internals from the date of shutdown until 2005–2007, when a number of investigations could be carried out. This lack of adequate characterization has limited the planning for decommissioning. For this reason, the first step before dismantling was to increase the understanding of the present state of the pile. Intrusive inspection into the fire affected zone (FAZ) was possible once safety related issues had been resolved. These issues presented a number of technical uncertainties that needed to be addressed so that a safe and cost effective decommissioning option could be selected. This section details the approaches taken to resolve the unknowns and provide a firm basis for future dismantling of the pile.

The accident damaged nature of the pile 1 reactor core has led to a range of issues that would not normally be encountered for a reactor system that had shut down following normal operations. Hence, from the decommissioning perspective, this project has been unconventional since the early stages, and has focused on the physical characterization of the damaged core to try to ascertain the issues that must be fully understood before decommissioning proceeds. Much investigative work has been carried out in support of the safety submissions required before decommissioning operations. A variety of unknowns have existed for the decommissioning programme, leading to research and development activities that have been conducted since the early 1990s.

Early decommissioning activities on pile 1 had been compromised by the inability to make intrusive inspections within the fire damaged region of the core. A variety of safety related concerns had been identified, which resulted in a hiatus for the decommissioning programme. However, desk top studies of the various issues relating to criticality, the possibility of uranium hydride being present and the possibility of graphite dust explosions have demonstrated successfully that such concerns have been largely unfounded. This conclusion has enabled the detailed planning for decommissioning work on pile 1 to be progressed from an initial round of non-intrusive visual inspection into the undamaged sections of pile 1 core through to intrusive inspection of the fire damaged core. The results of this work have underpinned the methodologies for removal of the remaining fuel and isotopes in the core of pile 1, because these constitute a major hazard. Further characterization work has been carried out to quantify the quantities of wastes in the main structure of the pile to assist in forward planning for decommissioning beyond the fuel removal stage.

IV–2.1. Description of the pile

A cross-sectional view of pile 1 is shown in Fig. IV–1. The reactor core consisted of a 2000 t graphite moderator/reflector comprising about 50 000 blocks of graphite keyed together using a system of graphite slats and tiles (Fig. IV–2), generating an interlocking structure of approximately 15 m × 15 m in cross-section and 7.5 m deep. The core was penetrated by 3444 horizontal fuel channels of 100 mm diameter and 977 isotope channels of 44 mm diameter. Each fuel channel contained a stringer of 21 solid uranium metal fuel rods clad in finned aluminium, and resting on individual, linked, graphite boats for loading and discharge purposes. The fresh fuel was loaded from the charge face from an ascending platform containing a refuelling machine. Fuel discharge was effected by pushing out the irradiated fuel by the incoming train of fresh fuel until the spent fuel fell under gravity from the pile discharge face into a rail mounted transfer skip contained in a water filled duct (see Fig. IV–1). Transfer skips were then towed remotely on the rails into a cooling pond for storage and graphite boat removal prior to subsequent reprocessing of the irradiated fuel. The pile was designed to operate at up to 180 MW·t power (no electricity was produced) and cooled from a bank of blowers that forced air through the pile into a collection plenum and then exhausted to the atmosphere through a vertical stack of ~130 m in height via filters. The graphite core was surrounded by steel thermal shield plates, insulation boxes and a core restraint girder system — all encased in a reinforced concrete bioshield surrounded by steel thermal shield plates.

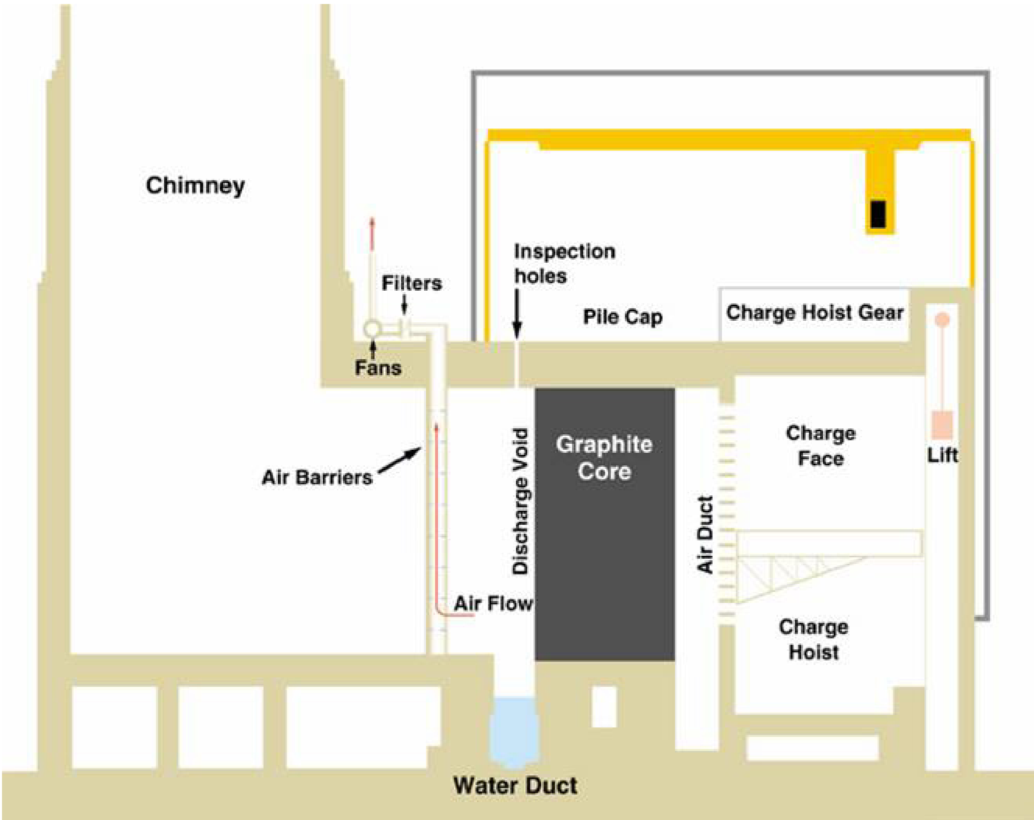

FIG. IV–1. Cross-section through Windscale pile 1 structure.

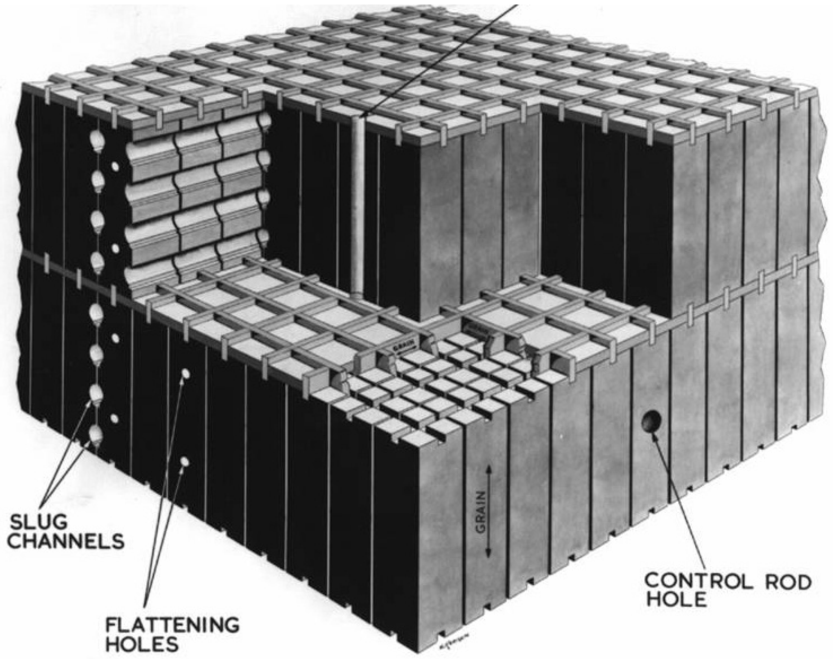

FIG. IV–2. Graphite block arrangement at Windscale pile 1.

IV–2.2. Pile operations

Design work on the piles started in the late 1940s. Pile 1 started to operate in 1950 as the principal provider of strategic defence materials for the UK nuclear deterrent. Subsequently, the second pile, pile 2, was completed and started to operate in 1951.

The nuclear properties of the various materials used to construct the piles were not fully understood at the time of design, in particular, the need to accommodate the growth in the graphite caused by neutron irradiation (Wigner growth) at the low irradiation temperatures encountered (20–153°C mean graphite temperature). Accordingly, the graphite core was designed with small gaps between the core blocks, back to front and side to side, whose size varied according to core position. The Wigner effect not only caused anisotropic growth in the graphite blocks, but also manifested itself as stored energy within the graphite crystal structure. Hence, one of the operational tasks was to limit both the growth and the stored energy by using nuclear heating to anneal the core. During the working life of both piles, nuclear heating with reduced air cooling was used to elevate the core temperature to a point where temperature excursions occurred caused by the release of stored Wigner energy. It was during one such incident in October 1957 that an uncontrollable temperature rise was experienced, which led to a fire in the reactor core. The fire was eventually extinguished by a combination of water pumped into the core and closing down the cooling airflow. The precise cause of the fire is still a source of conjecture. The sequence leading up to the fire, its ultimate control and post-fire recovery have been widely documented [IV–9]. It serves little purpose to describe events in more detail here, except to say that, after the accident, not all the remaining fuel could be ejected from the core (either by conventional or more energetic means), and up to 15 t may still remain. The use of water during the accident sequence had consequences, both for the pile in its current quiescent state and for ultimate decommissioning. These consequences and the approaches taken to determine their safety implications are developed in the rest of this section.

IV–2.3. Technical challenges

The work programme has centred on research activities to support a safety submission for pile 1 in its present quiescent state. The design basis accident [IV–10] under these circumstances is a seismic disturbance. Furthermore, to enable a safe and cost effective option to be selected for decommissioning [IV–11], the safety issues must be addressed and developed in future studies. The technical challenges to be addressed are detailed below:

— The remaining fuel mass and moderator are sufficient to present a potential criticality hazard.
— The graphite moderator was left in a partially annealed state following shutdown, and the quantity of Wigner energy within the graphite cannot be easily determined.
— The physical and chemical state of the fuel is presently unknown, and, owing to the injection of water in 1957, the presence of pyrophoric uranium hydride cannot be easily discounted. This material could be present in sealed pockets, which, on exposure to air, would oxidize exothermically. Hence, disturbance of the core, either by a seismic event or during dismantling, is considered to be a hazard, potentially leading to a thermal transient resulting in a release of Wigner energy and runaway oxidation of core materials.
— Damaged fuel, the accumulation of dusts and larger debris have been observed in the discharge exits to the horizontal fuel channels by closed circuit television (CCTV) survey (see Figs IV–3 and IV–4). It is postulated that the levitation of graphite dust during a seismic disturbance could constitute an explosion hazard if ignited by a pyrophoric material, with potential pressurization of the reactor containment and release of activity.

FIG. IV–3. Fuel element debris within the fire affected zone fuel channel.

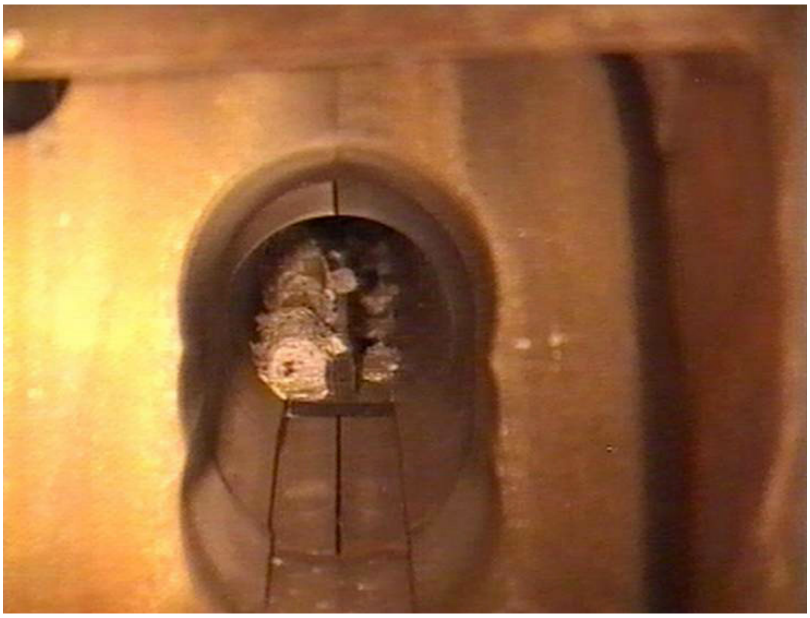

FIG. IV–4. Fire damaged fuel element displaced from its graphite boat.

IV–2.3.1. *Criticality*

The inventories of the fuel and moderator in the FAZ exceed the minimum values required for criticality in an idealized maximum reactivity lattice. Past theoretical criticality assessments of pile 1 have been unrealistically pessimistic, and have consequently indicated the subcriticality margin to be small. The theoretical modelling work has been compromised by a lack of detailed knowledge of the remaining core contents and configuration. From analysis of the core reactivity measurements by direct measurements [IV–12], it has been concluded that there is likely to be a substantial subcriticality margin. Recent modelling of credible seismic disturbance scenarios for moderator, fuel and neutron absorbers has shown conclusively that the measured margin of subcriticality would not be significantly changed. This has been supported by a sensitivity analysis of the effects of the numerous variables involved.

When considering the possible disturbance of fuel, isotope cartridges and the moderator, it is assumed that due to graphite oxidation during the 1957 fire, the channels of the inner regions of the FAZ may have increased in diameter, reducing the overall strength of the FAZ structure. Consequently, a likely outcome of a seismic shock could be fracture of the reduced graphite sections, with graphite fragments settling downwards, carrying fuel and isotope cartridges (as original or oxidized material) into a reduced vertical pitch array. It is pessimistically assumed that an increase in moderation could also occur due to the possible filling of cavities surrounding the fuel with graphite debris. The exact distribution and condition of the fuel and neutron absorbing materials is unknown, but the as-designed fuel array pitch and channel dimensions were very close to optimum for maximum reactivity. The analysis therefore assumes, pessimistically, that the horizontal pitch of the fuel remains unchanged.

The criticality safety assessment and the associated sensitivity studies have demonstrated that pile 1 will remain subcritical during current quiescent conditions, and a seismic disturbance of the FAZ cannot be expected to cause a criticality.

IV–2.3.2. *Uranium hydride issues*

During the 1957 fire, water was injected into pile 1 in order to extinguish the fire and remove heat. The possibility that uranium hydride may have been formed as a consequence and that it could present a pyrophoricity hazard on exposure to air has been identified. Although the formation and survival of uranium hydride in pile 1 is considered to be extremely unlikely, its presence cannot be ruled out definitively in regions that may have been sealed since the post-accident cleanup phase. It has therefore been considered for many years that fuel removal should only be undertaken with an inert gas cover. A detailed assessment of the practicability of this strategy revealed the impracticality of its implementation, prompting a reappraisal.

Historically, it has been considered that hydride in the core could be enclosed and protected from contact with air, and it would exothermically oxidize if the enclosing material was mechanically disturbed. It was further pessimistically assumed that the inventory of the hydride was sufficient to heat and ignite the uranium in contact with it. A further contribution of heat was considered to arise from the release of Wigner energy and the ignition of isotope cartridges, leading eventually to self-sustaining graphite oxidation and the potential for release of activity to the environment.

As part of the research, the formation and survival of uranium hydride in pile 1 has been reassessed in detail. A principal argument used in the safety analysis was that the open conditions in pile 1, with an air atmosphere, were never conducive to formation of uranium hydride, even during water injection. If hydride did form in local transiently anaerobic conditions in 1957, it is unlikely that it will have survived the subsequent period of aerobic (oxidizing) conditions. However, it has been assumed for the purpose of the safety argument that some hydride is currently present locally in pile 1. A thermal model has been developed using the Fluent computational fluid dynamics code [IV–13], tested and applied to the conceptualized arrangements of fuel in a pile 1 environment. The thermal model itself has several in-built pessimisms, and a sensitivity analysis has been carried out.

Under ideal conditions for propagation of a uranium hydride oxidation transient, with improbable hydride exposure and an impossibly concentrated inventory of hydride, it has been demonstrated that:

— The bulk uranium metal will not get heated enough to ignite or oxidize at a significant rate;
— The temperature increase at the graphite fuel channel wall will be so slight that neither graphite oxidation nor release of Wigner energy will be initiated;

— The isotope cartridges will not get heated enough to release the radiological inventory beyond that which would arise from physical damage in a seismic event;
— There is no significant thermal interaction between neighbouring fuel channels;
— The hydrogen generated from oxidation of uranium hydride cannot contribute to a thermal excursion, promoting release of activity.

The overall conclusion is that even if uranium hydride is assumed to be present, improbably protected in anaerobic conditions, its oxidation is stimulated by seismic disturbance, and a thermal excursion causing a significant activity release will not develop. Any additional uranium oxides generated by oxidation of the hydride alone will contribute an insignificant fraction to that already present and potentially rendered airborne.

The formation and survival of reactive compounds in addition to uranium hydride have also been considered; it was concluded that other reactive materials will be in a form and/or quantity that renders them insignificant.

IV–2.3.3. Graphite dust explosibility

The issue of graphite dust and its potential to cause an in-core explosion during decommissioning has received attention in the graphite decommissioning community [IV–14]. Many countries operating graphite moderated reactors have carried out research programmes, including France, Italy, Japan and the UK. It has been noted, that since around 1890, no dust explosions in the graphite industry have been recorded. However, recent work carried out as part of this research with pure nuclear grade graphite dust has demonstrated that under ideal laboratory conditions, it can be weakly explosible. In the safety analysis, it is argued that for pile 1 conditions, a graphite dust explosion is highly improbable and can be dismissed. The experimental work on graphite dust explosibility was carried out using pure nuclear grade graphite. In reality, the dusts observed to be present in the channels of pile 1 will be a heterogeneous mixture, probably dominated by metallic oxides. It is generically established that inert components of any dust have the effect of suppressing explosibility, and the use of pure graphite therefore represents a worst case scenario. Lead oxide, which is assumed pessimistically to be present, has an established catalytic effect, increasing the graphite oxidation rate. However, indicative tests have not shown any observable effects, for example, rendering the graphite dust more sensitive to ignition during an explosion scenario.

Ignition of airborne graphite dust suspensions requires a high energy and power source. Uranium hydride oxidation has been suggested as a possible ignition source, but even assuming sufficient hydride in a highly reactive form is present, the reaction cannot provide the level of ignition energy and power input required. Electrostatic charge buildup in a graphite environment will be minimal because graphite is an electrical conductor. An energy pulse from a criticality could, in theory, contribute to dust ignition, but the criticality event has been dismissed. No credible dust explosion ignition source has therefore been identified.

It has been established that only the very smallest particles contribute to a graphite dust explosion (<10 μm in diameter). Larger particles have the effect of acting as a heat sink, quenching the reaction. Inert additional material, for example, metallic oxides within the FAZ, act as suppressants. Even under laboratory conditions, it has proved extremely difficult to produce the small particle sizes required, and there has been a persistent tendency for the fine graphite dusts to rapidly age, forming spherical agglomerations, giving an apparent reduction in reactivity. In view of this experience, it is likely that an insufficient fraction of the dusts present in the core will be within the explosible size range.

A high concentration of airborne dust is required for an explosion to occur. The quantity of very fine graphite dust, free from inert material, required to produce an explosible airborne concentration in the fuel channels and in the enclosed voids within the pile structure would be considerable. It is argued that the graphite damage needed to produce the necessary concentration of fine particles could not credibly occur.

IV–2.3.4. Additional radiological hazards

From recent CCTV surveys of the pile discharge face, dusts and loose debris are known to be close to the exits of several fuel and isotope channels of the FAZ, and are also lodged on the burst slug scanning gear. In a seismic event, some of this material can be assumed to fall to the water duct floor. Fuel oxide dusts of a respirable size range (<10 μm in diameter), entrained by the ventilation airflow and discharged via the vent stack, would be the principal hazard.

Engineering substantiation work on the seismic performance of the bioshield has concluded that it is vulnerable to damage, and that the retention of the present level of containment is unlikely. Dust raised by a seismic disturbance may therefore be released via adventitious leak paths. However, the bioshield comprises multiple barriers and, as its total collapse is improbable, it is argued that its post-seismic decontamination factor will be sufficient to maintain on-site and off-site consequences within region 0 of the design basis accident criteria.

Assessment of the seismic withstand of the ventilation system has shown it to be limited owing to its location on the level of the pile cap, which produces an amplification effect. The high efficiency particulate air filters may be displaced and therefore wholly or partially bypassed. Similarly, the retention of airborne activity and dusts within the ducting could be potentially reduced.

IV–3. IMPLICATIONS FOR THE SAFETY ANALYSIS AND DECOMMISSIONING PROJECT DIRECTION

It has been shown in the safety analysis that in the current quiescent conditions, the perceived hazards of criticality, dust explosion, self-sustaining oxidation and Wigner energy release transients will not be initiated by a seismic disturbance of the core. No additional hazard management strategies are therefore required against a seismic disturbance for the core in its present state. As dismantling will be under controlled conditions, it will not routinely incur the level of uncertain disturbance that is inherent in a seismic event. However, core dismantling (or fuel and isotope removal) must comply with procedures that keep control of the core configuration and properties within acceptable limits. Activity releases and waste handling risks must be as low as reasonably achievable (ALARA), and control of the waste form maintained.

It is argued that in the event of a seismic disturbance of the core, in particular, in the FAZ:

— Existing dusts within the core cavities will be levitated, and, owing to bioshield cracking, will result in an airborne release of activity;
— An oxidation transient leading to significant thermally stimulated releases of activity will not occur;
— The core will not go critical, and an adequate margin of subcriticality will be retained;
— Conditions necessary for a graphite dust explosion are highly improbable, and the event can be dismissed.

IV–4. VISUAL INSPECTIONS

A systematic review of characterization technologies indicated that television/visual inspection methods would offer the best prospect for gaining the most information quickly on the unknown status of the reactor core. Such techniques should ideally:

— Identify anomalous features in the core structure:
  - Loss of graphite during the 1957 fire that resulted in reduced density/increased porosity via thermal oxidization mechanisms or the presence of voids;
  - Changes in the graphite structure that may have caused the core to slump, for example, identified by slippage of graphite blocks, slats and tiles and changes in the Wigner gaps (present between blocks to accommodate Wigner growth) — see Fig. IV–2 for the graphite core structure.

— Detect the presence and depth of fuel and isotope channel blockages from the charge and discharge faces of the reactor;
— Identify the location and quantities of uranium metal fuel and isotope cartridges remaining in the FAZ;
— Identify and characterize the combustion and corrosion products that are present in the core after the fire (e.g. uranium dioxide, uranium hydride, aluminium oxide and oxidation products of the isotope cartridges).

In addition to the fuel and isotope channels that pass horizontally through pile 1, there were a number of vertical full depth penetrations over 15 m in depth. These penetrations were foil holes used for the introduction of flux monitoring foils and irradiation experiments during pile operations. The holes provided a ready route for inspection of the internal condition of the pile.

Two phases of inspection work in the foil holes were carried out outside of the fire damaged region. Initially, it was decided to adopt a prudent approach to the inspection by carrying out a non-intrusive survey to prevent any possible disturbance to the core. Specialist viewing equipment was developed and deployed successfully. The principle behind the design was to use a long focal length CCTV system to provide a non-intrusive view from the top of the reactor down the depth of the foil hole.

A second inspection phase was carried out in June 2005 using an intrusive probe to confirm the earlier work (see Fig. IV–5). Figure IV–6 shows a view at the base of a foil hole, indicating debris and the graphite in this region to be in overall good condition.

The systems have allowed excellent images of the pile internals to be recorded and have indicated that, nearly 50 years after a major incident, the graphite core brick structure is still in excellent alignment. Such information is of considerable value for the planning of future decommissioning operations.

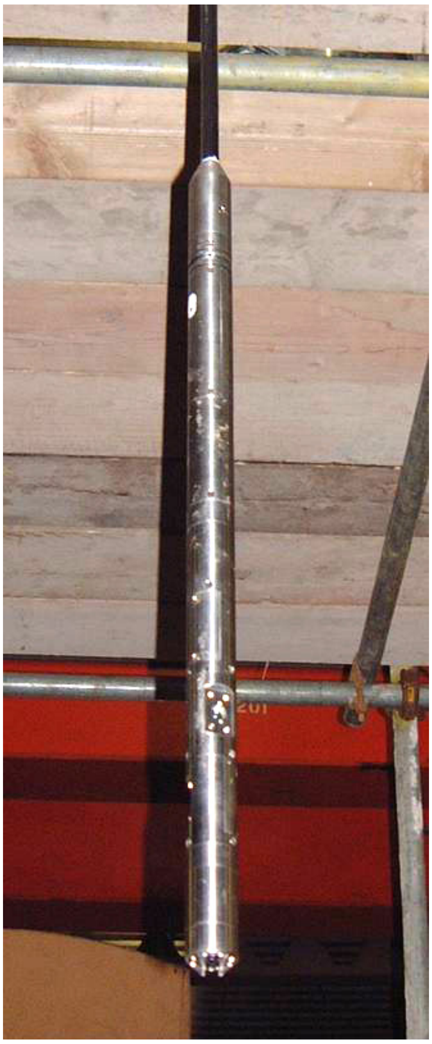

FIG. IV–5. Intrusive inspection equipment for foil hole examination at Windscale pile 1 and spring debris.

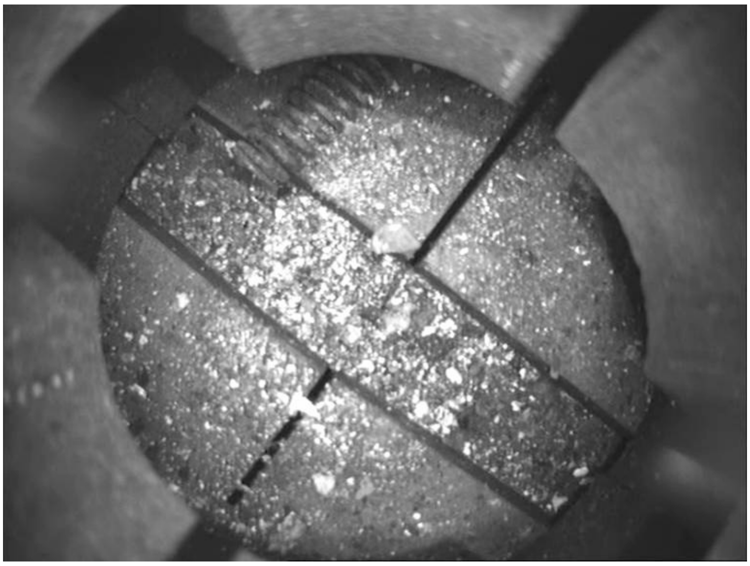

FIG. IV–6. View at the base of a foil hole showing the Wigner gap between the graphite block.

IV–5. FIRE AFFECTED ZONE ENDOSCOPE INSPECTIONS

A third inspection phase of work has now been possible to extend the visual inspection work to the FAZ by horizontal insertion of a commercial flexible endoscope into the fire affected fuel channels. A safety submission to support this work was accepted by the UK regulatory authorities on the basis of the desk based work and earlier inspection work. The initial phase of this work was started during August 2007.

The endoscope utilized a small diameter CCTV system and light emitting diode lighting on the end of a 14 m long flexible umbilical for direct insertion through the charge wall of pile 1 into the FAZ (see Figs IV–7(a) and (b)). This internal inspection work confirmed some of the earlier visual inspection work that had previously been carried out by views taken from the charge and discharge faces of the pile. A range of consequences of the 1957 fire were visible, from the mechanical disturbance of the fuel stringers as the result of post-fire removal exercises (Figs IV–8(a) and (b)), to the melted fuel residues (Fig. IV–9) and oxidation damage to the graphite structure (Fig. IV–10).

The inspection during August 2007 was the first time that the fire damaged region of the reactor core had been seen for the 50 years since shutdown, and it has assisted in reducing the uncertainties in core condition that have been conjectured for many years.

FIG. IV–7(a). Endoscope equipment for fire affected zone inspection at Windscale pile 1.

FIG. IV–7(b). Interfacing the endoscope with the Windscale pile 1 charge face.

FIG. IV–8(a). Fuel channel 24/53 BL internals showing a fuel element displaced from a graphite boat.

FIG. IV–8(b). Damaged graphite boats in channel 24/51 TR.

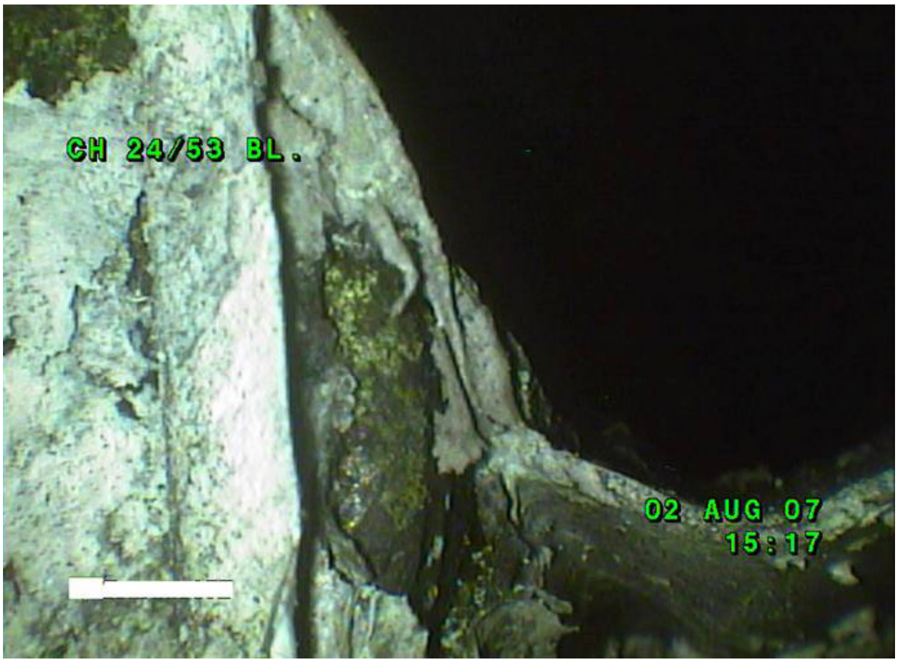

FIG. IV–9. Melted fuel in channel 24/53 BL.

FIG. IV–10. Oxidation damage to the graphite structure at channel 24/52 BL.

IV–6. CONCLUSIONS

The accident damaged nature of the pile 1 reactor core led to a range of issues that would not normally be encountered at a reactor system that had shut down following normal operations. Hence, from the decommissioning perspective, this project has been unconventional since the early stages, and has focused on the physical characterization of the damaged core to try to ascertain the issues that must be fully understood before decommissioning proceeds.

The criticality assessment has examined the effect of accidental (seismic) relocation of material in the FAZ. From this work, it can be deduced that, provided sufficient neutron absorbing isotope cartridges are retained in the FAZ, the movement of the fuel, graphite moderator, control rods or shutdown rods during dismantling will not cause a criticality. No additional neutron absorber or criticality shutdown systems will therefore be required during core dismantling.

Procedures for the orderly removal of material from the FAZ must be assessed and provide the control to ensure that criticality risks remain ALARA.

The formation of uranium hydride and its subsequent survival over 50 years in aerobic conditions is highly improbable. Analysis, based on an impossibly high uranium hydride inventory, shows that at ambient conditions, the oxidation thermal transient caused by disturbance and exposure to air will not propagate to adjacent material. Dismantling in an air environment will therefore be possible.

ALARA considerations will require that techniques for core dismantling, and fuel and isotope removal, should minimize energy input and limit temperature rise as a precautionary measure.

Although the risk of a graphite dust explosion can be dismissed, techniques that minimize the generation of any type of dust are recommended. This will ease the problem of dust handling, minimize the potential for airborne activity release and reduce the challenge to the core ventilation treatment system.

There is a need to satisfy ALARA requirements and control the basic radiological hazards of external radiation and airborne activity (e.g. avoid the intentional cutting of fuel and isotope cartridges).

The completion of this technical programme has been a major milestone for the pile 1 decommissioning project. The work described has reduced the uncertainties for the forward decommissioning programme, thus enabling momentum on this major UK decommissioning project to be maintained.

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Annex V

UNITED STATES OF AMERICA

V–1. HARSHAW CHEMICAL SITE

Many of the sites investigated under the Formerly Utilized Sites Remedial Action Programme (FUSRAP) have complex histories that have slowly been uncovered over the life of the project. The former Harshaw Chemical Site (HCS) exemplifies the complexity presented by an old, formerly heavily utilized industrial facility with a complicated past. The FUSRAP experience at HCS illustrates the critical role that non-sampling information plays in correctly understanding the potential for contamination and designing effective remedial investigation (RI). As the RI was under way, prior to its finalization, a number of unexpected findings, some in the form of field results and others in the form of additional historical documentation, called into question some of the basic assumptions underlying the design of the RI fieldwork. These included the following:

- An on-site gamma spectroscopy system was used as part of the RI field effort for quick turnaround ^{238}U results. This system had relatively high detection limits for ^{230}Th, but was not being operated with ^{230}Th in mind because it had not been identified initially as a contaminant of interest. However, detectable ^{230}Th activity concentrations at unexpected levels and locations began appearing in the on-site gamma spectroscopy RI data sets. These unexpected results were confirmed by off-site laboratory alpha spectroscopy.
- An evaluation of the uranium feedstock used as inputs to the Harshaw uranium purification process indicated the potential presence of ^{230}Th as an impurity in the feedstock. Thorium-230 would have been removed along with other impurities as part of the uranium purification process. The resulting waste streams could have had significant levels of ^{230}Th. Several additional documents were discovered that detailed the likely purification process employed at Harshaw, indicating that the waste product was probably liquid. This, in turn, raised questions about waste disposal practices at the time (e.g. buried waste lines, liquid waste pits, French drains, direct disposal into the Cuyahoga River, capture, containment and off-site disposal) that the original RI work plan was not designed to address.
- Uranium contamination above background levels was encountered, at least in localized pockets, all across the site. Historic record searches indicated that uranium processing activities took place in building G-1. However, the RI discovered uranium contamination, often buried and associated with building and/or construction debris, all across the 220 000 m^2 site. These observations again raised questions about the disposal procedures used at the site post-1940 with respect to potentially contaminated building debris that might have resulted from tear downs, remodelling and renovation work, demolition activities, etc., that the RI work plan was not designed to address.
- The US Army Corps of Engineers found additional historical aerial photographs of the site after the RI fieldwork had been completed. An initial review of these photographs identified the potential presence of now buried waste lagoons near building G-l. Wastes from the uranium refining processes in building G-l could have contained significant levels of ^{230}Th. If liquid wastes had been placed in lagoons, there was the potential for buried lenses of relatively high level ^{230}Th contaminated soils.
- The RI data sets hinted at the possibility of the presence of enriched uranium at the site, but they were not definitive. Historical records gathered as part of the RI indicated that small amounts of enriched uranium may have been processed at the site, but it was believed that these amounts were inconsequential. The presence or absence of enriched uranium, while not of significant risk or dose concern, does raise potentially significant waste categorization issues for the site during remediation, and thus would be a critical input into the planned feasibility study.
- Recycled uranium was determined to have been processed at the site in the 1950s. The issue with recycled uranium is that it raises the possibility for an additional set of contaminants of interest, including ^{99}Tc, ^{137}Cs, ^{241}Am, ^{236}U and plutonium (^{238}Pu, ^{239}Pu and ^{240}Pu). The presence of recycled uranium became known in 2003 with the release of a US Department of Energy (DOE) report identifying HCS as one of the recipients of recycled uranium, but initial indications suggested that there was not enough delivered to HCS to really be of concern. This concern was revisited after fieldwork was completed; the indications were that, in fact, the

amount may have been significant. In addition, ^{137}Cs was observed in some sample results at levels that were inconsistent with historical fallout.

Taken together, the discoveries led to the decision to take a step back and review the adequacy of the investigation process for HCS in light of the new information available. As a result of that review, it was decided to make significant investments in additional investigations and fieldwork to support an RI addendum [V–1].

V–2. OAK RIDGE NATIONAL LABORATORY

As field work on the retrieval of transuranic waste packages from the solid waste storage area (SWSA) 5 north at Oak Ridge National Laboratory (ORNL) progressed, a number of unexpected conditions were encountered. Operating experience also resulted in lessons learned on how to more effectively accomplish the project. The extensive preparation and robust, flexible approach adopted by the project team allowed the project to adapt to and incorporate the majority of these conditions into the planned waste retrieval with minimal impact.

Waste disposal trenches in the ORNL SWSA 5 south area were known to typically have been loaded in a stacked configuration, with the trench being backfilled with grout. During the scoping of the project, available information indicated that casks had been buried in each trench in a single row. However, as excavation proceeded, it was discovered that at least some of the casks had been stacked directly on top of one another during burial. Interviews with personnel did not reveal the complete information about these early activities, which is likely to be at least partially due to the amount of time that has elapsed and the evolution of storage practices. While historical records and personnel interviews are valuable, project planning needs to allow for incomplete or inconsistent information.

Containers other than concrete casks were encountered in one trench, identified as trench 13. This trench was expected to contain a total of nine drums: one 200 L carbon steel drum, one 110 L and seven 200 L stainless steel drums. As anticipated, it appeared that the carbon steel drum had deteriorated to the point where it was no longer intact. During trench 13 retrieval operations, metal that appeared to be the remnants of a deteriorated drum was excavated, along with approximately eight drums containing a white substance and several glass jars containing a black substance. A sample of the white substance was analysed and found to be vermiculite, apparently used as a packing material around the smaller glass jars when placed in the deteriorated drum. While retrieving the loose waste, a reaction occurred in the trench and excavator bucket. A flame that was 1.5–2.5 m high formed, and lasted approximately 5 s. Workers were evacuated from the retrieval enclosure to the boundary control station immediately. Before evacuating, the equipment operator emptied the excavator bucket back into the trench and swung the bucket away from the trench so as to minimize the potential for the reaction to involve the equipment's hydraulic hoses. No personnel contamination or release or spread was detected, either at the time of the event or during subsequent surveys. The barriers and controls in place on this project worked well during this event.

Subsequent investigation indicated that at least one of the glass jars in the trench was broken and spilled its contents. The contents (i.e. the black substance) are now believed to be uranium in the form of uranium carbide particles. Following extensive discussions, it was decided to stabilize trench 13 by placing concrete shoring blocks as a retaining barrier around the exposed sides of the excavation and covering the area of concern with layers of coke, sand and soil to prevent the potential for additional pyrophoric reactions [V–2].

Another example from ORNL illustrates the inadequate use of new equipment. For better waste characterization and sorting, several legacy steel drums, some of which were pressurized, were opened. Within a portable unit enclosure that was built for worker protection, the RapidPort Installation System — used in the sample port or vent installation process — inadvertently discharged during propellant chamber charging. The subsequent manufacturer's engineering evaluation determined that the discharge was caused by inadequate muzzle safety reset. Neither the possibility that personnel could be inside or in close proximity to the portable unit during an inadvertent discharge, nor the possibility that an inadvertent discharge could occur before or after the RapidPort was secured to the drum, were considered in the hazard analysis. This has been identified as an unanalysed accident and possibly an inadequate implementation of a credited specific administrative control.

The new vent and sample port delivery system, RapidPort, was not originally designed to be a remotely gas charged unit, but required operators to charge the system inside the portable unit before exiting to remotely activate the delivery system. According to the manufacturer's engineering evaluation, inadequate slide valve reset to activate the muzzle safety caused the propellant to inadvertently discharge. The manufacturer's operating manual did not include the facts that these particular operational controls were needed to prevent an inadvertent actuation recurrence and workers needed to be in close proximity when units are charged [V–3].

V–3. LOS ALAMOS NATIONAL LABORATORY

During a transfer operation to move radioactive targets from a shipping cask to a dispensary cell in a hot cell array, a radiological control technician (RCT) identified a high radiation area on the roof above the hot cells. Rooftop measurements exceeded 50 mSv/h during the transfer operation, and the RCT received a 1.1 mSv dose during the 10 s or so of exposure to the high radiation field.

The RCT, who had been performing the rooftop surveys as part of the site's ongoing effort to radiologically characterize the hot cell facility, immediately left the area when the instrumentation alarmed at full scale. The rooftop was posted as a high radiation zone, all access paths were controlled, and all site personnel who performed work that would require access to the roof were removed from the site's badge reader database to prevent them from coming on-site without first checking with the access controller. Under the direction of the facility manager, health physics personnel surveyed the entire technical area for additional unidentified radiation areas, and none were found. Personnel also verified that no unexplained radiological exposure incidents had occurred over the past few years that involved work on the hot cell rooftop. A radiological map of the roof was developed, and investigators determined that the hot cells in the U-shaped cell array were fully shielded, but that the warm corridor roof between the cells was not shielded. Additionally, the user group had modified the transfer procedure in the late 1980s after determining that the dispensary cell crane that was used to transfer targets from the warm corridor into the cell was underrated. A 6 t crane was used to place the targets next to the dispensary cell, and then a 2 t crane was used to lift off the shipping cask lids, with the targets attached, and place them in the cell. The high radiation area was created during the period of time in which the targets were lifted out of the casks and not yet placed in the cell. Although crane safety considerations were thoroughly evaluated before the transfer procedure was modified, changes in the radiation fields generated by the targets were overlooked [V–4].

V–4. PADUCAH GASEOUS DIFFUSION PLANT

The project described below is an example of using engineering, administrative and personal protective equipment (PPE) controls to protect against unknown hazardous and radioactive constituents.

V–4.1. Introduction

The Paducah Gaseous Diffusion Plant (PGDP), Kentucky, USA, commenced operations in the early 1950s to produce low enriched ^{235}U fuel for the commercial nuclear industry. During its long history, the plant's operations also included various chemical separation and recovery processes that were related to the mission of the US DOE and its predecessors. Many of these activities resulted in the accumulation of known and unknown hazardous and radioactive constituents. As part of an ongoing assessment throughout the plant, a visual survey was performed in a particular room, herein referred to as the case study room (CSR), in 1999. The survey revealed that the CSR, which measured approximately 5 m × 5 m, was filled with numerous containers, debris items and chemical process equipment. Surface swipes indicated the presence of loose radiological contamination, primarily ^{99}Tc, and gamma ray exposure rate measurements identified the presence of a radiation source.

This case study documents how the US DOE integrated safety management system (ISMS) and the Occupational Safety and Health Administration (OSHA) regulations were applied to mitigate the unknown hazards of the CSR using engineering and administrative controls, including PPE. The overall decommissioning objective was to remove and characterize these accumulated items so that access control (e.g. a radiation work permit) was no longer required for entry, thus returning the CSR to its original operating condition.

V–4.2. Thorough planning — applying integrated safety management

The initial condition of this project required thorough planning and sequencing of events consisting of characterizing and removing materials and items carefully. The principles of ISMS are defined by a cycle of steps that relies on emphasizing employee safety through planning and worker feedback to continuously improve the safe performance of work [V–5]. This cycle consists of five elements:

— Define the scope of work to be performed;
— Analyse hazards associated with work conditions;
— Develop and implement hazard mitigation controls;
— Perform the work;
— Assimilate worker feedback and field measurements to modify future work stages.

V–4.2.1. Unknown source terms and conditions — a high hazard site

Based on the suspect hazardous materials in the room, the CSR was designated a hazardous materials site in accordance with Title 29 of the Code of Federal Regulations, Part 1910.120 — Hazardous Waste Operations and Emergency Response (HAZWOPER) (29 CFR 1910.120) [V–6]. In keeping with the OSHA and health physics requirements, the following engineering controls and work (i.e. administrative) practices and PPE were used and adapted for the project.

V–4.2.2. Engineering controls

— Erecting an enclosure with a series of chambers to minimize the spread of chemical and radiological contamination (Fig. V–1).
— Use of ventilation (e.g. a negative air machine (NAM)) to remove vapours, gases and particulates generated from all activities and potential chemical reactions.
— Use of berms and tarps to maintain segregation of acids and bases.
— Availability of decontamination equipment, for example, showers and eye wash stations.

V–4.2.3. Administrative controls

— Posting facility entrance requirements to restrict access of non-essential personnel.
— When working inside the containment enclosure, the buddy system was used to ensure that rapid assistance could be provided in the event of an emergency. The buddy system organized work groups so that each worker inside the containment enclosure was observed by at least one other worker (i.e. line of sight) at all times. Should an emergency situation arise (e.g. chemical exposure, heat stress or breach in PPE), workers could communicate using prearranged hand signals.
— Providing personnel performing the work with the authority to control work related decisions based on their knowledge, experience, training and field observations.
— Conducting rehearsals prior to starting field activities to reveal any issues or problems with the project objectives so that corrective actions could be implemented. Specific roles and responsibilities for all project personnel were outlined in the project documentation.
— Routinely surveying (e.g. smears and direct readings) work areas, both inside and outside of the containment enclosure by the health physics technicians. A fixative agent was sprayed on highly contaminated surfaces to prevent contamination migration.
— Performing industrial hygiene and health physics monitoring prior to room entry and continuously during all activities to identify potential respiratory hazards. The entry team and standby rescue team members used supplied air while performing all room entries.
— Personnel monitoring, consisting of collecting bioassay samples and wearing whole body and extremity thermoluminescent dosimeters.
— Performing non-radiological airborne contamination monitoring for heavy metals including flammable and explosive vapours caused by radiolytic decomposition of wet and/or organic waste, if present.

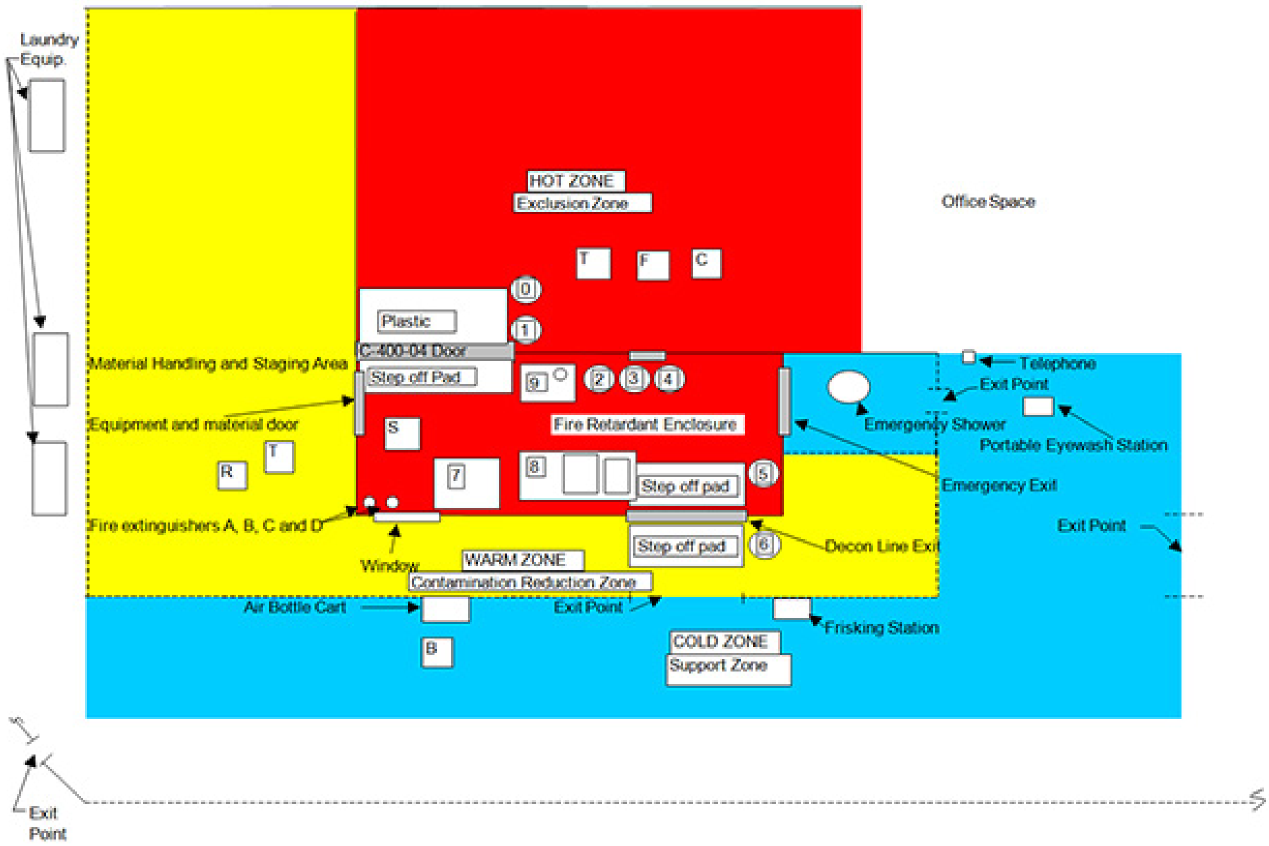

FIG. V–1. C-400-04 work area at Paducah Gaseous Diffusion Plant, United States of America. Zone demarcation: red = hot (exclusion zone); yellow = warm (contamination reduction zone); blue = cold (support zone). Equipment: 0 = 110 L drum for washable overboots; 1 = 110 L drum for outer nitrile gloves; 2 = 110 L drum for outer tape, saranex suits and silver shield aprons that become contaminated; 3 = 110 L drum for silver shield aprons (reusable, if not contaminated); 4 = 110 L drum for silver shield gloves (reusable, if not contaminated); 5 = 110 L drum for disposable boots and nitrile gloves; 6 = 110 L drum for cotton liners; 7 = table for equipment; 8 = table for holding bins for respirators and escape pack units; 9 = wash tub with sprayer and brushes for light decontamination. Personnel: B = bottle wash technician; T = support technician; R = radiological control technician; F = entry team leader; C = nuclear criticality safety evaluator; S = safety watch.

— Fully communicating the shared site resource requirements, action plans and contingencies to affected managers.
— Reviewing each planned activity through prejob briefings and rehearsals with all affected project personnel including the entry team and shared site support teams, for example, fire services and emergency squad representatives.
— Documenting and reviewing information gained from previous stages of the project and modifying project documentation and related plans, as needed, prior to performing work in subsequent stages.
— Giving explicit authority and direction for any worker associated with the project to stop work if an unsafe condition was observed.

Project documentation, such as the work plan and health and safety plan (HASP), was developed in accordance with 29 CFR 1910.120 requirements to incorporate the following sections:

— Safety and health programme;
— Hazard communication programme;
— Medical surveillance programme;
— Decontamination programme;
— Material handling programme, for example, drum and container handling;

— Training programme;
— Emergency response programme.

Project and stage specific attachments included:

— Field work requests;
— Activity hazard analyses [V–7];
— Quality assurance plan;
— Respiratory protection plan developed in accordance with Title 29 of the Code of Federal Regulations, Part 1910.134, Respiratory Protection (29 CFR 1910.134) [V–8];
— Radiological control plan developed in accordance with Title 10 of the Code of Federal Regulations, Part 835, Occupational Radiation Protection (10 CFR 835) [V–9];
— Sampling and analysis plan;
— Waste generation plan.

V–4.2.4. Hold points and emergency notifications

The work plan/HASP included various hold points and emergency actions that would require the entry team to momentarily stop, evaluate and mitigate unexpected hazardous conditions or situations during each work stage. Depending on the complexity of the condition or emergency situation, the project team would decide on a course of action before proceeding with field activities. For example, PPE failure or alteration was identified as a hold point. Therefore, if an employee experienced a PPE failure or alteration (e.g. torn or ripped garment), the affected employee was to immediately leave the containment enclosure and proceed through the decontamination line. Re-entry was not permitted until the PPE had been replaced and the source of the failure or alteration had been corrected (e.g. cover sharp edges to eliminate direct contact). In the event of a minor leak or spill, absorbents and berms were staged in the work area and containment enclosure to prevent migration. Other hold points included, but were not limited to:

— Detection of contamination outside the containment enclosure;
— Radiological and industrial hygiene meter readings exceeding predetermined action limits;
— Unfavourable atmospheres (e.g. detecting flammable or explosive vapours);
— High efficiency particulate air (HEPA) filtered NAM shutdown;
— Instrument failure;
— Radioactive or chemical contamination on PPE;
— Unusual weather conditions (e.g. high temperatures).

Any of the following events would have required prompt notification and response from site support organizations:

— Containment enclosure collapse;
— Fire;
— Worker losing consciousness.

Emergency contacts (e.g. telephone numbers, radio call-out numbers or routes to medical facilities) were maintained in a visible location at the entrance to the building and work area.

V–4.3. Work area mobilization

Mobilization of the CSR work area included assembling and staging all monitoring and survey instruments, PPE, breathing air supplies, and other supplies and equipment. Because of the close proximity of the CSR to other occupied spaces in the building, the entry team requested that a fire retardant enclosure be fabricated and installed immediately outside the CSR door. The enclosure provided a barrier to occupied spaces in the contamination reduction and support zones in the event of a spillage of reactive chemicals and subsequent exothermic release.

The enclosure also served as an equipment staging area and decontamination line for the entry team. It was fitted with several doors including an emergency egress door that led directly to the emergency shower and eyewash stations. The enclosure was designed and constructed with fire retardant material to satisfy National Fire Protection Association code requirements. As the existing ventilation system servicing the CSR was not operational, a temporary HEPA filtered exhaust ventilation system was designed, installed and tested prior to performing the initial entry. As with all hazardous site remediation projects, the work area was divided into an exclusion zone (hot zone), a contamination reduction zone (warm zone) and a support zone (cold zone). The final work area configuration is shown in Fig. V–1.

V–4.4. Multistage recovery plan

The first iteration of the work plan and stage specific HASPs detailed the following four work stage modules:

— Stage 1 module: initial entry;
— Stage 2 module: sampling and transfer of potential hazardous constituents;
— Stage 3 module: opening of drums potentially containing high level hazardous material;
— Stage 4 module: final cleanup activities.

The purpose of the stage 1 initial entry was to assess the initial hazardous conditions in the CSR by performing direct observations, conducting instrument surveys and collecting swipe samples. Also in stage 1, the entry team was tasked with identifying as many potential hazards and debris items as possible utilizing a low light, high resolution video camera. The entry team used level B PPE (the level appropriate for circumstances requiring the highest level of respiratory protection), consisting of a positive pressure airline respirator equipped with an escape air supply. The standby rescue team members were equipped with a positive pressure self-contained breathing apparatus.

During stage 1, the entry team identified a container of sodium orthosilicate pellets, coated with sodium hydroxide, and numerous unmarked containers. A heavily rusted 200 L steel drum suspected of containing hydrofluoric acid (HF), a highly reactive, corrosive and acutely toxic chemical [V–10], was also discovered. This was later confirmed through sampling and characterization. Typically, aqueous HF is shipped from the manufacturer in drums composed of polypentene, which has one of the highest corrosion resistance ratings for HF. However, 20 years ago, the typical HF container configuration consisted of an inner polyethylene bladder encased in an outer steel drum that served as a protective shell for the inner bladder. Polyethylene is adequate for storing HF in the short term, but can become embrittled after a long period of contact with the acid.

The discovery of suspected HF significantly elevated the level of hazard presented by the project, yielding a revision to the stage 2 technical approach. Consequently, the work plan and HASPs were revised to divide stage 2 into two substages. Stage 2A would include two separate entries: (i) sample the drum contents to confirm HF and (ii) if the sample results confirmed the presence of HF, transfer it to a stable container and neutralize the HF residues remaining in the 200 L drum. Stage 2B would encompass the recovery of the remaining hazardous chemical containers from the CSR. To accommodate this change in work scope, the work plan was revised to include the following modules:

— Stage 1 module: initial entry;
— Stage 2A module: HF sampling, repackaging and transfer;
— Stage 2B module: sampling and transfer of other potential hazardous constituents;
— Stage 3 module: opening of 110 L drums potentially containing high level hazardous materials;
— Stage 4 module: final cleanup activities.

V–4.4.1. Summary of stage 2A — hydrofluoric acid sampling, repackaging and transfer

During the sampling and characterization of HF, the PPE was upgraded to level A. As HF can be absorbed through the skin and is very toxic, the level A PPE ensemble consisted of an MSA self-contained breathing apparatus with a 60 min air cylinder, a Kappler hazardous materials responder fully encapsulating chemical proof suit, and HF resistant outer boots and outer gloves. This was based on the known hazard associated with the HF, combined with the concentrated acids and bases identified during the initial entry. Many of the original containers were corroded: the HF, for example, had to be transferred into a new container before it could be removed from the room. The invasive nature of the HF transfer increased the likelihood of a container breach, with the potential for splashing and exposure to harmful vapours.

Only two entry team personnel were allowed to enter the CSR at any given time during stage 2A activities in order to avoid accidental disturbance of containers and debris items by contact with the bulky level A suits. During the stage 2A HF sampling entry, a high airborne concentration of HF vapours was generated as soon as the bung cap was removed from the drum lid. A Draeger tube measurement confirmed that the vapour contained HF.

V–4.4.2. Summary of stages 2B through to 4

Once the HF was removed and the room contents segregated according to chemical compatibility, the PPE was downgraded to level B.

Multiple entries in level B PPE were completed during stage 2B to sample the various suspect chemical containers and, following nuclear criticality safety exemption, transfer them out of the DMSA (DOE material storage area). With the rapid sample analysis turnaround time achieved by the PGDP analytical laboratory, the entry team quickly developed a routine, efficient process to transfer the reactive chemicals and scores of suspect containers and debris items out of the DMSA. The containers of aqua regia, organic bleach, sodium orthosilicate and nitric acid/^{237}Np solution were all transferred to safe containers and recovered from the room without incident. The separate layers of liquid and precipitate in the nitric acid/^{237}Np container were each sampled and analysed, and were determined to be chemically stable, that is, they were not shock sensitive.

The Stage 3 assessment revealed that several of the drums contained only used oil, and the rest were completely empty. The 110-L drums were then transferred out of the DMSA for further characterization and waste disposition

In stage 4, PGDP support team personnel transferred the remaining debris items contaminated with radioactive material out of the DMSA, and cleaned the C-400-04 floor with an HEPA filtered vacuum cleaner. The transferred debris items were subsequently surveyed and packaged as radioactive waste in accordance with the results of swipe analyses. Room C-400-04's DMSA designation was terminated, and the room was placed in standby condition, awaiting final decommissioning.

V–4.4.3. Achievements

The entry and support teams completed stages 1, 2A, 2B, 3 and 4 without significant radiation exposure, and without undue exposure of project personnel to any of the other hazards present. The selection of the appropriate PPE level for each entry was a key decision, leading to the safe and successful completion of the DMSA recovery project.

Virtually all of the objectives established in each stage's work plan module were completed as planned, with a minimum number of entries. The final numbers of entries associated with each work stage were as follows:

— Stage 1 module 4 entries
— Stage 2A module 4 entries
— Stage 2B module 12 entries
— Stage 3 module 2 entries
— Stage 4 module 1 entry
— **Total 23 entries**

Following each entry, post-entry debriefings were conducted, and lessons learned were integrated into the next planned entry or work stage. When unexpected hazardous conditions were encountered in the DMSA, the entry and support teams and the Weskem operations manager promptly evaluated the potential consequences, and designed and implemented the necessary mitigating controls. The work plan and stage specific HASPs were continuously modified, as necessary, to ensure continued safe work practices, in accordance with the DOE ISMS principles. Furthermore, all work stage activities were completed without any occurrence or incident.

V–4.5. Containment enclosure demobilization

When all materials were removed from the containment enclosures, a series of coordinated steps were taken to seal all doors and inlet ports and either (i) disconnect the NAM and relocate the containment enclosure to an equipment surplus area for reuse or (ii) systematically disconnect the containment enclosure membrane from its frame, and collapse the containment enclosure, while regulating airflow through the NAM. If the enclosure was to be collapsed and disposed of as radioactive waste, workers rolled and folded the membrane towards the NAM, where it was finally disconnected from the NAM under health physics supervision. The membrane was then placed into a suitable disposal container. The various work areas were surveyed, and loose contamination was either fixed or removed, thus allowing for downposting of these areas. This final demobilization returned these areas to their original operating conditions.

V–4.6. Lessons learned

Numerous lessons learned were identified and implemented during the course of these projects:

- Produce a clearly defined scope of work and set of goals, which demands a thorough planning process.
- Assign decision authority and individual accountability to complete project tasks.
- Use a flexible work plan structure (e.g. work stage modules) to allow project plans to be easily modified to address new discoveries and changing site conditions.
- Perform pre-entry briefings to help ensure that personnel understand and effectively execute their responsibilities.
- Plan and perform work using clear, effective, closed loop communications, which is essential for success (i.e. communicate, communicate, communicate!).
- Conduct crew briefings to emphasize stop work authority and attention to detail, for example, donning/doffing techniques and performing detailed PPE inspections before each entry and during cutting/repackaging operations to prevent cross-contamination.
- Monitor floor and airlock contamination levels within the enclosure to verify that the contamination does not spread, and apply fixatives as needed.
- Install a portable frisker at the step-off pad to survey the employee’s shoes for contamination.
- Frequently change or replace temporary sticky pads on the floor in the work areas to minimize buildup of radioactive contamination.
- Install a camera to critique work practices within the containment enclosure.
- Use an HEPA vacuum cleaner to remove debris.
- Have backup equipment (e.g. an air distribution box) available in the event of a malfunction.

V–4.7. Metrics

The entry and support teams completed the work activities without significant radiation exposure and without undue exposure from other hazards. The selection of the appropriate PPE level for each entry was a key decision leading to the safe and successful completion of the field project. All project objectives were completed after performing 23 entries.

V–4.8. Conclusion

Section V–4 summarizes the successful field activities associated with remediating a room containing both hazardous (e.g. HF) and radioactive constituents. The planning process included a detailed review of all of the suspect hazardous constituents, radioactive materials and conditions. Consistent with the principles of the ISMS, the multistage approach (i.e. segmenting work activities) allowed the project team members the authority to control work related decisions based on their knowledge, experience, expertise and field observations. The information and experience gained from each previous stage, as well as rehearsals, contributed to modifying subsequent entries, as well as emphasizing the importance of developing hold points and incorporating lessons learned.

However, it is often overlooked that the PPE itself can create significant worker hazards, that is, the greater the level of PPE, the greater the associated risks. As the PPE ensemble is just one part of a comprehensive programme to protect employees against all site specific hazards, engineering and administrative controls must be used together to prevent the generation of either chemical or radioactive airborne contamination. Proper implementation of both engineering and administrative controls reduces the potential of employee exposure occurring, thus providing justification for downgrading PPE requirements without increasing the risk of worker exposure.

ACKNOWLEDGMENTS TO ANNEX V

The work described in Section V–4 was supported by the US DOE under subcontract number 23900-BA-RM005F.

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GLOSSARY

activation. The process of inducing radioactivity, most commonly used to refer to induction of radioactivity in moderators, coolants and the structures and shielding caused by irradiation with neutrons.

as low as reasonably achievable (ALARA). The process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, 'as low as reasonably achievable, economic and social factors being taken into account'.

clearance. Removal of radioactive material or radioactive objects within authorized practices from any further regulatory control by the regulatory body.

configuration management (CM). The process of identifying and documenting the characteristics of a facility's structures, systems and components (including computer systems and software), and of ensuring that changes to these characteristics are properly developed, assessed, approved, issued, implemented, verified, recorded and incorporated into the facility documentation. Configuration is used in the sense of the physical, functional and operational characteristics of the structures, systems and components and parts of a facility.

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

decommissioning. Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (except for a repository or for certain nuclear facilities used for the disposal of residues from the mining and processing of radioactive material, which are closed and not decommissioned).

decommissioning plan. A document containing detailed information on the proposed decommissioning.

decontamination. The complete or partial removal of contamination by a deliberate physical, chemical or biological process.

demolition. In the context of this publication, demolition is the overall process of removing the facility and usually, but not exclusively, relates to civil structures.

dismantling. The disassembly and removal of any structure, system and component during decommissioning.

disposal. Emplacement of waste in an appropriate facility without the intention of retrieval.

event. In the context of the reporting and analysis of events, an event is any occurrence unintended by the operator, including operating error, equipment failure or other mishap, and deliberate action on the part of others, the consequences or potential consequences of which are not negligible from the point of view of protection or safety.

facility configuration information. Record information that describes, specifies, reports, certifies or provides data or results regarding the design requirements or design basis, or pertains to other information attributes associated with the facility and its structures, systems and components. This information may be contained in original hard media (e.g. Mylar, etc.), paper copies, electronic media and any other sources of information used to make sound technical decisions regarding design procurement, modification, and operation and maintenance of the facility. It includes current information, pending information and records. The scope of facility configuration information to be controlled is defined, and the level of control is determined using a graded approach.

mixed waste. Radioactive waste that also contains non-radioactive, toxic or hazardous substances.

near miss. A potential significant event that could have occurred as the consequence of a sequence of actual occurrences, but that did not occur, owing to the plant conditions prevailing at the time. Other familiar terms for these events are a close call, or in the case of moving objects, a near collision or a near hit.

risk management. The process of identifying, assessing and controlling risks arising from operational factors and making decisions that balance risk cost with mission benefits.

robot. An industrial robot is an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications. The term robot is currently used for systems that have motion and intelligence rather than being multipurpose. A teleoperated robot is a robot that can be remotely operated by a human operator.

safe enclosure. Safe enclosure (sometimes called safe storage, safe store or deferred dismantling) is the strategy in which parts of a facility containing radioactive contaminants are either processed or placed in such a condition that they can be safely stored and maintained until they can subsequently be decontaminated and/or dismantled to levels that permit the facility to be released for unrestricted use or with restrictions imposed by the regulatory body.

safety management. An organizational function which ensures that all safety risks have been identified, assessed and satisfactorily mitigated. Safety management is commonly understood as applying a set of principles, framework, processes and measures to prevent accidents, injuries and other adverse consequences that may be caused by using a service or a product. It is that function which exists to assist managers in better discharging their responsibilities for operational system design and implementation through either the prediction of the system's deficiencies before errors occur or the identification and correction of the system's deficiencies by professional analysis of safety occurrences. Safety management implies a systematic approach to managing safety, including the necessary organizational structure, accountabilities, policies and procedures.

safety performance. The quality of safety related work; safety related work is regarded as the efforts made to achieve safety. Safety performance can be considered as a subset of the total performance of an organization.

spent fuel. Nuclear fuel removed from a reactor following irradiation, which is no longer usable in its present form because of depletion of fissile material, buildup of poison or radiation damage.

stakeholder. Interested party or concerned party.

storage. The holding of radioactive sources, spent fuel or radioactive waste in a facility that provides for containment, with the intention of retrieval.

structures, systems and components (SSCs). A general term encompassing all of the elements (items) of a facility or activity that contribute to protection and safety, except human factors. Structures are the passive elements: buildings, vessels, shielding, etc. A system comprises several components, assembled in such a way as to perform a specific (active) function. A component is a discrete element of a system. Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves.

unrestricted use. The use of an area or material without any radiologically based restrictions.

ABBREVIATIONS

ALARA	as low as reasonably achievable
ANL	Argonne National Laboratory
ARA	auxiliary reactor area
CAD	computer aided design
CCTV	closed circuit television
CERS	comprehensive engineering and radiation survey
CM	configuration management
CPT	cable protection tube
CSR	case study room
DMSA	United States Department of Energy material storage area
DOE	United States Department of Energy
DSA	documented safety analysis
EBWR	experimental boiling water reactor
ETTP	East Tennessee Technology Park
FAZ	fire affected zone
FCM	fuel containing material
FP	fission product
FUSRAP	Formerly Utilized Sites Remedial Action Programme
HASP	health and safety plan
HCS	Harshaw Chemical Site
HDR	superheated steam reactor
HEPA	high efficiency particulate air
HVAC	heating, ventilation and air-conditioning
INEEL	Idaho National Engineering and Environmental Laboratory
ISMS	integrated safety management system
ISO	International Organization for Standardization
ISTC	Interdisciplinary Scientific and Technical Centre
JCO	justification for continued operation
KKN	Niederaichbach nuclear power plant
LILW	low and intermediate level waste
LLNL	Lawrence Livermore National Laboratory
NAM	negative air machine
NDA	non-destructive assay
NURES	nuclide removal system
ORNL	Oak Ridge National Laboratory
ORPS	Occurrence Reporting and Processing System
OSHA	United States Occupational Safety and Health Administration
PCB	polychlorinated biphenyl
PGDP	Paducah Gaseous Diffusion Plant
PPE	personal protective equipment
RCT	radiological control technician
RI	remedial investigation
ROV	remotely operated vehicle
R&D	research and development
SARRY	simplified active water retrieve and recovery
SFP	spent fuel pool
SIP	shelter implementation plan
SSC	structures, systems and components
TEPCO	Tokyo Electric Power Company
TM	technological material
TMI	Three Mile Island

ÚJV	ÚJV Řež, a. s. (Řež Nuclear Research Institute)
UU	uncertainty/unknown
WCD	work control document
WCH	Washington Closure Hanford
WP&C	work planning and control
3-D	three dimensional

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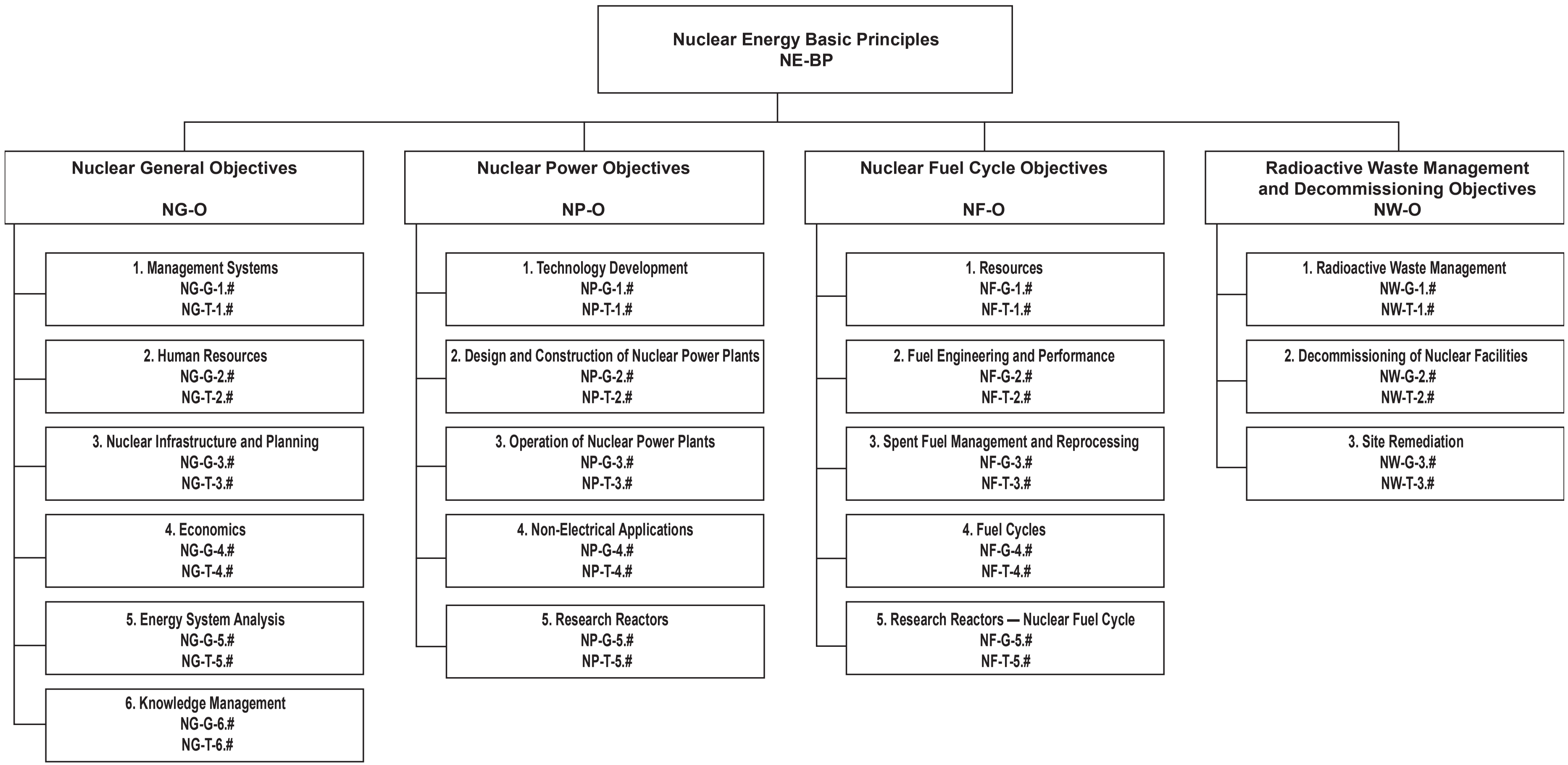

Key

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