IAEA Nuclear Energy Series

No. NW-T-2.7

# Experiences and Lessons Learned Worldwide in the Cleanup and Decommissioning of Nuclear Facilities in the Aftermath of Accidents

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# IAEA NUCLEAR ENERGY SERIES PUBLICATIONS

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# EXPERIENCES AND LESSONS LEARNED WORLDWIDE IN THE CLEANUP AND DECOMMISSIONING OF NUCLEAR FACILITIES IN THE AFTERMATH OF ACCIDENTS

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2014

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email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
September 2014
STI/PUB/1644

**IAEA Library Cataloguing in Publication Data**

Experiences and lessons learned worldwide in the cleanup and decommissioning of nuclear facilities in the aftermath of accidents.. — Vienna : International Atomic Energy Agency, 2014.
p. ; 30 cm. — (IAEA nuclear energy series, ISSN 1995–7807 ; no. NW-T-2.7)
STI/PUB/1644
ISBN 978–92–0–101214–2
Includes bibliographical references.

1. Nuclear facilities — Accidents. 2. Nuclear facilities — Decommissioning. 3. Nuclear reactor accidents. 4. Nuclear power plants — Accidents. I. International Atomic Energy Agency. II. Series.

IAEAL 14–00926

# 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.

Although much information exists on decommissioning and remediation following historical nuclear accidents, it is timely, particularly in the light of the accident at the Fukushima Daiichi nuclear power plant in March 2011, to review the experience gained in managing post-accident activities, particularly for accidents involving significant damage to nuclear fuel.

Following the accident at the Three Mile Island (TMI-2) nuclear power plant and the Chernobyl accident, the IAEA issued several publications providing technical guidance and recommendations on the management of damaged nuclear fuel, sealing of the reactor buildings, post-accident cleanup of large contaminated areas, and cleanup and decommissioning of reactors which have undergone a severe accident. These publications are now more than 20 years old, and therefore do not address experiences and lessons learned from cleanup and decommissioning activities performed in several Member States (Canada, Japan, the Russian Federation, Slovakia, Ukraine, the United Kingdom and the United States of America) during the past two decades.

This publication relates to Item 10 of the IAEA Action Plan on Nuclear Safety, which has the objective, inter alia, of reviewing existing experiences in Member States in the cleanup and decommissioning of nuclear facilities in the aftermath of accidents, reporting on experiences and lessons learned worldwide, and making the results available to Member States.

The IAEA officers responsible for this publication were P.J. O'Sullivan of the Division of Nuclear Fuel Cycle and Waste Technology and V. Ljubenov of the Division of Radiation, Transport and Waste Safety.

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# CONTENTS

# SUMMARY

The purpose of this publication is to review IAEA Member States' experiences in in the cleanup and decommissioning of nuclear facilities in the aftermath of accidents, and to report on the experiences and lessons learned worldwide. Much of the information that has been published by the IAEA following the Three Mile Island and Chernobyl accidents is still appropriate for post-accident lessons learned. This publication focuses on what has changed in the interim. The following subject areas have been chosen as the most appropriate:

- Stakeholder communications and involvement;
- Strategic planning, phases and specification of a cleanup end state;
- Post-accident stabilization;
- Damaged fuel and fuel debris, and technological advances for remotely operated equipment for their retrieval;
- Technological advances for characterization activities and characterization data management;
- Considerations for final decommissioning and site remediation;
- Waste management as it differs from normal practices.

This publication discusses the applicable techniques and best practices to support cleanup and decommissioning following accidents at nuclear facilities (events broadly comparable to levels 4–7 on the INES, the International Nuclear Event Scale). There is some discussion of cleanup and decommissioning following incidents (broadly equivalent to levels 1–3 on the INES), though, in general, decommissioning and remediation of facilities that have experienced such incidents follow standard approaches. Key points from each chapter are described below to summarize the contents of the publication.

Stakeholder interface: Communication with and the involvement of stakeholders has gained considerable importance over time. Stakeholders will be intensely interested in the post-accident cleanup. The facility owner/operator should designate organizational elements to support stakeholder communications. Timely release of accurate information is important so that stakeholders know what is happening and the status of real and perceived hazardous conditions. Communication with stakeholders regarding near term actions and long range strategic planning is essential. The opportunity to take account of advice from stakeholders during planning should be strongly considered.

Post-accident planning: This publication focuses on planning principles and important functional areas to be addressed for strategic planning. Strategic planning should be conducted early, even if the information needed is not complete. Plans will be revised as information and data are acquired and as unexpected conditions are encountered while progress is achieved. Interim milestones and final end state goals will need to be defined. One important end state plan addresses the conditions to be achieved prior to transitioning to a final decommissioning strategy. Criteria and detailed specifications should be used to provide guidance and requirements for establishing physical conditions for these milestones and end states. And, while the cleanup is in progress, alternative approaches and options for the decommissioning strategy will need to be carried forward until the preferred option emerges.

Stabilization: Stabilization refers to those activities during and subsequent to the emergency response that are needed prior to beginning intensive post-accident cleanup. Stabilization actions and goals must have a sound design basis and be approved by appropriate authorities. All the stabilization measures must be designed and conducted carefully to assure the safety of workers and the public. Successful containment, cooling and criticality control must be achieved and maintained throughout the post-accident activities, to the degree possible without hampering the decommissioning activities.

Characterization: Each accident will encounter unique challenges that require the adaptation of existing technologies to conduct characterization. Characterizing damage to systems, equipment and facilities will require bespoke and novel applications. Remote technologies will very likely be required for local and close to event characterization; their deployment will be challenging, especially for those devices that measure data and gather information. Characterization results are necessarily used to ensure the project baseline plan remains robust.

Damaged fuel and fuel debris: This is usually the most challenging aspect of post-accident cleanup. In many cases, its removal presents the greatest hazard; achieving removal provides the most significant hazard reduction. Until visual evidence of the physical form is available, there will be great uncertainty in designing the tools, machines and methods for fuel removal. The selection of fuel removal hardware must be such that its failure in use will not significantly impact continued operations. Planning and design must address the entire fuel removal

and disposition campaign from beginning to end. These activities must also integrate a diverse set of functions. In addition to tools and equipment for removal, they must address worker health and safety, containers for the materials, the need to quantify removed materials and debris, interim on-site storage, material packaging and transportation considerations.

Decommissioning and site remediation: Very few facilities that have experienced a severe accident have entered into final decommissioning and site remediation. Many sites opt for an extended period of safe storage with care and maintenance that will allow for radioactive decay. Deployment of decommissioning techniques for post-accident recovery has also been very limited. In preparing for extended storage, it is important that knowledge capture be conducted to archive and make retrievable information that will be needed for future planning of decommissioning activities such as hazardous material removal and demolition.

Waste management: While most post-accident waste types have been managed before and most treatment methods have been used, the large volumes, activity concentrations and radiation levels associated with severe accidents can present unique challenges. Contamination of reactor coolant with fission products, primarily by $^{137}$Cs and spent fuel particles, will create high dose rates, prompting an urgent need for process systems and storage of treated water and purification media. Damaged nuclear fuel and fuel debris are unique types of waste unlikely to have readily available disposition pathways. Where there has been dispersal of fuel particles outside the site facilities, the resulting debris creates a similar urgent need to find and collect it. New facilities will be needed to house systems, store waste and eventually prepare and package waste for transport to disposal facilities.

# 1. INTRODUCTION

## 1.1. BACKGROUND

During the past 60 years, a number of accidents have occurred at nuclear installations and at some other facilities where radioactive material was being used or was in storage, causing considerable public anxiety and financial hardships for people, corporations and governments. These past events have ranged from small, contained incidents to full scale accidents that have had a significant effect on the surrounding population and the environment. Some of these accidents have even had environmental impacts beyond national borders, in particular the chemical explosion in a tank containing radioactive waste in Mayak (Kyshtym) in 1957, the accident at Chernobyl in 1986, and the radiological accident at Goiânia (Brazil) in 1987. Other significant nuclear accidents include Three Mile Island (TMI-2) in 1979 and the Fukushima Daiichi accident in 2011.

When an accident occurs, the main focus is to bring the facility to a stable condition and to ensure the safety of facility workers at the site and members of the public residing in the vicinity of the site, and to protect the surrounding environment. After the immediate danger to workers and public has ended, stabilization and cleanup activities begin, which are eventually followed by decommissioning and/or remediation. By understanding the dynamics of past accidents, such as the measures applied to stabilize the situation and the interaction of initial actions with decommissioning and remediation activities, important issues can be identified and captured for future situations.

Several IAEA reports offer experience and insight to facilitate better preparation for fuel damage events. The value of these reports and other accident cleanup lessons has been demonstrated. Over the course of the first two years following the Fukushima Daiichi accident, planning its post-accident cleanup has benefitted from the experience of past accidents, as well as from conventional nuclear decommissioning and area remediation projects that have occurred over the past 20 years. That experience was made available to the Fukushima Daiichi planners in the form of reports, technology workshops in Japan and expertise from around the world.

## 1.2. PURPOSE

At the IAEA Ministerial Conference on Nuclear Safety, held in June 2011, the IAEA was requested to prepare an Action Plan on Nuclear Safety, with the overall objective of strengthening nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. The action plan defines a comprehensive program of work covering 12 thematic areas, including ensuring the ongoing protection of people and the environment from ionizing radiation following a nuclear emergency. This publication is part of the work undertaken as part of this thematic area.

The purpose of this publication is to review experiences in IAEA Member States in the cleanup and decommissioning of nuclear facilities in the aftermath of accidents and to report on the experiences and lessons learned worldwide.

## 1.3. SCOPE

Following the Chernobyl accident in 1986, the IAEA conducted a programme to make the TMI-2 and other accident experience available to those dealing with Chernobyl and to make the lessons learned from those events available to others. Publications resulting from that effort included:

- IAEA Technical Reports Series No. 321, Management of Severely Damaged Nuclear Fuel and Related Waste [1], which addresses activities for post-accident management leading to an interim end state in which the potential for an uncontrolled release to the environment no longer exists;
- IAEA Technical Reports Series No. 346, Cleanup and Decommissioning of a Nuclear Reactor After a Severe Accident [2], which provides an overview of factors relevant to the cleanup requirements and the choice of a decommissioning option for a severely damaged nuclear power plant;

- IAEA TECDOC No. 935, Issues and Decisions for Nuclear Power Plant Management after Fuel Damage Events [3], which considers on-site activities associated with in-plant systems, processes and fuel (and including minor fuel damage events).

This publication provides an overview of lessons across a broad range of topics, including examples, and updates information from earlier reports, though it does not supersede these reports, as they still provide useful information on the detailed topical areas being addressed. The subject areas addressed by this publication include:

- The importance of communication and stakeholder interactions and involvement;
- Strategic planning, phases and specification of a cleanup end state;
- Post-accident stabilization;
- Technological advances for remotely operated equipment for the removal of damaged fuel and debris;
- Technological advances for characterization activities and characterization data management;
- Waste management, as it differs from normal practices;
- Considerations for final decommissioning and site remediation.

As shown in Fig. 1, this update relates specifically to stabilization, post-accident cleanup, safe enclosure (dependent upon the severity of the event and recovery plans) and, ultimately, longer term decommissioning and site remediation. Actions taken in response to the nuclear or radiological emergency in order to mitigate its consequences for human health and safety, quality of life, property and the environment are outside the scope of this publication. The following terms are used in Fig. 1:

- *Stabilization* refers to those activities during and subsequent to the emergency response actions that are needed prior to beginning intensive post-accident cleanup.
- *Post-accident cleanup* encompasses cleanup activities necessary to achieve an interim end state in which the potential for an uncontrolled release to the environment no longer exists. There will typically be some overlap between the stabilization and accident cleanup phases.
- *Characterization* is concerned with understanding the physical and radiological status of the plant, including dose rates, inventories and distribution of radionuclides, the chemical and physical form of the radioactive materials and the integrity of the plant structures.
- *Accident waste management* includes conditioning, packaging and storage during, and possibly beyond the end of, post-accident cleanup.

Representation of the above activities as discrete phases of work is necessarily a simplification of actual situations; in practice, there are likely to be significant overlaps between each of these activities.

The main accidents discussed in the report, and their current status with regard to cleanup and decommissioning, are listed in Table 1.

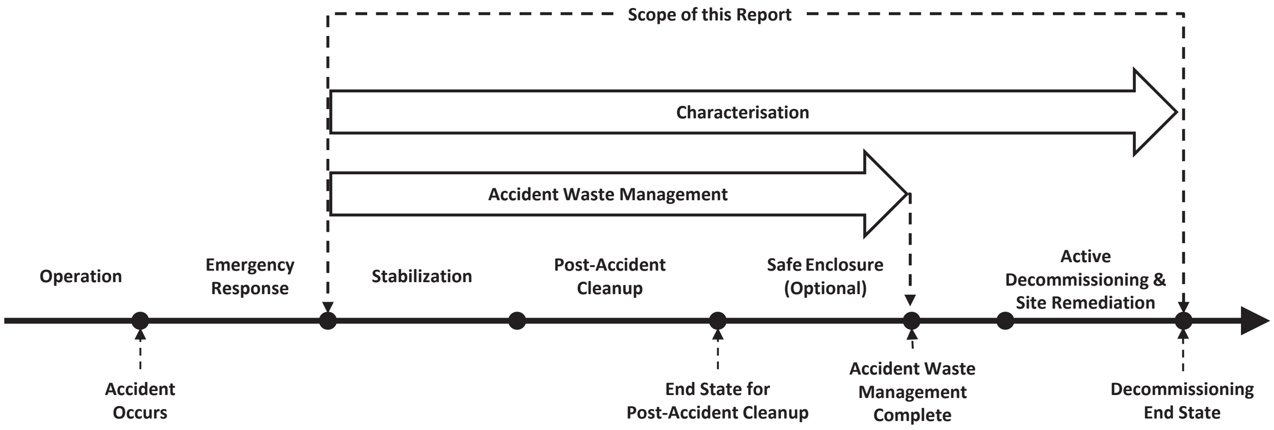

*FIG. 1. Timeline of accident recovery activities.*

TABLE 1. CURRENT STATUS OF NUCLEAR ACCIDENT FACILITIES

| Accident | Current Status |
|---|---|
| Windscale | Care and maintenance/safe enclosure |
| Three Mile Island | Care and maintenance/safe enclosure |
| Chernobyl | Post-accident cleanup/safe enclosure/additional confinement in progress |
| Fukushima | Stabilization and post-accident cleanup |
| Kyshtym | Site remediation |
| Bohunice A-1 | Safe enclosure/decommissioning |

## 1.4. INTERNATIONAL NUCLEAR AND RADIOLOGICAL EVENT SCALE

The International Nuclear and Radiological Event Scale (INES) is a tool for communicating to the public in a consistent way the safety significance of nuclear and radiological events [4]. The scale distinguishes between ‘accidents’, which have INES levels 4–7, and ‘incidents’, which have INES levels 1–3 — see Fig. 2. This publication discusses the applicable techniques and best practices to support the cleanup and decommissioning of facilities that have suffered accidents. Although a link is made in particular discussions in the report with events in specific INES levels, INES levels are used with the intention to convey to the reader the safety significance of these events rather than to generalize the applicability of particular activities, techniques and best practices for events

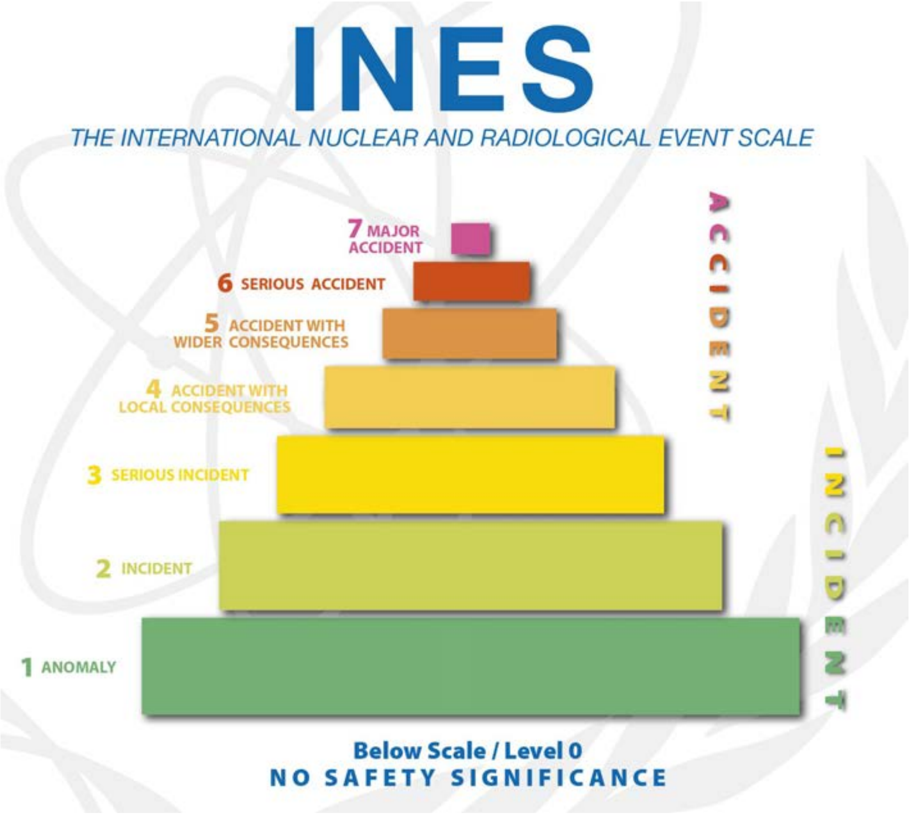

*FIG. 2. The International Nuclear and Radiological Event Scale.*

in a specific INES level; this needs to be considered on the case by case basis. For severe accidents (i.e. those broadly corresponding to INES levels 5–7), it is unlikely that the facility will resume operation, resulting in the commencement of decommissioning and remediation activities.

Table 2 describes an example of each of the INES levels. The information in this publication is drawn mainly from events that have been rated INES level 5 or higher.

TABLE 2. EXAMPLES OF PAST EVENTS AT NUCLEAR FACILITIES WITH DIFFERENT INES LEVELS

| INES level:<br>The general criteria for rating an event within the level | Example event | Event description |
|---|---|---|
| Major accident (INES Level 7):<br>A major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended counter-measures | 1986<br>Chernobyl, Ukraine | A nuclear reactor located at a power plant in Chernobyl experienced a steam explosion and fire that caused a meltdown, releasing massive quantities of radioactive material. The releases from Unit 4 continued for 10 days, and included radioactive gases, condensed aerosols and a large amount of fuel particles. Large areas of Europe were affected to some degree and contamination affected an area of more than 200 000 km$^2$. |
| Serious accident (INES Level 6):<br>A significant release of radioactive material likely to require implementation of planned counter-measures. | 1957<br>(Reprocessing plant)<br>Kyshtym,<br>Union of Soviet Socialist Republics | On 29 September, evaporation of cooling liquid in a tank and a rise in temperature of the 70–80 t of radioactive waste present resulted in a chemical explosion within the tank, which later became known as the Kyshtym accident. Approximately 90% of the 740 PBq of mixed fission products released were deposited as particulate material within 5 km of the tank while the remaining 74 PBq of radioactive material was deposited as dry fallout over an area some 30–50 km in width and some 300 km in length stretching north-north-east of the Mayak facility. Some 15 000–20 000 km$^2$ received contamination higher than 3.7 kBq/m$^2$ of Sr-90. This delineated an area of approximately 1000 km$^2$ that became known as the East Urals Radioactive Trace. |
| Accident with wider consequences (INES Level 5):<br>A limited release of radioactive material likely to require implementation of some planned counter-measures. Several deaths from radiation. | 1979<br>(Reactor)<br>Three Mile Island,<br>Pennsylvania,<br>United States of America | On 28 March 1979, a malfunction of components that maintain the flow of coolant water to steam generators in the secondary loop occurred. This resulted in a loss of ability to remove heat from the primary loop causing the coolant water temperature and pressure to increase rapidly. This in turn caused a relief valve on the pressurizer to open. Steam and water were discharged to the reactor coolant drain tank, which is located in the basement and is equipped with a pressure limiting rupture disk. The accident generated significant quantities of radioactive waste. Approximately 2500 m$^3$ of water with an activity of 1 TBq/m$^3$ were released into the auxiliary building, fuel handling building, service building and diesel generator building. |

TABLE 2. EXAMPLES OF PAST EVENTS AT NUCLEAR FACILITIES WITH DIFFERENT INES LEVELS (cont.)

| INES level:<br>The general criteria for rating an event within the level | Example event | Event description |
|---|---|---|
| Accident with local consequences (INES Level 4):<br>Any of the following: A minor release of radioactive material unlikely to result in implementation of planned counter-measures other than local food controls. At least one death from radiation. Fuel melt or damage to fuel resulting in more than 0.1% release of core inventory. Release of significant quantities of radioactive material within an installation with a high probability of significant public exposure. | 1977<br>(Reactor)<br>Jaslovské Bohunice, Slovakia | Fuel integrity was lost as a result of two fuel loading events resulting in extensive damage of fuel cladding and release of radioactivity. |
| Serious incident (INES Level 3)<br>Any of the following: Exposure in excess of ten times the statutory annual limit for workers. Non-lethal deterministic health effects from radiation. Exposure rates of more than 1 Sv/h in an operating area. Severe contamination in an area not expected by design, with a low probability of significant public exposure. Near accident at a nuclear power plant with no safety provisions remaining. Lost or stolen highly radioactive sealed source. Misdirected highly radioactive sealed source without adequate radiation procedures in place to handle it. | 2006<br>(Reprocessing plant)<br>THORP Reprocessing Plant<br>Sellafield Ltd,<br>United Kingdom | Following plant mass balance calculations, a pool of 83 m$^3$ of product liquor was discovered within the feed clarification cell of the THORP reprocessing plant. No liquor was lost to the environment and no persons were injured or contaminated following this event. |
| Incident (INES Level 2)<br>Any of the following: Exposure of a member of the public in excess of 10 mSv. Exposure of a worker in excess of the statutory annual limits. Radiation levels in an operating area of more than 50 mSv/h. Significant contamination within the facility into an area not expected by design. Significant failures in safety provisions but with no actual consequences. Found highly radioactive sealed orphan source, device or transport package with safety provisions intact. Inadequate packaging of a highly radioactive sealed source. | 2005<br>Atucha Nuclear Power Plant,<br>Argentina | Overexposure of a worker at a power reactor exceeding the annual limit. |
| Anomaly (INES Level 1):<br>Any of the following: Overexposure of a member of the public in excess of statutory annual limits. Minor problems with safety components with significant defence in depth remaining. Low activity lost or stolen radioactive source, device or transport package. | 2004<br>(Reactor)<br>Mihama Nuclear Power Plant,<br>Japan | A water pipe in a turbine building adjoining the Mihama 3 reactor burst suddenly as workers prepared to conduct a routine safety inspection. Though no radiation was released, the steam explosion killed five plant workers and injured others. |

### 1.5. STRUCTURE OF THIS PUBLICATION

The sections of this publication address the main subject areas considered relevant to the post-emergency phase of an accident through to preparations for final decommissioning and site remediation:

- Section 2 (Stakeholder communication and involvement) discusses communication with and involvement of stakeholders during the post-accident phase.
- Section 3 (Post-accident planning) focuses on planning principles and important functional areas to be addressed in strategic planning.
- Section 4 (Stabilization) is concerned with those activities during and subsequent to the emergency response actions that are needed prior to beginning intensive post-accident cleanup.
- Section 5 (Characterization) describes the technological requirements for developing an understanding of the physical and radiological status of the plant.
- Section 6 (Damaged fuel and fuel debris) discusses the issues impacting on the removal of damaged fuel and fuel debris from the plant.
- Section 7 (Decommissioning and site remediation) is concerned with the preparatory work required to ensure that the accident damaged facility can eventually be removed and the site remediated.
- Section 8 (Waste management) describes the considerations involved in processing and ultimately disposing of the waste arising from the cleanup of an accident damaged facility.

# 2. STAKEHOLDER COMMUNICATION AND INVOLVEMENT

**KEY LESSONS LEARNED**

- Stakeholder interest in cleanup and decommissioning activities in the aftermath of a severe accident at a nuclear facility will be intense, requiring the facility owner/operator and the national authorities to establish appropriate arrangements for providing information and involving the stakeholders in planning these activities.
- The primary objectives of communication should be to protect life and to minimise fear and anxiety by ensuring understanding of and compliance with protective actions.
- Stakeholders will want to be involved in the near term and long range strategic planning. Early release of accurate information to stakeholders is crucial to maintaining their trust throughout the development and implementation of cleanup and decommissioning plans.
- Regular public outreach programmes during normal, pre-accident, operations, can promote public trust, thereby minimizing the impact of the accident and facilitating the determination of the end state.

### 2.1. INTRODUCTION

While incidents corresponding to INES levels 1–3 are always important from a safety and technical standpoint, the consequences of these events are confined to the facility itself, with little, if any, radiation leakage into the surrounding environment. Recovery from such events is much less problematic than from more severe accidents and, in general, normal operations are resumed as soon as is practicable following the event. Subsequently, the incident is likely to generate much less stakeholder input or response than would be the case for more significant events.

In the immediate aftermath of a severe accident, local and national communities are likely to be impacted and, in some cases, may be displaced from their homes and normal lives. It is not unusual for these stakeholders to experience anger and distrust towards the facility management and towards local, state and national government entities.

Communicating effectively with the public about nuclear or radiological emergencies is a key aspect of successful emergency management and, accordingly, arrangements should be established in advance to ensure that this kind of communication takes place effectively in the event of an accident [5–7]. Effective communication will help mitigate the risks, support the implementation of protective actions and other response actions, and contribute to minimizing adverse non-radiological impacts. This will also encourage the smooth implementation of appropriate actions in response to the emergency by people at risk and reassure individuals who are not directly at risk by reducing rumours and fears. It can facilitate relief efforts and also maintain public trust and confidence in the organizations responsible for ensuring the welfare of the public.

Evacuations of local residents, even those of a temporary nature, the development of plans for decommissioning and for off-site remediation, future land use, habitability and financial impact are all of paramount concern to nearby residents and commercial enterprises. It is imperative, therefore, that those responsible for addressing these issues communicate with and engage the public and other stakeholders, such as policy makers, environmental regulators, industry, neighbouring countries and international organizations, on an ongoing basis.

## 2.2. STAKEHOLDER ENGAGEMENT FOR SITE CLEANUP AND DECOMMISSIONING

Effective stakeholder engagement, along with a comprehensive, regular public outreach programme during normal operations, can promote public trust, thereby minimizing the impact of the crisis and facilitating the determination of the end state.

It is essential that those responsible for facility management in the aftermath of an accident develop a comprehensive strategy for stakeholder interactions concerning the development and implementation of plans for the cleanup and future decommissioning of the facility. To ensure a smooth transition to cleanup and decommissioning the facility must build and develop relationships based upon honesty, integrity and open communication by releasing unambiguous information on a regular and routine basis. It is also important that facility managers deliver on promises to provide information during this post-accident phase; otherwise they risk losing this trust. Such information should include updates on the recovery process, remediatory actions and/or investigations.

As this relationship to support decommissioning operations develops, many stakeholders demand to be part of the solution and request public consultation on the following areas:

- Development of the decommissioning programme;
- Observational visits to the facility to view the work to be undertaken and to increase understanding of potential impacts;
- Development and implementation of a local stakeholder liaison meeting to support and facilitate relationships.

The involvement of key stakeholders can provide understanding, acceptance and support to future decommissioning operations; however, building this relationship will require considerable time and patience on behalf of the facility’s executives, managers and workers. It is also likely to involve skills the facility may not have previously had access to, such as translation services.

Public communications during the TMI-2 accident were poorly coordinated between the plant operator, Metropolitan Edison, and the Pennsylvania Emergency Management Agency, often leading to conflicting messages being given to the local community. Over time, this situation was improved and the need for intensive post-emergency communications activities was recognised by the authorities responsible for the cleanup activities. A year after the TMI-2 accident, the NRC convened a 12 member independent citizens’ advisory panel to reflect on the decontamination and cleanup of the facility. The panel met 78 times over a period of 13 years, holding public meetings in the vicinity of TMI-2, and it also met regularly with NRC Commissioners in Washington, DC. The panel served to reduce public anxiety about the accident and cleanup, and ultimately to ensure the concerns of the public were accepted and addressed. In general, the panel was perceived by participants and observers as a success in promoting dialogue between the public and the NRC [8].

In the case of the accident at Chernobyl, in recent years, the United Nations and affected governments have modified their approach to the region around Chernobyl by shifting emphasis from emergency response to sustainable development. Since 2009, the IAEA has been working with the United Nations Development Programme, the United Nations Children’s Fund and the World Health Organization to inform local communities about the effects of Chernobyl and to enhance understanding of scientific research regarding health and environmental aspects of radiation. The International Chernobyl Research and Information Network project is a multi-year effort to create information centres in rural areas, disseminate information through schools, health care systems and media, and implement small scale community infrastructure projects aimed at improving living conditions and promoting self-reliance.

Since the Fukushima event, TEPCO provides frequent updates of progress on-site via their web site, which provides up to date information in an open and transparent manner. The web site includes live feeds from cameras in the facility and still photographs of progress made in cleanup operations. In addition, TEPCO has adopted social media channels to provide instantaneous information to a worldwide audience. The Local Nuclear Emergency Response Headquarters provided newsletters, fact-sheets and other literature and responded to telephone inquiries from residents around the nuclear power plant (NPP).

Confusion results in distrust and poor relations within both the community local to the accident facility and the wider general public that, if not addressed, could have a significant impact on the cleanup and interim or end state of the facility. Successful engagement of stakeholders, transparency and open communication will ensure the actions to mitigate accident damage and recovery are met with cooperation and end state goals are achieved.

# 3. POST-ACCIDENT PLANNING

**KEY LESSONS LEARNED**

- Strategic planning for cleanup should be conducted early with the understanding that plans will be revised as information and data are acquired and that unexpected conditions will be encountered as progress is made.
- Interim and final end states goals will need to be defined. An important interim end state plan addresses the conditions to be achieved for cleanup prior to transitioning to a final decommissioning strategy.
- Criteria and detailed specifications should be used to provide guidance for establishing physical conditions for interim milestones and the cleanup end state.
- Alternative approaches and options for the decommissioning strategy will be carried forward until one emerges as a preferred option.

## 3.1. INTRODUCTION

Planning activities for post-accident stabilization and cleanup is considerably different from planning normal power plant operations or standard decommissioning. In a post-accident situation, much of the information and data needed for planning and decision making only becomes available as cleanup progresses. Planning evolves as the conditions inside the plant become better understood. Thus, there can be several options for major courses of action that will be refined as conditions become better characterized.

The purpose of this section is to describe important perspectives for planning during post-accident stabilization and cleanup leading to a pre-decommissioning end state. For this end state, the facility and site physical conditions are established for proceeding directly to final decommissioning or to a safe storage period preceding final decommissioning — see Fig. 3.

This section addresses four subject areas:

(1) Post-accident cleanup phases that require planning and identification of activities in each phase;
(2) Strategic planning during the cleanup period prior to the pre-decommissioning end state;
(3) Steps to establishing a pre-decommissioning end state;
(4) End state criteria and specifications.

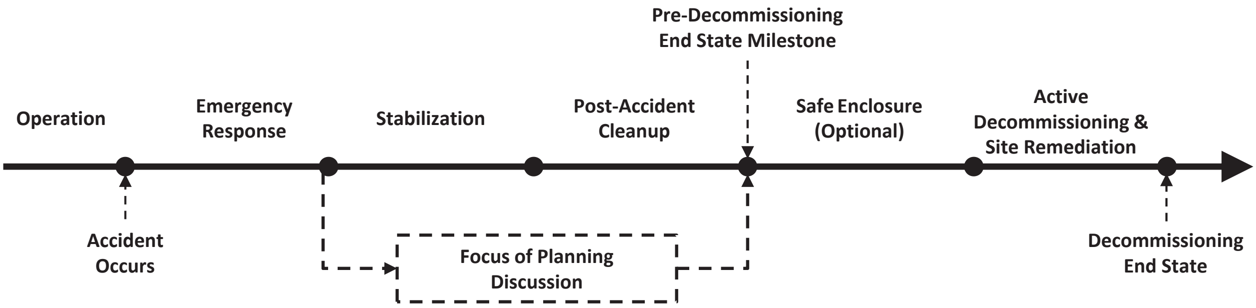

*FIG. 3. Focus of planning discussion.*

## 3.2. PLANNING PHASES OF CLEANUP

Planning under normal circumstances for facility outages and improvement projects, and for standard decommissioning, is typically from a reference state of known conditions. Under these circumstances, preliminary characterization work to gain a good understanding of the physical and radiological conditions in the plant is conducted well ahead of intensive project work. Standard project management approaches establish a detailed project scope, schedule and cost. Prior construction or decommissioning project experience provides the ability to make reasonable assumptions without a great amount of uncertainty. These assumptions are used for analyses and evaluations that include, but are not limited to, input to technical planning, bases for the project cost estimate, project risk assessments, development of procurement specifications and others.

In contrast to normal conditions, accident stabilization and cleanup planning begins with uncertain physical conditions in inaccessible areas of the facility. A significant complication in planning is the need for data and information that will be difficult to obtain because the nature of parameters to be measured will be unique compared to standard operations. In addition, the plant's normal equipment will inevitably not be suitable for many characterization needs.

Table 3 shows the planning phases associated with post-accident cleanup projects and the types of activities emphasized in each phase. The table is based on present experience about the specific activities to be undertaken within the four major phases in the cleanup needed following past incidents and accidents at nuclear facilities. The variation from the normal planning methods for incidents may not be overly challenging. An example is the damaged fuel resulting from overheating in a cleaning vessel at the Paks NPP [9]. In sharp contrast, information for detailed activity planning (and related schedule and cost estimates) for severe accidents (e.g. those broadly comparable to INES levels 5–7) can only be developed as progress is achieved.

For severe accidents, detailed scheduling and cost estimating may be severely restricted by the lack of detailed information. The TEPCO plan described further in Section 3.3 defines the near term relatively well because stabilization and cleanup activities are reasonably understood based on known conditions outside of the reactor and reactor buildings. The longer term can only be broadly defined until detailed information and data are obtained.

Planning of the scope, schedule and cost for the activities listed in Table 3 will evolve continuously during the project. A few of these activities are subjects of standard planning, such as managing water and waste; the methods used, however, may be considerably different and the magnitude of their operations will likely be much greater. For these two types of activities, the dominance of fission products (e.g. $^{137}$Cs, $^{90}$Sr) will dominate the planning considerations. Other unique issues, such as controlling algae, may present unique challenges. Technical aspects of water chemistry control and the magnitude of waste product storage will require special attention. The TMI-2 technical history report [10] and the ongoing Fukushima Daiichi project illustrates these and other planning challenges for post-accident activities.

TABLE 3. PLANNING PHASES IN CLEANUP

| Cleanup activities[a] | Phases of activity following incidents[b] | | | | Phases of activity following accidents[c] | | | |
|---|---|---|---|---|---|---|---|---|
| | Stabilize | Cleanup | Restore/ operate | Completion | Stabilize | Cleanup | | |
| | | | | | | Early | Final | After |
| Reactor/source control | ● | | | | ● | | | |
| Decay heat removal | — | | | | ● | | | |
| Gain access and information for stabilization | ● | | | | ● | | | |
| Plant characterization | • | ● | • | | ● | ● | ● | |
| Facility condition assessment | ● | • | | | ● | | | |
| Fuel/source condition assessment | ● | | | | ● | ● | | |
| Enclosure structures (large) | — | | | | ● | | | |
| Water storage | ○ | | | | ● | • | • | |
| Gas and air processing and release | ○ | | | | ● | | | |
| Water processing/ characterization | ○ | ● | | | • | ● | • | |
| Decontamination for access | | ● | | | | ● | | |
| Damaged fuel/source removal | | ● | | | | ● | | |
| Damaged fuel/source storage | | | ● | | | | ● | |
| Waste shipping and disposal | | ● | • | • | | ● | • | • |
| Decontamination for operation | | | ● | | | | — | |
| Return to operation | | | ● | | | | — | |
| Waste storage | | | ○ | | | | ● | ? |
| Decontamination for cleanup | | | ● | | | | ● | |
| Establish completion conditions | | | ● | | | | ● | |
| Fuel on-site storage and shipping | | | | ● | | | | ● |

[a] Categories of activities in the first column are technical areas within a post-accident cleanup project.
[b] i.e. events comparable to INES level 1–3
[c] i.e. events comparable to INES level 4–7
● Indicates phases when certain activities are at their greatest intensity.
• Indicates other phases where the activities will also be intense.
○ Indicates that following particular incidents and accidents, the activity may not be important or non-existent.
— Means the activity is non-applicable for particular incidents or accidents.
? Is concerned with interim waste storage in cases where there is no available disposal facility for specific types of waste.

## 3.3. STRATEGIC PLANNING

Despite the uncertainties during the early post-accident stabilization and cleanup, it is important to establish a long term strategy at an early stage to provide a path forward and to communicate the objectives and technical complexity to all involved, including external organizations and stakeholders. For this purpose, a strategic plan is needed. On-site strategic planning provides technical direction for operations, maintenance, facilities needed, concept development, procurement and other post-accident cleanup activities that include, among others:

- Special requirements for ensuring that the reactor remains under control and a plan for monitoring to ensure this control. Maintaining a subcritical condition is especially important. Implementing methods for short and long term decay heat removal may require means other than those used in standard operations.
- Selection of methods for processing water and gases.
- Requirements for conditioning solid waste based on anticipated disposal constraints.
- An overall approach to fuel removal, detailed to the degree that the fuel condition is understood.
- Requirements for interim storage of retrieved fuel and, where relevant, of conditioned waste.
- A listing and brief function of systems and facilities that may be needed. This includes special requirements (such as mobile laboratories) plus the use of existing plant facilities, systems and equipment in ways not originally intended by the designers.
- Strengthening barriers where necessary to reduce the spread of fuel and waste.
- Guidance as to types of activities that can be indefinitely deferred to the future; for example, maintenance on equipment that may never be used again.
- Special safety, safeguards and security measures.
- Special considerations for personnel, public and environmental protection.
- Recognizing the conditions and timing when complex techniques, such as robotics applications and chemical decontamination, should be considered.

Planning the post-accident cleanup involves much more than these technical subjects. Three additional areas of special significance are described below:

*Need for off-site resources.* Off-site strategic issues involve factors not under the control of the plant owner that can affect post-accident cleanup decisions. Dealing with these issues may require participation by the government and technical resources that exist at national or international organizations. Where and how to dispose of damaged fuel and accident waste is one such issue for which related planning decisions will influence conditioning and packaging.

*Regulatory flexibility.* Strategic planning can be significantly influenced by the responsible regulatory organizations. The regulator needs to have an intensive interaction with those responsible for the development of the strategic plan, while ensuring that regulatory independence is not compromised. In particular, it is important to understand that certain prescriptive regulations intended for standard operating conditions may need to be adjusted or, in some instances, abandoned for many post-accident cleanup situations. A process needs to be established with the regulatory authority for diverging from established rules and regulations that do not cover post-accident physical and operational circumstances. One such example is when customary standards and measurements cannot be reasonably applied, such as gram quantity accountability for fissionable material. In this example, the material may be an agglomeration of fuel, core structure and reactor material — all in shapes and types of materials that cannot be assayed to the degree required to meet the regulation.

*Worker safety.* The general methods and equipment for worker protection are similar for normal operations. However, post-accident cleanup requires an order of magnitude more effort owing to (a) the greater intensity of radiation and contamination, decontamination and waste management and (b) the presence of significant radiation in locations not normally encountered, such as on surfaces around the site. These conditions necessitate special protective equipment, worker exposure dosimetry and tracking that will be needed in greater quantities, which presents a logistical challenge.

Although it continues to evolve, the Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4 [11] is one such strategic plan. At the highest level, the roadmap has three major phases extending over a 30–40 year period:

- Phase 1 is the period prior to fuel removal from the spent fuel pools located inside of the boiling water reactor buildings. While working towards this major milestone, there are many planning activities to address the phases shown in Table 3.
- Phase 2 is the period prior to the removal or stabilizing fuel debris. As was the case at TMI-2, getting to this point is one of the major challenges of the entire project because of the difficulties of determining the physical condition of the debris and the difficulty of gaining access to it.
- Phase 3 is the period through to final decommissioning and site remediation. Getting to this point will not only require removal, packaging and the establishment of storage for the fuel debris, but will involve many other challenges, such as waste management, and the establishment of all other physical conditions necessary to proceed with the decommissioning strategy.

The road map, which is readily accessible via the internet, is one example of strategic planning. The conditions of any other accident will require a plan suited to its conditions.

### 3.4. ESTABLISHING INTERIM AND FINAL END STATES FOR POST-ACCIDENT CLEANUP

'End state' refers to a set of physical conditions that represent the completion of a planned major phase of activities. In the context of a project schedule, an end state may be considered a completion milestone. It is important to recognize and define interim and final end states for major phases of a post-accident cleanup project. Such end states are important elements for communicating an overall strategic plan to workers, regulators, key stakeholders and the public.

This subsection addresses the long term planning horizon for post-accident cleanup. End states are established when damaged fuel, fuel debris and non-standard wastes are packaged for either interim storage or final disposal and activities are in place to either restore the facilities to service or establish a safe state from which decommissioning planning can start. A goal of returning facilities to their original mission or to a new mission is much more likely in the case of incidents or minor accidents than for severe accidents. Some fundamental principles for establishing end states for an accident plant include [12]:

- There should be a hierarchy of end states for the project as a whole, for subprojects and even individual tasks, that should be applied to the entire site, major structures, compartments, systems and equipment as appropriate for the planning objective.
- When appropriate, end states must be quantitative and measurable to the extent possible.
- End states should not be arbitrary: each should be driven by a logical assessment of downstream needs and risks.
- End states for a damaged plant need to be tailored for its specific circumstances.

At TMI-2, a project end state known as 'post defuelling monitored storage' was established that was purposefully different from any of the Nuclear Regulatory Commission's (NRC) then approved decommissioning modes, reflecting the fact that none of the established decommissioning end states would be achievable and appropriate for TMI-2. This is an interim end state awaiting final decommissioning when the adjacent Unit 1 is decommissioned, which may be up to 50 years into the future.

The process followed for determining a post-accident cleanup end state involved a series of questions for each structure, system and component. As an example, for a space (e.g. a room or compartment in a building), several questions emerged:

- Is access to this space needed for cleanup work or can it be isolated for radioactive decay to take its course?
- Is the contamination loose or fixed?
- Does the ventilation system move airborne contamination from this space to another?

— Is the contamination or radioactive material severe enough to cause higher general area dose rates in adjacent spaces?

From such questions it can be decided whether complete, partial, or no decontamination is needed. The answers and underlying criteria then need to be captured and documented well.

The following points should also be considered:

(1) It may be important to segment the planning of some complex tasks in order to achieve maximum near term benefit. A prime example is the recovery and packaging of fissile material. Even if the final disposition is not known, actions to retrieve and safely package and store damaged fuel is an essential priority. The interim end state for fuel can be set, achieved, and then later on (maybe much later) the final end state for shipping and disposal can be planned.

(2) End states must be flexible, because to some extent they will be driven by ongoing characterization that reveals actual conditions versus what was assumed in planning. It is important to establish the end state early, based on the best information available or even based on conservative educated guesses. Then, as more is learned, the plan can be continually revisited and adjusted as needed. This approach is much more effective than waiting until everything is known before finalizing the end state.

(3) Implicit in a cleanup end state is clarity on what the cleanup end state is not. It is not expected that a severely damaged plant will ever be decontaminated to the background levels existing before the operation of the plant. Therefore, the target of physical configuration and boundaries and limits on residual site contamination should be based on acceptable methods of pathways dose modelling and analysis.

### 3.5. ESTABLISHING A PRE-DECOMMISSIONING END STATE

Post-accident planning is complex. There may be a need for several interim end states, e.g. corresponding to the phases in Table 3, with interim milestones within each phase. For example, what is referred to as a ‘stabilization phase’ can include achieving an interim end state providing conditions for which: (a) criticality cannot occur, (b) decay heat removal is under control, and (c) access has been achieved for characterization of the damaged fuel — all three of which have different planning approaches.

Figure 4 is a simplified logic for the decision process in planning an end state. In the extreme case where damage is so severe that meaningful rehabilitation is impossible, this decision to decommission is straightforward. When the long term goal is to establish an end state following which the activities leading to final decommissioning can proceed, as shown in the lower half of Fig. 4, there are two possibilities for consideration. One is a case in which the final decommissioning project can begin in the very near term. In such a case, final decommissioning planning should have been conducted well before the end state has been achieved. A second case for the post-accident cleanup end state is one in which the facilities will be placed in an established set of conditions that allows for medium to long term, safe storage (SAFSTOR) mode; a plan for final decommissioning must still be developed, though at a lower level of detail. A combination of both options may also be possible, with some structures being in SAFSTOR mode and others being subject to early dismantling.

In contrast, where damage is not so severe (e.g. events at levels 1–3 on the INES) the decision to rehabilitate will be complex and should be based on a number of factors. At the strategic level, these include some of the factors in the activity titled ‘Assess Return to Operation’ in Fig. 4. If the decision to do so is made, the next step will be to clean up and restore the facility to a condition of operational readiness.

After a damaged reactor has been stabilized and cleanup is well under way, the decision whether to return a reactor to operation versus committing to decommissioning should be taken; the taking of such decisions is addressed in Ref. [2]. Reference [2] discusses the many factors and considerations related to such a decision; it also addresses the options and actions for whichever path is chosen.

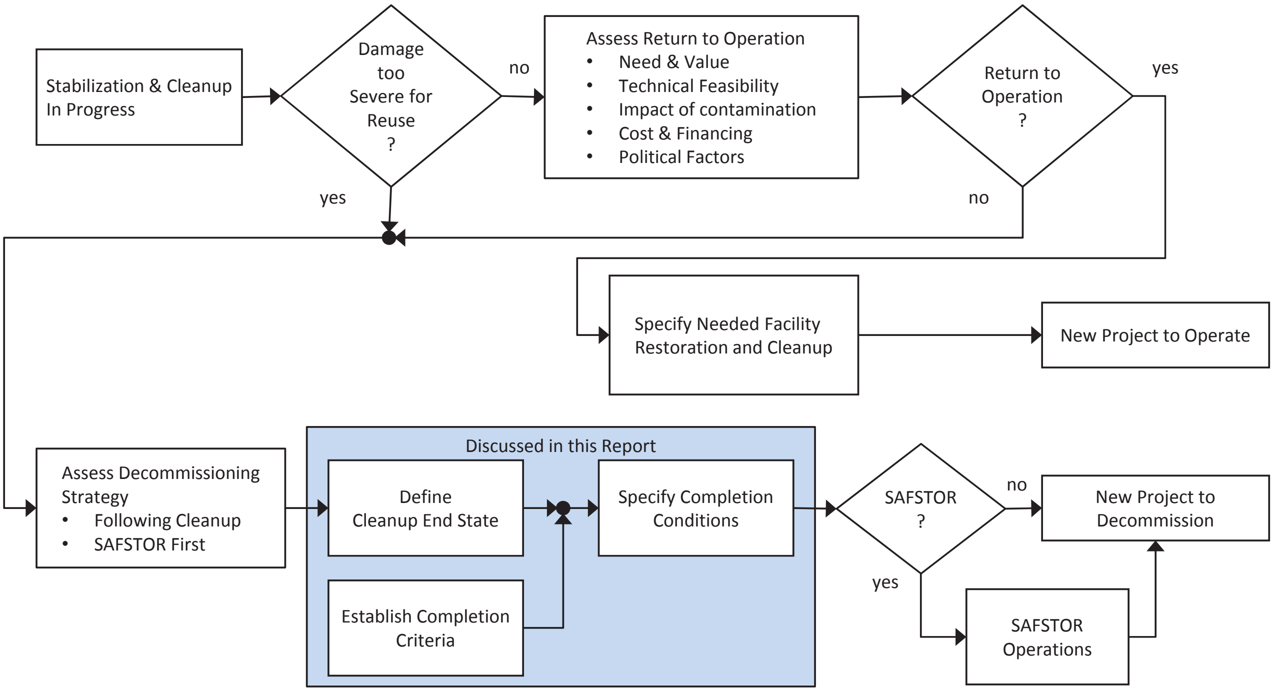

*FIG. 4. Approach to deciding and specifying a project cleanup end state.*

### 3.6. CLEANUP END STATE CRITERIA

Planning the cleanup end state requires specific goals, from which the detailed specifications for the conditions to be achieved are derived. Figure 5 illustrates a process for specifying these conditions used to plan and implement the TMI2 ‘post defuelling monitored storage’ described above. That process was subsequently used for the transition from operations to decommissioning for non-accident facilities; the overall process has been reported by the IAEA [13].

The steps in Figure 5 can be briefly described as follows:

- The end state vision is a mission statement. It is a high level description that will help determine what remains operational and what features need to be emplaced to prevent the migration of contamination into the environment.
- The post end state activities are those required to protect the health and safety of personnel who make entries for periodic inspection and maintenance, as may be required.
- Structures, systems and components (SSC) refers to every room and structure, every system and major component that will have to be placed in a specified condition to achieve the end state.
- Criteria/drivers are shown by example in Table 4. Any specific project will determine which of these criteria apply and whether additional ones are needed. In some cases it may be necessary to conduct a pathways analysis to establish isolation criteria.
- SSC conditions are established based on the criteria. As examples, rooms can be entered routinely, infrequently or never; systems may be permanently shut down or maintained operational to support the end state (e.g. ventilation to ensure contamination control).
- The criteria, such as those shown in Table 4, must be converted to specific requirements for the conditions to be established for each SSC that has been identified as important to the end state. For example, specifications for ventilation will indicate which parts of the system will remain operational and whether additional equipment must be added for the needed functionality.

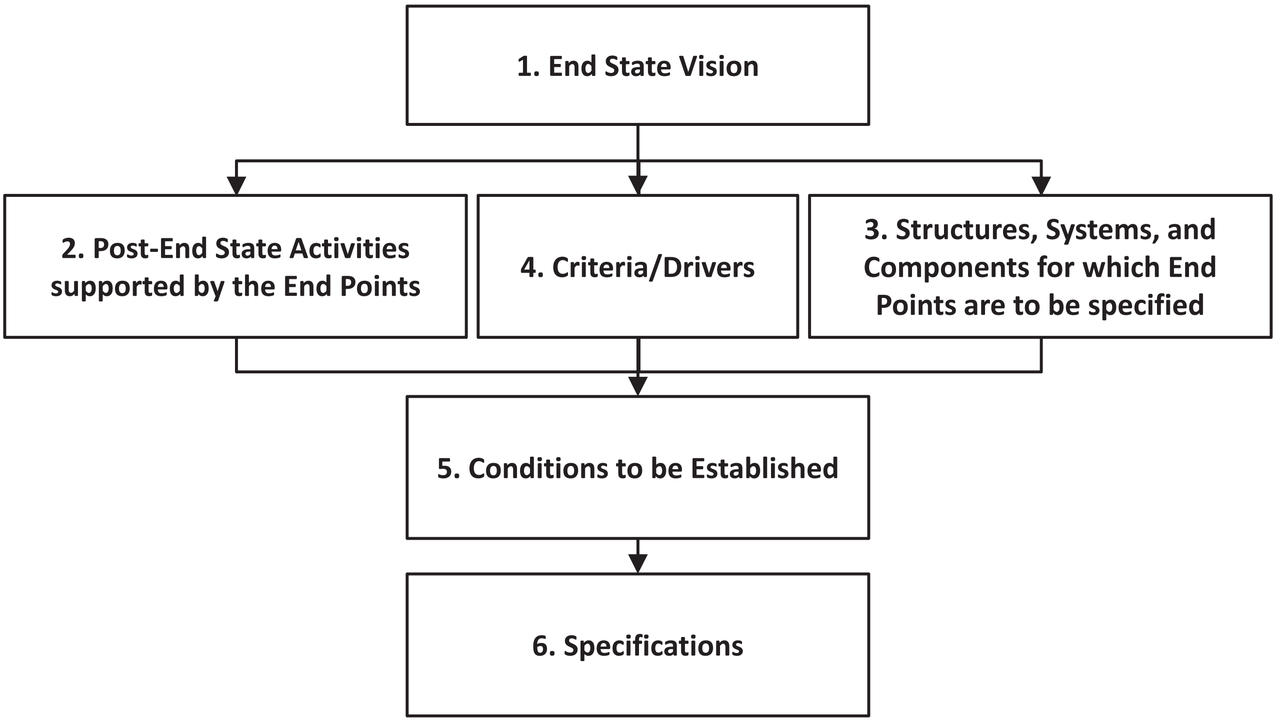

*FIG. 5. End state specification development steps (post-accident cleanup phase).*

TABLE 4. EXAMPLE OF END STATE SPECIFICATION CRITERIA FOR THE POST-ACCIDENT CLEANUP END STATE

| Criteria subjects | Criteria statements (examples taken from TMI-2) |
|---|---|
| Structural and boundary integrity | Structural and boundary integrity will be such that: (a) inspection personnel are safe, (b) contamination or hazardous materials remaining in the facility are contained, and (c) intrusion by unauthorized personnel, as well as animals and plants, are prevented. |
| Nuclear materials and criticality | Nuclear fuel and debris will be removed to the extent practical. Residual fissile material must be reduced to a level such that criticality cannot occur. |
| Hazardous materials | Hazardous materials and chemicals will be removed in accordance with environmental regulations. Fixed in place hazardous materials remaining in the facility will be contained in limited areas or stabilized to prevent release. The amount and location of remaining hazardous materials will be documented. |
| Process systems and equipment | Process systems and equipment have been abandoned in place, isolated or sealed off for the safety of future personnel, or removed where there is a compelling reason to do so. |
| Service and utility systems and equipment | Only systems required to support the SAFSTOR state and maintain the stable condition are operational. Other utility systems will be abandoned in place, isolated or sealed off for the safety of personnel or removed where there is a compelling reason to do so. |
| Personnel safety | Inspection personnel are safeguarded by stable conditions, postings and written procedures established in accordance with standard procedures for radiological protection and industrial safety practice. |

TABLE 4. EXAMPLE OF END STATE SPECIFICATION CRITERIA FOR THE POST-ACCIDENT CLEANUP END STATE (cont.)

| Criteria subjects | Criteria statements (examples taken from TMI-2) |
|---|---|
| Waste and liquid effluents | Waste will have been removed to the extent practical. Waste may remain if removal is extremely difficult. The only liquids remaining are minor quantities that cannot be readily removed with installed equipment. |
| Radiation protection | Established in accordance with standard procedures. In particular, the periodic inspection path will be subjected to ALARA review. Contamination remaining in the facility will be contained in limited areas or stabilized to prevent release. |
| Housekeeping and miscellaneous materials | Valuable materials will be removed. Rubbish and non-contaminated furniture, loose equipment, etc. will be removed. |

Facility engineers will carry out this process and develop the related specifications, the value of this being that the specifications are readily understood by those who have to implement them. Further, the level of detail the specifications provide offers assurances to regulators and stakeholders that a comprehensive and systematic effort is being taken to ensure the safety and stability of the facility at the completion of the cleanup.

# 4. STABILIZATION

**KEY LESSONS LEARNED**

- Stabilization of structures, systems and/or components of a facility may be needed in order to proceed with intensive post-accident cleanup and decommissioning.
- Stabilization must have a sound design basis and be approved by appropriate authorities.
- All the stabilization measures must be designed and conducted carefully to assure the safety of workers and the public.
- Successful containment, cooling and criticality control should be achieved and maintained throughout the post-accident activities without compromising the decommissioning activities.
- Potential synergies and interference between the measures should be taken into account.

## 4.1. INTRODUCTION

Following the accident, it will be necessary to bring the facility to a stabilized condition to prepare either for cleanup and decommissioning activities in the case of severe accidents, or for return to service in cases where that is feasible. Stabilization objectives should be achieved with regard to:

- Containment of radioactivity;
- Cooling and ventilation;
- Criticality control;
- Structural integrity.

For most incidents and less severe accidents, a certain level of stabilization is achieved as the result of the emergency response actions. Conversely, for severe accidents, it is usually necessary to take many additional stabilization measures. It may take months before reaching an initial stage where the facility is stable enough to allow cleanup and decommissioning activities to commence.

An appropriate level of stabilization must be achieved and maintained for each successive stage of the cleanup and decommissioning activities; further necessary actions may be taken as required to support stabilization. The measures for stabilization must be proved to have a sound design basis and be approved by appropriate authorities so cleanup can be carried out safely in terms of protecting both workers and the public.

Contingent stabilization measures to facilitate future cleanup and decommissioning activities can also cause difficulties. In many cases, some cleanup or demolition may be necessary prior to stabilization. Accordingly, the entire stabilization phase should be planned and managed to minimize difficulties created for the follow-on cleanup.

## 4.2. CONTAINMENT OF RADIOACTIVITY

The purpose of containment is to protect site personnel and equipment, as well as the residents and environment of the surrounding area.

### 4.2.1. Radioactivity release during the accident

If large scale fire or explosions occur during the accident, it is possible the original containment systems will be extensively damaged and radioactive materials inside the facility exposed. Radioactive gases and liquids, contaminated rubble and fuel materials may then be directly released into the atmosphere. Dropping materials onto the exposed radioactive materials, e.g. fuel elements, may reduce potential releases in those cases. But it should be noted this measure may cause additional damage to the buildings and structures and affect their long term integrity, which is itself a prerequisite for undertaking intensive cleanup and decommissioning activities.

In light of the above, different measures that could be applied to control the release of radioactivity should be carefully considered for their pros and cons:

- At Kyshtym, where the radioactive liquid tank was destroyed by the chemical explosion, no special measures to control the release were taken because most of the liquid was discharged as an aerosol plume [14].
- At Chernobyl, where the upper half of the reactor building was blown off by the explosion after the reactivity excursion, only noble gases and some of the volatile fission products were released. More than half of the fission products inventory and most of the fuel materials remained in the core. Therefore, to cool these materials and control the release as much as possible, lead, dolomite, boron carbide, clay and other materials were dropped from helicopters. These materials hit the remaining building structures and caused additional damage, resulting in a significant challenge in designing and constructing the engineered enclosure, the ‘shelter’ or ‘sarcophagus’, which is supported by the remaining structures [15].

### 4.2.2. Containment of radioactive materials dispersed during the accident

When explosions occur during the accident, contaminated rubble can be produced and scattered over the site. Also, owing to excess temperature or pressure, radioactive materials can be released through the designed discharge paths, or from the failed boundaries, and result in scattered debris and hot particles. These materials should be retrieved and safely stored as soon as practicable following the accident. Many of the remote technologies described in the Annex can be utilized to reduce the dose during both characterization and actual handling of the objects. Siting of interim and final storage must be carefully considered such that the radiation effect within the site and surrounding area can be minimized. Storage should be planned with cleanup waste and future decommissioning activities in mind; physical limitations will constrain such planning.

At Chernobyl, in preparation for the construction of the sarcophagus, rubble was collected and buried in the ground near the reactor, together with the heavy machines used for collection. Concrete was poured over the ground as the cover. A concrete shielding wall, the ‘pioneer wall’, was constructed on the ground to secure a better working environment. After several years of discussion about the most appropriate interim end state for the damaged Chernobyl plant, work is under way to develop the new safe confinement (NSC), also requiring the removal of concrete groundcover and retrieval of previously buried materials [16].

At Fukushima Daiichi, rubble is being collected and stored in temporary facilities at the site, together with the debris generated from the partial dismantling of the reactor building. This is required to prepare for the reconstruction of the upper portions of the building and to ensure full enclosure [17, 18].

Providing ground cover or shielding can reduce the radiation effect and further dispersion of materials that are difficult to retrieve, such as dusts. These first measures enable the next steps of stabilization, which make the preparation for cleanup and decommissioning possible. For any particular situation, the measures to be taken depend closely on the type of radionuclides deposited on the ground after the accident. Other measures that could be considered include the use of chemicals for adsorption and retention of certain radionuclides.

### 4.2.3. Post-accident containment of radioactive gas and liquid

After the situation is under control, additional release of radioactive materials into the environment must be managed throughout the course of cleanup and decommissioning to secure good working conditions within the site and to avoid further risks to the surrounding area. In the cases where the containment is significantly destroyed, the priority would be installing additional measures, such as covers, fences and walls, since the radioactivity of the failed part of the containment may be too high to precisely locate or conduct any repairs.

Even when the original containment integrity is preserved, any special emergency measures for cooling, containing radioactivity or other purposes may be installed during the accident. The effects of these measures on the containment function should be carefully assessed.

It should be noted that these additional measures cannot achieve complete containment, and there are possibilities of creating undetectable new paths for releases. These measures can be equipped with functions for further stabilization or cleanup and decommissioning, such as a reactor cover with ventilation, monitoring and fuel handling. If there is a plan for the construction of more reliable containment in the future, this should be taken into account in designing these interim measures.

In the cases of some past accidents rated as level 5 on the INES, e.g. NRX in Chalk River [19], Windscale Pile 1 [20] and TMI-2 [21], the original containment functions were not lost. The radioactivity released to the environment was mainly gases from the discharge stacks produced during the accident. The contaminated cooling water was kept within the containment. But later at NRX, it became necessary to pump out the water from the basement and send it to an external storage building to prevent leakage. At Windscale, when developing decommissioning plans more than 40 years after the fire, it was necessary to assess the possibility of pyrophoric uranium hydride formation owing to the accumulated water in the core and confirm that its ignition was unlikely [22]. At TMI-2, the contaminated water was stored for a long enough time and finally evaporated [23].

In terms of stopping airborne releases in the cases where the original containment function is lost, the construction of a building cover would be the most effective measure. At Chernobyl, the sarcophagus enclosure was constructed by the modular method within six months of the accident. The sarcophagus was equipped with electricity, ventilation, fire extinguishing system monitoring and other features. It has been working as an effective containment since its construction. However, because a limited time was allowed for design and construction, problems have arisen, such as the inaccessibility of many important structures, including parts of the original building that need anti-corrosion treatment. It is anticipated the lifetime of the sarcophagus is limited to approximately 30 years because of this problem. The project to construct the NSC (in effect, a new shelter) is now under way (Fig. 6). The primary function of the NSC is to confine radionuclides for minimum of 100 years. The decision for full scale decommissioning activities is still under consideration. The NSC will enable good working conditions for full scale decommissioning activities, such as fuel debris retrieval and waste treatment, when the decision is eventually taken to proceed with these activities.

At Fukushima Daiichi, building covers for Units 1, 3 and 4, where the upper parts of the reactor building were destroyed during the accident, are being installed [11]. The covers consist of frames and panels. The covers for Units 1 and 3, which have fuel materials in the core, are self-supporting. The cover for Unit 4, where all the fuel remains within the spent fuel pool, uses the reactor building for support. The Unit 1 cover was built within nine months of the accident and has been an effective containment. The covers for Unit 3 will be built during 2014 and that for Unit 4 was built during the second half of 2013. Fuel removal from that unit began in November 2013. The covers are being equipped with equipment for removal of fuel from the respective spent fuel pools. Cover construction for Unit 1 is shown in Fig. 7 [24].

*FIG. 6. Chernobyl sarcophagus (on the left); NSC concept (on the right).*

*FIG. 7. Reactor cover construction at Fukushima Daiichi Unit 1. Photograph courtesy of the Tokyo Electric Power Company (TEPCO) [24].*

In addition to the covers, for each of Units 1, 2 and 3, a system has been installed to control the gas discharge from the original containment vessel by keeping the gas at a negative pressure with filtered circulation. It also has a function to inject nitrogen to prevent hydrogen explosion. Construction of more reliable containment that enables good working conditions for full scale cleanup activities, such as fuel debris retrieval, will ultimately occur. Figure 8 shows the gas control system installed in Unit 2 [25].

As for the leakage of contaminated cooling water or other liquids, locating the paths and installing seals, barriers and other means of containment would be the most effective counter-measures. Since paths may be hidden deep inside the building, vessels or equipment, it is necessary to effectively utilize remote measurement and handling technologies. In some cases, conducting mock-up tests may help the development of measures. Materials and methods should be chosen carefully so as not to significantly increase the burdens for cleanup and decommissioning.

At Chernobyl, during the years after the accident, rainwater and groundwater washed into the core via various paths. They reacted with the lava-like fuel containing material and structures creating a huge amount of contaminated water. The influx of rain water and melted snow into the shelter is estimated to be in the order of 1200 t a year, and its content has been analyzed by manual sampling. Some hundreds of tonnes of the accumulated water inside the shelter are thought to have leaked into the ground. As a counter-measure to protect the Pripiyat River from contamination from all sources in the evacuation zone, including from the shelter, a clay underground water shielding wall of approximately 13 km in length was constructed downstream of the facility. Also, many wells were sunk along the wall to pump out the groundwater. But the effect of the wall was not clearly confirmed since the concerned area was too wide to be covered by this wall [26].

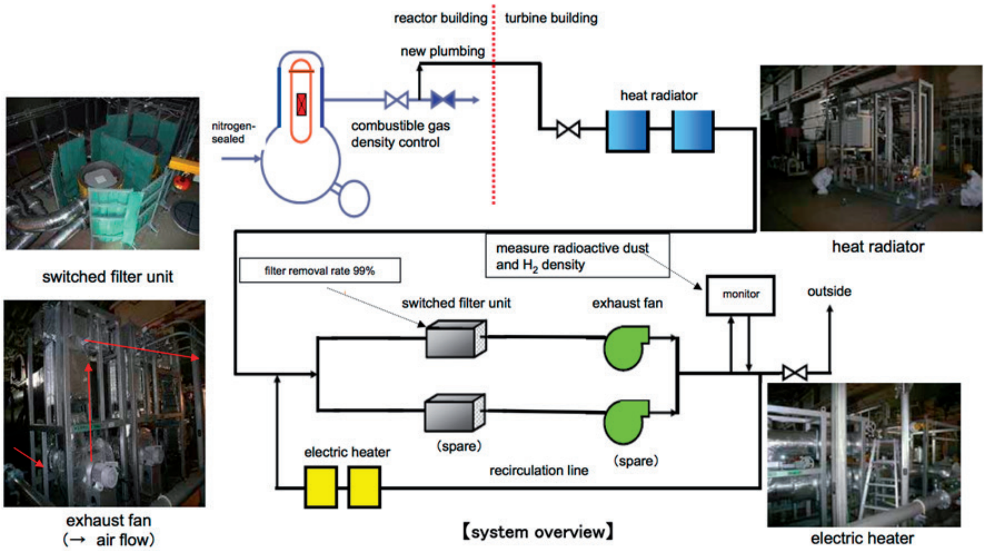

*FIG. 8. Overview of Fukushima Daiichi Unit 2 primary containment vessel gas control system. Photograph courtesy of the Tokyo Electric Power Company (TEPCO) [25].*

When the containment at Fukushima Daiichi Units 1–3 was breached during the accident, highly contaminated cooling water leaked and flooded in the basement of reactor buildings and turbine buildings. It then leaked into the drainage ditches discharging to the quay. The leakage paths were quickly determined and blocked with sealants. To preclude further distribution of leaked water, silt fences were set in the quay.

Subsequently, it was realized that undetected paths existed between the accumulated water in the basement and the groundwater around the reactors; the accumulated water was pumped out to keep its level lower than the groundwater. The pumped water was sent to a treatment system for decontamination, which is described below. A part of the treated water was sent back to the core for injection cooling. The remaining part was stored as excess. But since the incoming groundwater volume was very large, about 400 t per day, the volume of the treated water increased very rapidly, causing a significant challenge to storage construction. The total volume of the highly contaminated water in the turbine buildings reached nearly 100 000 t before the start of treatment with an injection cooling system in June 2011. Since then, it has been kept at 70 000–80 000 t. The quantity of treated water excess is over 300 000 t as of June 2013, and increasing.

To cope with this problem, further measures are being considered and tested, such as applying further decontamination to the excess non-radioactive water, which is then routed to temporary storage tanks pending a decision on whether it could be discharged safely into the environment, or constructing a groundwater bypass from the upstream to the sea to reduce incoming flow. In addition, a water sealing wall is being constructed at the quay as a precaution. As a way of improving containment, future plans include locating the leakage path and appropriately sealing the vessels or the buildings, and installing a closed-loop cooling system within or alongside the reactor buildings. To realize this plan, it will be necessary to establish a good working environment for equipment installation and other activities by providing effective cleanup and/or shielding.

### 4.2.4. Monitoring

To confirm that all the radioactive materials are securely contained, it is necessary to conduct monitoring at the site boundary. To achieve reliable monitoring, an effective combination of those measurement and data evaluation technologies described in the Annex is needed, especially because the distribution of the source is not well defined and sufficient sampling cannot be expected. In some cases, additional work is needed to assist the measurement. For example, if the background is high owing to the fallout, it is necessary to clean up the immediate vicinity of the monitoring posts to generate a low background area. Modelling and simulations can be useful in choosing appropriate locations and timings to ensure the quality of the groundwater samples.

### 4.3. COOLING AND VENTILATION

The process of bringing nuclear reactors to a cold shutdown state is achieved through the use of the cooling and ventilation systems. For accident damaged facilities, these systems are subsequently used for the removal of decay heat and explosive gases, in order to prevent further damage to the facility or the surrounding area owing to excessive temperature or pressure. This activity also contributes to reducing the level of reliance on containment measures. Decay heat removal is a key requirement during stabilization, being a prerequisite for proceeding with intensive cleanup activities.

During the accident, if the normal cooling and ventilation function is lost or is insufficient, special emergency measures are needed. Although the priority is to achieve effective cooling and ventilation, it is better to avoid using materials or methods that may cause problems during the subsequent stabilization, cleanup and decommissioning activities. If contaminated cooling water or other radioactive materials are produced as a result, they should be properly stored until decontamination and waste management begin.

In light of the above, measures taken to implement emergency cooling and ventilation should be undertaken following an evaluation of the pros and cons of different options:

- At NRX, it became necessary to treat the contaminated water which was accumulated in the reactor building basement as a result of continued cooling water injection into the core after the fuel melting.
- At Windscale Pile 1, normal air cooling or carbon dioxide injection could not extinguish the fire and water was injected. As a result, years later during decommissioning planning, assessment of the effect of the water on the formation of pyrophoric materials within the core was needed.
- The purpose of dropping materials onto the core at Chernobyl was cooling, as well as containment. It was not recognized at the time the materials would later cause challenges to decommissioning.
- At Fukushima Daiichi, sea water was injected to the core with fire engines or cement pumping cars after the normal cooling systems were lost. As the result, the impact of the salt on the corrosion of structural materials had to be assessed and measures taken accordingly to retain integrity [27].

If the normal cooling and ventilation function is maintained in operation during the post-accident phase, this may be used for the removal of the decay heat. At TMI-2, both primary and secondary systems remained functional after the accident. Cold shutdown with natural circulation was established in the primary system using circulating water through the secondary system. This was performed to avoid use of the normal decay heat removal system, which would have circulated highly radioactive water within the auxiliary building.

If the original function is lost, installation of new cooling systems will be needed. In those cases, it is likely that instruments for temperature, pressure and other monitoring are lost or damaged. System maintenance or replacement would be an important element of the installation. Many of those remote technologies described in the Annex can be useful both for characterization and system installation.

At Fukushima Daiichi Units 1–4, temporary cooling and desalination systems for the spent fuel pool were installed and have been operating. To keep Units 1–3 in cold shutdown, a circulating injection cooling system loop of about 4 km in length was constructed and has been operating. With this system, the contaminated water is pumped out from the turbine building and returned to the reactor for injection cooling after decontamination and desalination. Absorption and/or precipitation methods are used for decontamination. It should be borne in mind that processing and disposal of the used absorber and sludge of fairly high radioactivity will ultimately pose a significant challenge for the waste treatment system. After decontamination, the water is desalinated by ion exchange or evaporation. Dealing with the excess water is a significant and ongoing issue. Also, storing and processing the condensed salt water remains an issue.

For the replacement of the damaged temperature sensors inside the vessels, remote operations will be applied with the aid of mock-up feasibility tests. To achieve each of these measures within a good working environment, cleanup and shielding is required. Construction of a more reliable closed-loop cooling system is planned for the future, which will enhance cleanup and shielding. Decommissioning of some of the currently applied measures is envisioned.

### 4.4. CRITICALITY CONTROL

In the case of a core disruption accident, it is important to prevent the core from returning to a criticality condition and releasing energy on a large scale. If the disruption is limited, it may be possible to use the normal neutronic instruments and reactivity shutdown systems for emergency responses and monitoring following stabilization.

When a large disruption occurs and these instruments and systems are lost, normal systems cannot be relied on and it is necessary to initiate fission monitoring and poison injection capability as soon as possible. Assessment of the core status, such as the distribution and composition of failed fuel and fuel debris by simulation, is very difficult. Usually, the accurate status is found only after successful observations using remote sampling, monitoring and measurement technologies. With knowledge of the actual reactor and fuel conditions, effective prediction of the material location can be possible. Based on such predictions, criticality prevention can be designed and implemented. Also, it becomes possible to design effective ways to defuel the core to the extent that any inadvertent criticality is permanently precluded:

- At TMI-2, boron concentration in the coolant was raised significantly to prevent re-criticality. A source range monitor was available for checking the neutron levels. The defuelling plan was established based on the result of the core observations.
- At Chernobyl, there were no measures available for criticality monitoring. It is believed that criticality incidents continued after the core was flooded with water.
- At Fukushima Daiichi, fission is monitored by detecting short lived noble gases using the containment vessel gas control system.

### 4.5. STRUCTURAL INTEGRITY

Since buildings and structures may be damaged by an accident, it is necessary to confirm the damage and evaluate the structural integrity of the remaining structures, and take proper measures, such as reinforcement to maintain the structures throughout the stabilization, cleanup and decommissioning processes. During the evaluation, consideration must be given to the possibility of further degradation caused by the lasting impact of the accident, or by actions and measures taken during the emergency response phase, such as the introduction of sea water. Analytical and experimental research of the chemical and structural effects must be conducted to clarify the impacts of the measures on the long term integrity.

As described above, the lifetime of the Chernobyl sarcophagus is limited to approximately 30 years owing to challenges to its structural integrity. The NSC that is being constructed to provide ongoing containment of radioactivity is designed to last at least 100 years.

There was little damage to the containment building of TMI-2, but molten core material caused thermal damage to the lower head region of the reactor pressure vessel [28]. Its long term integrity was assessed, however, and proved to be sufficient.

For all Fukushima Daiichi units, the integrity of the buildings and structures was evaluated taking the impacts of the earthquake, tsunami, explosion and other events into account. The results were examined and approved by the safety authority. Following those initial evaluations, continuous monitoring of the building and structures and potential re-evaluation are being conducted. This includes analytical and experimental researches to clarify the long term corrosion effects of the salt water [29].

# 5. CHARACTERIZATION

**KEY LESSONS LEARNED**

- Each accident will present unique challenges that will require the adaptation of existing technologies to conduct characterization.
- Assessment of damage to systems, equipment and facilities will require custom and novel applications.
- Characterization for various purposes will be ongoing throughout the phases of cleanup and require regular review to ensure the baseline data remains robust.
- Rapid and extensive area characterization is necessary to inform the strategic objectives.
- Remote technologies will very likely be required for local and close to event characterization, and deployment will be challenging.
- Robust radiological characterization will support stakeholder confidence and a return to ‘normal’ living conditions.

## 5.1. INTRODUCTION

During post-accident stabilization and cleanup, high priority must be given to planning and conducting characterization activities, as accurate information about the physical and radiological conditions may often represent a pre-condition for proceeding with planned activities. Characterization must be performed in many different and varied locations and for a wide range of objectives. The overall purposes of characterization include:

- Determining the distribution and intensity of dose rates, radionuclides (i.e. alpha, beta and gamma emitting) and fissile material;
- Estimating the inventories of these materials at specific locations within the equipment, the facility and the surrounding areas;
- Assessing the radionuclide composition and mobility of contamination in the facility;
- Identifying the chemical and physical form of the radioactive materials with particular emphasis on unusual phases or compounds that may have been generated either in the initial accident or as a result of efforts to terminate the accident.

The distribution of dose rates, radionuclide inventories and radionuclide compositions are determined: (a) within systems and equipment, (b) inside the facility, (c) on the surfaces of buildings (including the degree of penetration) and (d) in the surrounding site (e.g. soil, plants, woodland), as well as in the subsoil region and groundwater.

The results of characterization support many cleanup activities, for example:

- Estimating personnel exposure and limitations;
- Determining areas where decontamination will be needed;
- Water processing and water inventory management;
- Assessment of radioactive waste properties for conditioning, packaging, storage, transport and disposal to comply with waste acceptance criteria at storage and disposal facilities;
- Decisions for and conduct of the removal of damaged fuel, fuel debris and/or other highly radioactive materials;
- Estimating costs of decommissioning;
- Conducting post-cleanup radiation surveys to demonstrate compliance with cleanup standards;
- Accounting for the residual inventory of fissile materials that are not removed during cleanup.

There is limited accident unique characterization experience from previous events. However, over the past 20 years there has been much advancement in characterization technology and methods as a result of fuel reprocessing, defence waste cleanup programs and reactor and processing facility decommissioning. Many characterization challenges have been solved with regard to accessing difficult locations, sensors, instrument capability, characterizing difficult radionuclides, data management and presenting results.

There are two aspects for addressing characterization following nuclear accidents that provide the basis for this section's organization. The first is what to characterize, specifically fuel type and location at the facility, i.e. inside or outside areas. These subjects, which in this specific publication are on-site events, are followed by a description of current methods and techniques for characterization; descriptions of specific technologies are included in the Annex. The second aspect is how to conduct characterization. This subject is addressed with descriptions of techniques and methods.

Although not specifically addressed in this publication, it is noted that area characterization external to the facility is equally important. In this regard, surveys are necessary to characterize the contamination; plan radiation protection and decontamination measures; assess the effects on the environment and ecosystems; predict source terms for releases with water and air; and characterize the resulting radioactive waste in terms of quantity, activity and costs. Radiation surveys must be repeated routinely to check and confirm the progress and success of remedial actions (e.g. removal of activity, decontamination, water treatment, reduction of source terms) resulting in reductions in dose rates, radioactive inventories and airborne contamination. In the immediate vicinity of the facility, environmental measurements will be required to identify any leakage and provide data for the management and control of radioactive materials entering the ecosystem. Many of the methods and techniques described in the Annex are applicable to area characterization.

## 5.2. DAMAGED FUEL AND FUEL DEBRIS CHARACTERIZATION

Before a fuel removal strategy can be defined, together with the resulting programme of work, including the design of any tool or equipment packages, it is necessary to establish a reliable database and model of the damaged reactor core. Information regarding the extent of the damage, condition of the fuel and its location is needed. A related high priority action is to establish a scenario of the accident.

These will be difficult but necessary tasks. As the ultimate fuel removal programme commences, further information is used to update the model and scenario, eventually converging on the actual condition of the fuel and the accuracy of the accident transient modelling. Experience from previous fuel damage events underscores the imperative to gather as much information as possible on the state of the reactor core before embarking upon elaborate plans for fuel removal and/or the design of any necessary tooling. A critical management action is to determine when information is sufficiently accurate to decide to proceed with detailed plans, procurement and staffing for fuel removal.

In order to predict the state of the reactor core, a number of techniques need to be considered, subject to the caveat that access to the damaged area is possible. Several types of fuel evaluations and analyses are required, including:

- Putting in place methods to directly or remotely view the damaged fuel as soon as possible is essential. In particular, the ability to visualize physical conditions is very important because much of what will be seen will undoubtedly be different from prior experience or analytical modelling. Pictures are invaluable, whether in the direct form of photographs and video or with the use of devices, such as infrared and ultraviolet viewers, or computer imaging of the physical situation that cannot otherwise be photographed.
- Neutron flux, core temperature, the presence of neutron moderator when combined with a loss or redistribution of neutron control and poison material, could create a new criticality situation. This concern is most important while fuel movement is possible, whether caused by flow forces or human removal activities. While criticality may be unlikely, nevertheless, it is extremely important that the potential for criticality be frequently evaluated.
- Details of the core operational history prior to the event are important for understanding fission products, fissile and transuranic isotope inventories.

- An assessment of the state of the fuel can be made with knowledge of the fission products released during the accident. A number of computer based models exist that can be used to determine the state of the fuel based upon fission product release.
- Maintaining an accounting of fuel material is required because there are national and international requirements to do so even where the question of the diversion of fissile material may not be an issue. Further, it is important to the cleanup effort to understand how much fuel might be distributed to other parts of the primary circuit. If there are extremes of fuel damage, normal identification and counting methods may not be practical. In such cases, a special effort may be necessary to determine how much of the accessible fuel is unaccounted for after removal.

Remote viewing techniques are required for in situ viewing of the damaged fuel. This is one of the most important characterization functions on which to base decisions. Equipment is available today that will function underwater or in high radiation levels to provide close-up views of the items of interest. Available equipment includes endoscopes, glass fibre optics and radiation hardened closed circuit television (CCTV) systems which are small enough to access difficult areas. These can provide access to concealed objects even through curved or offset centreline pathways. However, optical viewing is fully dependent on adequate lighting and, for underwater application, on the clarity of the water.

### 5.3. FACILITY CHARACTERIZATION

For the radiological characterization of surfaces and structures of buildings and components in nuclear facilities after accidents, a wide range of available sampling and measurement techniques can be applied. Most of these techniques are also routinely used for radiological characterization under normal circumstances. The main difference is the restricted accessibility of certain areas where measurements or sampling have to be performed.

Much plant characterization data will be required in support of a variety of tasks. These include, for example:

- *Surface contamination.* Much of the same concern will exist as for sample analysis capability resulting in a need for additional measurement capability.
- *Water.* In particular, the management of water chemistry can be complex because of the need for criticality control, corrosion minimization and treatment to avoid biological growth, and perhaps to minimize radiolytic hydrogen generation. Accordingly, the radiological characterization of water is necessarily supported by frequent water chemistry analysis.
- *Waste.* There may be large quantities of waste, and although many of the characterization techniques used are typical of the nuclear industry, the presence of activity levels many times greater than normal at the operating plants, and the high degree of contamination by tritium, caesium, strontium and transuranic elements, may require special systems/facilities. In addition, water contamination complications, such as micro-organisms, high particulate content and the need to maintain high concentrations of boron, can contribute to the complexity of the analysis of liquid waste.
- *Radiological health physics.* During decontamination activities and fuel removal preparation, it is possible that alpha and beta particles will become airborne. This may require special instruments and analysis capability to provide timely sample results.
- *Structural.* Determining the physical properties of radioactive materials in the form of particles or pieces of structures or equipment may require special instruments, special handling equipment or use of off-site hot cells.
- Past experience suggests there may also be a need for highly non-standard data and analyses, concerned with (for example):
  - Degradation of ion exchange resins (to determine if these can be removed by the existing system);
  - Pyrophoricity of core materials when exposed to air to make sure there is no possibility for the ignition of metals;
  - Nature of biological growth in the water within the reactor vessel and in other storage locations.

These specific analyses will not necessarily be an issue for other fuel damage recovery programmes. However, it can be expected that some unforeseen characterization challenges will arise.

## 5.4. MEASUREMENT TECHNIQUES FOR RADIOLOGICAL CHARACTERIZATION

The following list gives an overview of techniques that are used to determine dose rates, composition of the contamination and activation and activity values for both normal and accident situations:

- Dose rate measurements with fast sodium iodide (NaI) or other types of detectors for determination of the β and γ dose rates;
- Wipe tests with subsequent evaluation of total α, β and γ activities or for spectrometric measurements, which are mainly used for the determination of the removable part of the contamination and for the nuclide composition;
- All types of sampling methods with subsequent measurements of the samples in various field and laboratory measurement techniques (e.g. shielded in situ gamma spectrometers or with laboratory α, β or γ spectrometry, if necessary after appropriate radiochemical separation), mainly for determination of the radionuclide composition, for measurements of the activities of hard-to-measure nuclides, for determination of depth distributions (from sections of drilling cores) and many other purposes;
- Surface contamination measurements with large area proportional counters or scintillation counters for determination of the total α, β and γ activities on surfaces;
- In situ gamma spectrometry with or without collimation to determine the activity of gamma emitting nuclides present on or in the first part of all types of surfaces;
- Use of thermoluminescent dosimetry for long term measurements in otherwise inaccessible parts of buildings, e.g. building gaps where contamination is suspected;
- Neutron measurements with scintillation detectors, especially in cases where nuclear fuel is present in some areas.

## 5.5. CURRENT TECHNOLOGIES

This section describes some advances in technologies for characterization over the past 20 years.

### 5.5.1. Fast overview and reconnaissance of the radiological situation

Depending on the severity of the event, it may be necessary in the immediate aftermath to first gain a fast overview of the situation with respect to structural damage and radiological properties and to explore the distribution of the damage and radioactive material. There are numerous techniques available for this purpose, ranging from remote controlled or autonomous robotic vehicles with cameras and radiation measurement equipment, to protective measures for personnel entering the facility. An overview of these techniques is in the Annex. Although these techniques have been developed mainly for the management of emergency situations and for intervention purposes where manned access to parts of a nuclear facility is impossible, they can also be used for rapidly characterizing a nuclear facility and its surroundings in preparation for decommissioning when there are still elevated radiation levels.

### 5.5.2. Techniques for rapid geometry acquisition

Over the last decade, 3-D laser scanning has evolved to a mature technique for rapid acquisition of geometries. While widely used in the acquisition of geometries of industrial buildings and systems, as well as in architecture and the conservation of historic monuments, this technique is also valuable for gaining a precise overview of the structural and geometrical situation in nuclear facilities after accidents. Software allows the combination of many single 3-D laser images to a whole model of rooms or entire buildings and from there to CAD models. Exact measures can then be taken from these models, thus helping to minimize the necessity of entry into the facility. Examples of these technologies are further explained in the Annex.

### 5.5.3. Support by geospatial positioning systems

While it has become common practice to link measurements outside buildings to geocoordinates acquired from geospatial positioning system (GPS) measurements, the same technique can be used inside buildings. Since the GPS signal from the satellites is too weak to penetrate the thick walls of buildings of nuclear installations, in order to use a GPS receiver indoors, the signal has to be received outside and then amplified and rebroadcast inside. The receiving antenna has to be placed outside at a known location. The signal broadcast into the building will contain the position information relating to the external antenna location. The amplifier in the GPS re-radiating device provides a signal that is capable of being broadcast at a level high enough for the GPS receivers in the buildings.

### 5.5.4. Characterization of sub-surface areas

Characterizations of sub-surface areas are far less straightforward to implement than surveys of buildings and the accessible parts of sites. In the later phases of remediation work, it may be necessary to undertake surveys by drilling holes at places where contamination may be expected, and later to excavate those parts of the soil where contamination has penetrated and is present above levels considered suitable for release of the land. Examples for the required sampling and the evaluation of sampling results, as well as for deep excavation operations, are shown in Fig. 9.

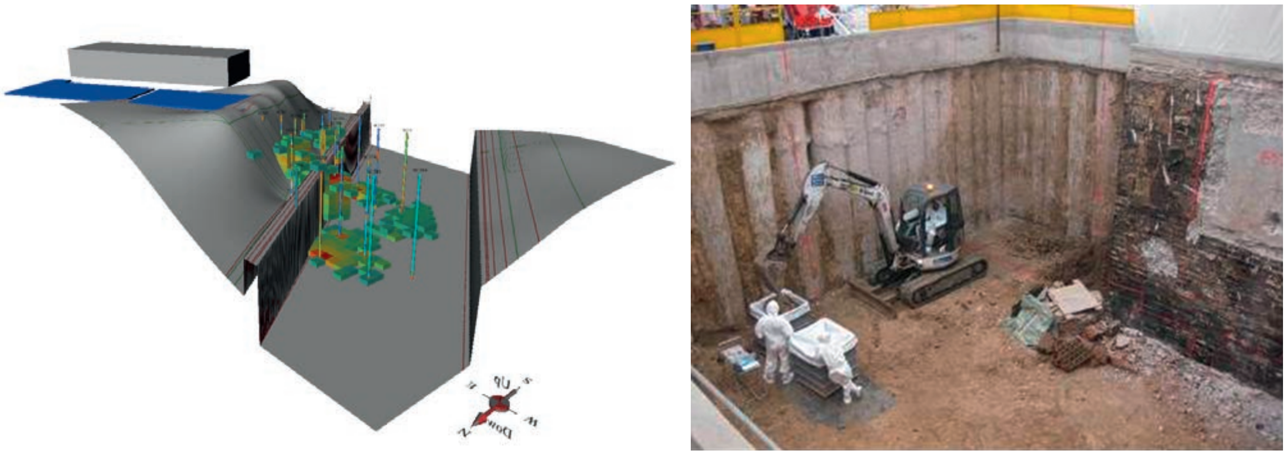

*FIG. 9. Sampling practices for deep excavation operations.*

Sampling of wells, rivers and lakes known to be in connection to the groundwater system is also of great importance to gain an overview of the radionuclide distribution. In this case, the migration velocity of radionuclides to the groundwater table, and with the groundwater to the wells or the surface water bodies, must be taken into consideration.

After an accident, certain underground structures such as tunnels, ducts, pipes, etc. may not be accessible as before. In addition, they might be affected by contaminated water flowing to the lowest part of the facility. Techniques for surveys and sampling in these areas are addressed in Ref. [30].

### 5.6. UNCERTAINTY IN MEASUREMENT DATA

In all measurement and characterization techniques described in this section, understanding the uncertainty in measurements and interpretation of the results are important.[1] For normal decommissioning or decommissioning following limited events, the uncertainty is readily quantified and interpretation is usually straightforward. In contrast, the uncertainty following an accident will be much greater for several reasons:

- Usually, the operating history allows many conclusions for the nuclide composition to be drawn (i.e. whether the presence of alpha emitting nuclides is expected in specific locations or systems or not). This is no longer the case after accidents because the contamination mechanism will be severely altered. The normal operating history can no longer be taken as the basis for decisions concerning the radiological characterization strategy.
- Nuclear fuel may form part of the contamination.
- Radionuclides that play only a minor or no role in nuclear facilities in normal contamination situations may now become relevant. High contamination levels of fission products (caesium, strontium) and transuranics (plutonium) isotopes throughout the plant create unusual challenges for accurate measurement.
- The distribution of contamination has been altered significantly as contamination has been transported into areas of the facility that would have otherwise been free of contamination.
- Contamination may have penetrated much deeper into building surfaces, even at places where no such mechanism would have been suspected, owing to a large distribution of contaminated media inside the facility.

### 5.7. SAMPLING AND LABORATORY ANALYSES

Special analysis facilities that are not available in the plant may be necessary to conduct characterization analyses, owing to the unique post-accident conditions of the facility, for example:

- Samples are likely to be more radioactive than usual;
- Beta and alpha emitters can be present;
- Larger numbers of analyses may be needed;
- Analyses procedures are likely to be different from those normally used in power plants.

The types of capabilities required are shielded wet chemistry stations and gamma spectrometers. Reference counting standards for high and low energy photons will be needed.

The need for timely results will mean that radiochemical capability should be established on-site or in close proximity. Such facilities can be established in existing buildings or can be provided in custom built mobile or transportable trailers.

Detailed information on the physical and chemical status of fuel or structural components may be obtained by collecting samples and by the use of probing tools. Physical properties may be judged by the degree of force needed to collect samples. Analysing fuel samples of any size will require heavily shielded facilities with remote manipulators. These types of analyses will require a hot cell, which does not normally exist at a power plant. To conduct off-site analyses, special shipping containers will be required to bring the materials to the hot cell. Since this is likely to require several weeks after a sample has been obtained, the number of such analyses required to support decision making should be kept to the minimum necessary.

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[1] Measurement programmes including data evaluation and detailed definition of data quality objectives for characterization of nuclear facilities have been defined in many places, such as in the widely used MARSSIM and EURSSEM recommendations. More generally, ISO 11929:2010 addresses characterization limits such as decision thresholds, detection limits and limits of confidence intervals.

### 5.8. COMPUTATIONAL ANALYSES AND EVALUATIONS

A capability for various computational analyses will be required. The tools and expertise for most such needs are likely to exist within the operating company. Almost all will require the use of computers and relevant software. Much analytical computer software is available from libraries maintained by various international agencies. Examples of data management and computational analyses tasks include:

- Radiation calculations providing dose assessments for the purposes of temporary shielding design and personnel exposure assessments;
- Sample tracking by maintaining a database of samples and analysis results;
- Waste inventory management to include tracking and reporting liquid, gas and solid waste quantities by volume and radionuclide content;
- Spectrographic analysis/gamma scan evaluations for determining locations of fuel and evaluation of fission product spread;
- Source calculation analyses assessing the relative amounts of fission products as they decay with time;
- Dose rate tracking by maintaining a database of area dose rates, surface contamination and airborne activity;
- Simulators reconstructing the event sequence and changes since the event, including material, radiation and thermal conditions;
- 3-D visualization software showing the progress of activities, specifically fuel removal, but also the temporary location of equipment and waste within the containment;
- 2-D drawing software for tasks, such as design of special fixtures and components and flow path elevation analyses for decontamination flush flow path evaluation.

# 6. DAMAGED FUEL MANAGEMENT

**KEY LESSONS LEARNED**

- Damaged fuel removal is the most challenging aspect of post-accident cleanup; however, in many cases, it provides the greatest hazard reduction.
- Until visual evidence of the physical form is available, there will be great uncertainty for designing the tools, machines and methods for fuel removal.
- Planning and design must address the entire fuel removal and disposition campaign from beginning to end. This integration must include worker health and safety, physical removal tools and equipment, containers, various measurements of removed materials and debris, interim on-site storage, and material packaging and transportation considerations.
- Processing, in lieu of storage and disposal, is an option that should be considered and evaluated.
- Selection of fuel removal hardware must be such that its failure in use will not significantly impact continued removal operations.

### 6.1. INTRODUCTION

Damaged fuel removal is the major post-accident cleanup challenge owing to several factors including, but not limited to:

- Unpredictability of the post-accident configuration and physical characteristics;
- Loss of structural integrity of the fuel/core support structure/vessel;
- High radiation from the fuel and surroundings;

— Difficulty of access, whether in air or water, poor visibility and the reach distances from work areas to the furthest location of fuel material to be removed.

There have been five major reactor accidents in which the core has been severely damaged. Effective fuel removal and transport off-site was accomplished to completion at Bohunice A-1 and TMI-2. Windscale's fuel debris remains in situ (on the basis of a supporting safety case) until the entire facility is decommissioned. The removal of damaged fuel from Chernobyl has been postponed until after the erection of the NSC; activities performed to date are limited to the removal of particulate matter strewn outside Unit 4, which followed from an effort to find and remove local hot spots. There is as yet little experience from Fukushima. At this time, the best documented approach addressing fuel removal issues of severely damaged fuel is the TMI-2 case, which has been reported extensively, including in IAEA reports.

The purpose of this publication is to update past reported experience with A-1 and TMI-2 from the 1990s with regard to three subjects:

— Perspectives of major fuel damage;
— Improvements in technology as might be applied to damaged fuel management;
— Long term stabilization or disposition of the fuel for Windscale, Bohunice and TMI-2.

## 6.2. DAMAGED FUEL PERSPECTIVE

Table 5 is a chronological tabulation of fuel damage events published in Ref. [3] and updated to include Paks and Fukushima Daiichi. A few earlier events have been included for completeness.

TABLE 5. FUEL DAMAGE EVENTS ARRANGED CHRONOLOGICALLY

| Plant (year) | Country | Primary cause | Description |
|---|---|---|---|
| NRX (1952)<br>Water cooled, heavy water moderated | Canada | Design, operator error | A reactor runaway from a combination of design flaws and operator error resulted in damage of fuel and leakage of moderator water, flooding the building. Returned to service. |
| Windscale (1957)<br>Gas cooled graphite pile | UK | Lack of information for operators | Uncontrolled release of Wigner energy, fire and destruction of a substantial portion of air cooled core, some fission products released to the environment. |
| SL-1 (1961)<br>Small prototype pressurized water reactor | USA | Design | Prompt critical while shutdown with head off, reconnecting control rod-to-drive mechanism, destruction of the core, substantially contained within the building. |
| Chapelcross (1967)<br>Magnox carbon dioxide cooled, graphite moderated | UK | Depends on whether the cause of the debris was design or operation. | Graphite debris partially blocked a fuel channel causing a fuel element to melt and catch fire. Contamination was confined to the reactor core. The core was repaired and restarted. |
| Fermi 1 (1968)<br>Sodium cooled | USA | Design | Splitter plates below the core vibrated loose and blocked fuel channels, causing melting of several assemblies, contained within primary system. Returned to service. |

TABLE 5. FUEL DAMAGE EVENTS ARRANGED CHRONOLOGICALLY (cont.)

| Plant (year) | Country | Primary cause | Description |
|---|---|---|---|
| Ågesta (1968)<br>Water cooled | Sweden | Design | Spacer grid spring relaxation and flow vibration. 15 fuel assemblies failed. Returned to service with modified fuel. |
| St. Laurent (1968)<br>Gas cooled, graphite moderated | France | Procedure | Flow reducer for a control channel placed in a fuel channel. Fuel overheating and destruction of 5 cartridges. Returned to service. |
| Lucens (1969)<br>Experimental<br>Gas cooled, heavy water moderated | Switzerland | Channel flow blockage | Coolant leakage, followed by moderator tank rupture, and severe damage to a single fuel assembly. |
| Jaslovské Bohunice, A-1, (1977) gas cooled, heavy water moderated | Slovakia | Operator error, blocked fuel channel | Rupture of fuel cladding and de-cladding of fuel occurred in the upper 30 to 100 cm of fuel elements; 148 assemblies affected. Reactor Building contaminated. |
| Three Mile Island (1979)<br>Pressurized water reactor | USA | Design and operator error, relief valve stuck open | Failed to keep core covered with water, destruction of the core with large fraction melted, fuel contained within systems; fission product contamination to the containment building. |
| Chernobyl (1986)<br>Water cooled, graphite moderated | Ukraine | Design and violation of operating procedures | Prompt critical reaction caused destruction of the reactor with substantial distribution of fuel and fission products outside the primary envelope and to the environment. |
| Paks (2003)<br>Pressurized water reactor | Hungary | Design, operational delay | Fuel rod damage in cleaning tank. |
| Fukushima Daiichi (2011),<br>3 boiling water reactors | Japan | Tsunami, design | Severe damage to the reactor cores in 3 of the 4 units. |

### 6.2.1. Descriptions of damaged fuel

The results of a severe accident involving fuel melting or other forms of fuel damage can vary widely. This subsection shows the conditions that resulted at the NPPs at Paks, TMI-2, Chernobyl and Fukushima Daiichi. As the environmental consequences of the Paks incident were insignificant and the damaged fuel was completely contained, it is only shown for perspective. Figure 10 illustrates the situation that occurred at Paks, in which the fuel was not in the reactor [9]. This event, rated as INES level 3, can be considered representative of others of similar scale listed in Table 5 where the root cause of damage was overheating.

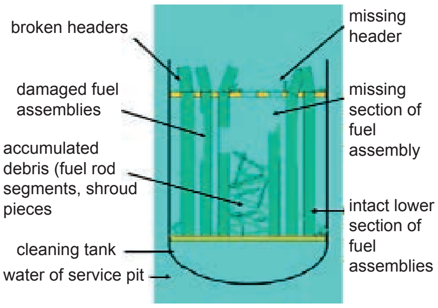

FIG. 10. Paks damaged fuel.

Figure 11 shows the extent of the TMI-2 fuel damage and views of the fuel ranging from partial fuel assemblies, individual rods and rock-like material. The TMI-2 experience provides a good example of the need for direct characterization and the risk of over-relying on assumptions and models. The true extent and physical forms of the damaged fuel were not understood until video images and sonar mapping was conducted in 1983, four years after the accident. Core sample drilling was accomplished in 1986, and video inspections behind the core sidewall a year later. The complete story of the many attempts to predict damage fuel and core conditions is contained in Ref. [10], which also describes the many proposed methods for removing the damaged fuel.

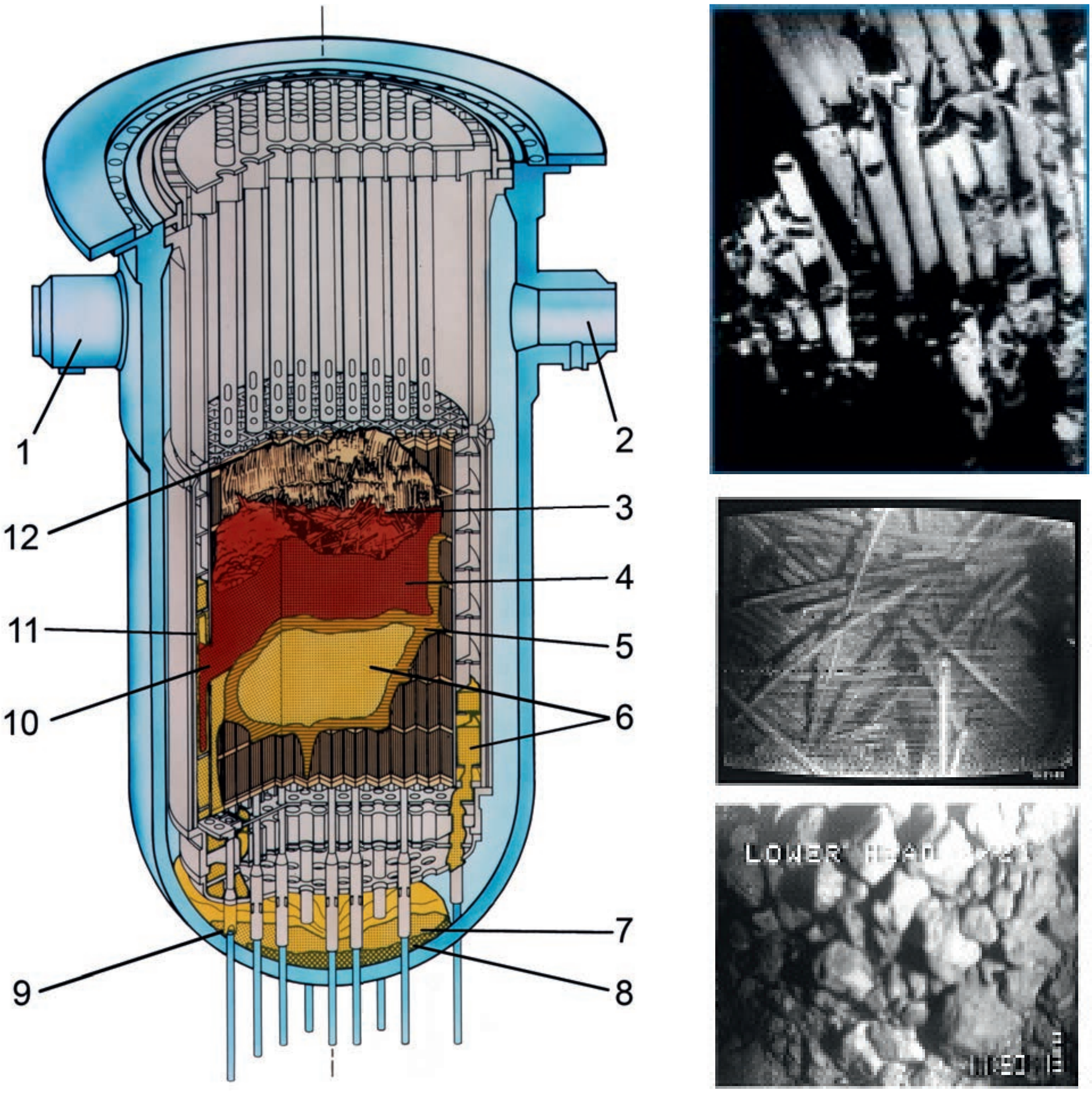

*FIG. 11. TMI-2 core damage and fuel debris. Legend: 1: 2B inlet. 2: IA inlet. 3: Cavity. 4: Loose core debris. 5: Crust. 6: Previously molten material. 7: Lower plenum debris. 8. Region possibly depleted in uranium. 9: Ablated incore instrument guide. 10: Hole in baffle plate. 11: Coating of previously molten material on bypass region interior surfaces. 12: Upper grid damage.*

In contrast to the TMI-2 conditions, Fig. 12 shows pictures from Chernobyl for which the fuel has no resemblance to its pre-accident configuration. On the left is the cavity where the core initially existed, and on the right are examples of ‘corium’[2]. Both of these accidents and their post-accident cleanup actions have been extensively reported and are not described further here.

*FIG. 12. Chernobyl core cavity and corium.*

At Fukushima Daiichi, as of December 2011, a technical analysis by TEPCO concluded that the fuel in Fukushima Daiichi Unit 1 has mostly melted out of the reactor pressure vessel and into the primary containment vessel. It also concluded that fuel has melted in Units 2 and 3, but has mostly remained within the vessels. Artists’ impressions of the Fukushima Daiichi core melt in Units 1 (left) and Units 2 and 3 (right) are shown in Fig. 13 [31]. The right image includes two cases; a best case estimate based on data collected in March 2012 (top circle), and a worst case estimate (bottom circle). Unit 4 had no fuel loaded in the core at the time of the incident, and so was not damaged.

Unit 1 estimates are that most of the fuel has drained out of the reactor pressure vessel (RPV), via the bottom mounted control rod tubes or instrumentation penetrations, into the concrete primary containment vessel (PCV). The reasoning is based on the unit’s decay heat that significantly exceeded the RPV water and materials’ heat absorption capacity; it also explains why the RPV temperature had been low from an early stage. Based on realistic assumptions and PCV gas analysis results, it has been estimated that the corium eroded the 2 m thick PCV floor by about 70 cm before being cooled with sea water injection.

In the cases of Units 2 and 3, lesser amounts of fuel are assumed to have dropped out of the RPV and into the PCV because the decay heat was less than the total heat absorption capacity of water in the core and because of RPV temperature trends after water injection restarted.

Just as the TMI-2, Windscale, Bohunice and Chernobyl fuel conditions were in no way similar to one another, the accident at Fukushima Daiichi has further shown that every accident varies widely in the conditions of the damaged fuel. For events greater than INES 4, conditions within the reactor and its surrounding area have also differed significantly in every case.

The characteristics of accidents of lesser severity have also varied widely. These variations mean that, while the principles of planning, design and operations may apply in past and future events, the details of implementation are likely to be significantly different.

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[2] Corium is a general term used to describe the once molten mixture of components of a nuclear reactor. It can consist of nuclear fuel, fission products, control rods, structural materials from the affected parts of the reactor, products of their chemical reaction with air, water and steam, and, if the reactor vessel has been breached, concrete from the structure of the reactor space.

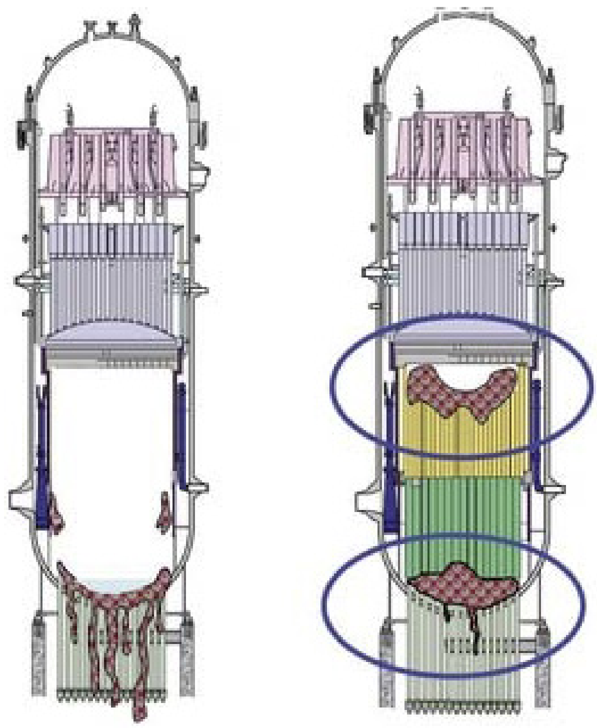

*FIG. 13. Artist's depiction of Fukushima Daiichi corium relocation; Unit 1 (on the left); Units 2 and 3 (on the right) [31].*

## 6.3. TECHNOLOGY APPLICATION

In any case of an accident with damaged fuel — mild or severe — the normal fuel handling equipment will not be suitable for use as designed, if at all. Special tooling and equipment will be needed to some degree in every phase of removing the damaged fuel. As stated earlier, one of the primary changes since the TMI-2 and Chernobyl accidents is the advancement in technology. This is of special importance because the radiation and contamination levels associated with damaged fuel and its surrounding will almost always require remote handling methods for fuel removal, even if they are manually operated.

Depending on conditions, size reduction may be needed. Remote handling and size reduction will usually require custom adaptation and development of tools and equipment for the physical, radiological and perhaps chemical constraints of the material location. Shielding and transfer containers will need to be part of the design. Remotely operated video monitoring will likely be required; radiation monitors may also be needed. All of these constraints and needs are made more challenging in the case of Fukushima Daiichi because it is likely that much of the operations will be underwater at depths of 30 m or more.

Figure 14 shows the TMI-2 core boring machine adapted from standard mining equipment. This machine was successful in 'grinding' the once-molten core debris into sizes that could be removed with long-handled manual tools. Although manually operated, this represents perhaps the most useful application at TMI-2 of what might be called remote technology.

Figure 15 is an illustration of more modern underwater equipment designed for disassembly inside the BR-3 reactor vessel; however, this equipment is not for fuel removal. Advancements during the past 30 years in remote technology, sensors, video equipment and other needed equipment, including software for display and analysis, can be major assets for fuel removal. Remote Handling Techniques in Decommissioning [32] shows many examples of equipment that could in principle be developed or adapted for damaged fuel removal.

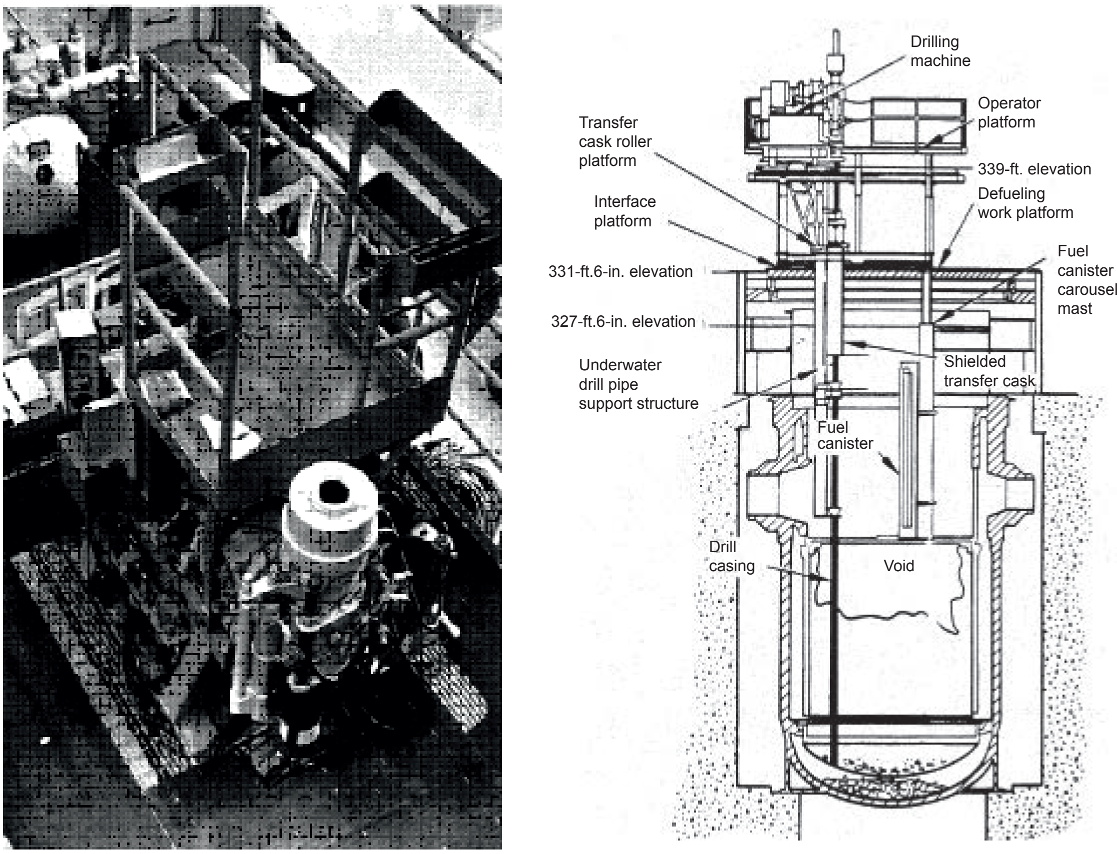

*FIG. 14. TMI-2 core boring machine.*

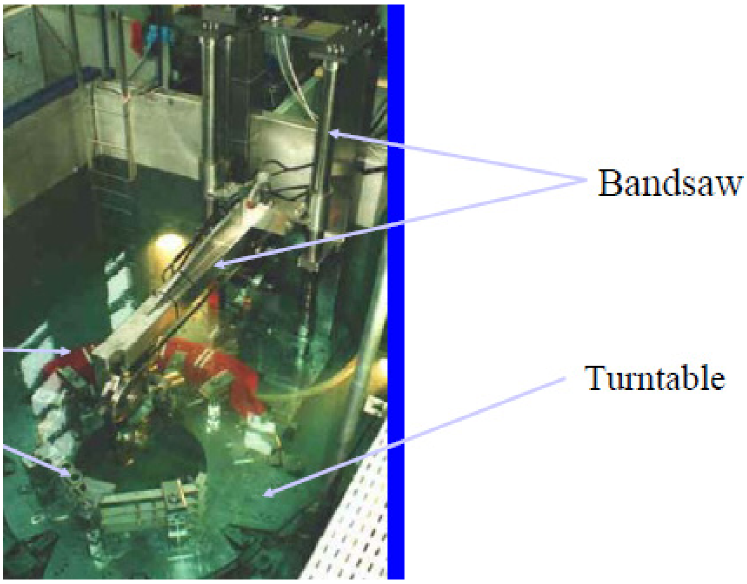

*FIG. 15. Equipment developed for deployment inside the BR-3 vessel.*

Because each accident situation is unique, specific technological applications can only be planned, designed and put into practice once the physical conditions have been adequately determined. Therefore, the discussion here has been limited to describing the complexity involved in developing and applying current technology for functions that may be needed for damaged fuel management.

The top level of the flowchart in Fig. 16 illustrates the functions for which remote technology can be applied during the phases of damaged fuel management. At the top of the figure are three major phases and many of the subfunctions for carrying out the campaign of damaged fuel removal. At first it is necessary to obtain sufficient information and data required to plan and implement the removal. This information is obtained both in situ and by analysis of samples retrieved. Removal operations consist of activities for disassembly and size reduction of fuel and other components that are part of, bonded to, or interfering with access to the fuel. Positioning of tools is a major aspect of remote technology applications. The third phase is physical removal for disposition.

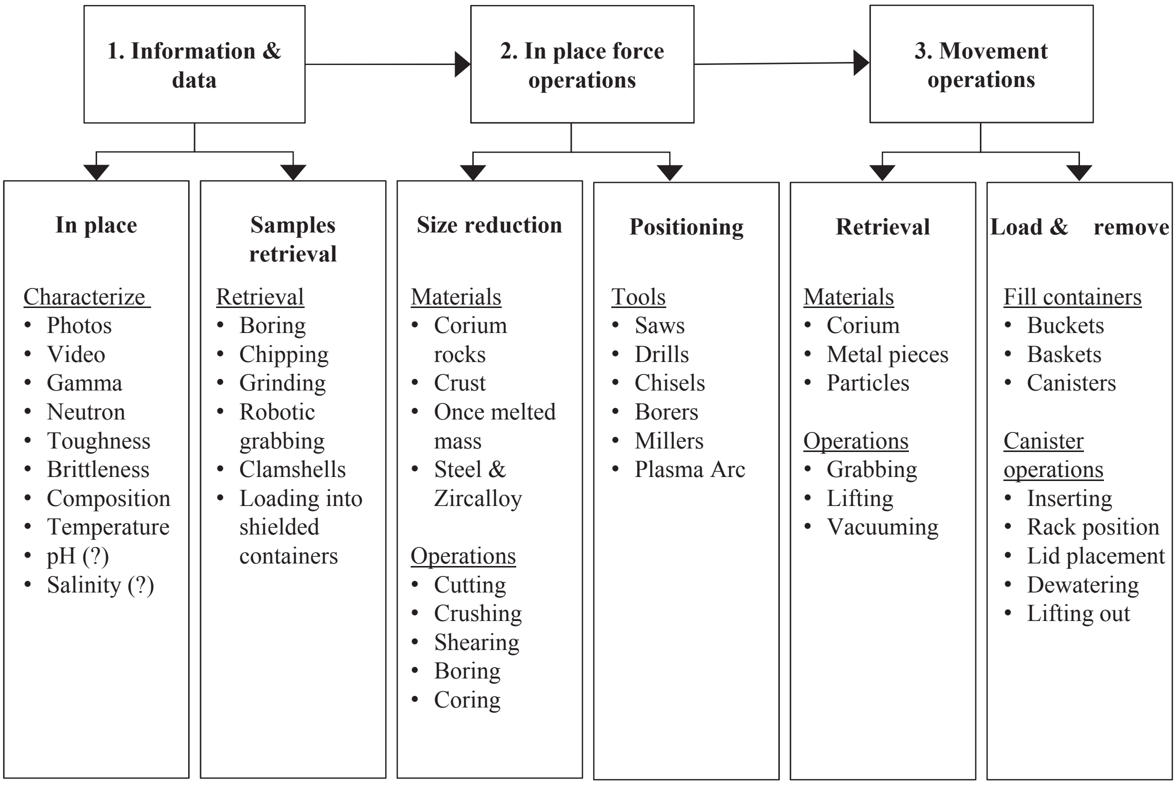

*FIG. 16. Types of operation for remote technology application. (?) — 'if required'.*

There are approximately 40 operational functions shown in Fig. 16, considering variations in materials, tools and equipment. Developing remotely controlled equipment for any one of these can be considered a project or part of a project that will develop equipment for multiple functions. Figure 17 shows the phases for each development project. Each can take weeks or months, depending on the complexity and availability of components that can be adapted to the situation; in many situations complete development will be needed.

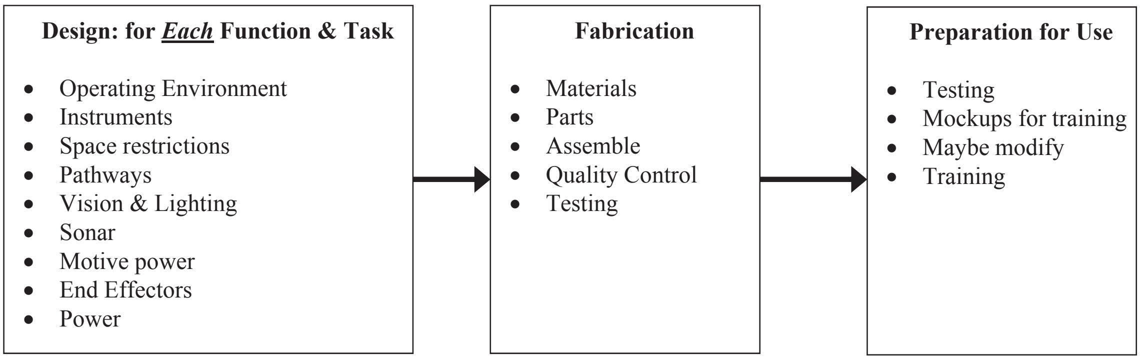

*FIG. 17. Project steps for each remote technology application.*

Insights for what is needed are best provided by those at the site who are using the equipment, in view of the experience they gain as the cleanup proceeds. It is recommended that an on-site or near site organization be established as part of a team that maintains records and includes chosen suppliers. This organization should be staffed with operators, engineers and technicians who will be responsible for the ultimate application of the technologies and will provide the site interface with designers and manufacturers.

## 6.4. STATUS AND DIRECT DISPOSITION OF DAMAGED FUEL

This subsection presents three cases with varying approaches for the disposition of damaged fuel after cleanup.

### 6.4.1. Windscale

The Windscale damaged fuel remains within the reactor. Visual inspection using CCTV has shown that the vast majority of fuel channels were damaged. For example, of the 104 channels inspected in one of the surveys, only one of the channels had a chance of a relatively intact set of fuel elements. In the majority of cases, the survey indicated damaged but complete fuel elements, combined with degraded fuel and debris in various states, ranging from previously molten and re-solidified material to beds of ash.

The status of the facility is in a state of ‘passive safety’ and has a defined surveillance and maintenance programme and procedures. An operational safety case hazard assessment and engineering substantiation indicates the absence of any cliff edge effects, such as drastically increased levels of hazards, accelerated degradation of the radioactive inventory or failures of the safety systems or plant structures, which would present a threat to the safety of the facility beyond 2016 until decommissioning. In addition, the asset care process will ensure that the integrity of the main structures or the availability of the safety systems will not be compromised as a result of the extended Pile 1 surveillance and maintenance regime.

### 6.4.2. Bohunice A-1 Reactor

Transfer of non-damaged and lightly spent fuel assemblies (439 of the total 571) using standard procedures started in 1984, and was completed in 1991.

Because the severely damaged fuel could not be removed from the in core cooling channels by standard means, new technology was required for its packaging and preparation for transport. A two step process was developed:

(1) The reactor coolant that was highly contaminated with fission products and transuranics, and cladding metal, was drained;
(2) The drained coolant channels containing the damage fuel assemblies were removed and repackaged into hermetically sealed containers.

By 1991, four damaged fuel assemblies had been repackaged; at this time progress was interrupted until 1996, as a result of a reactor hall contamination incident. By 1996, a new facility had been commissioned for preparing and repackaging the damaged fuel in an inert argon atmosphere. An interim storage facility for the damaged fuel was commissioned in 1998. The highly damaged fuel was transported to the Russian Federation from 1997–1999 [33].

### 6.4.3. Three Mile Island Unit 2

The TMI-2 core debris and spent nuclear fuel were shipped to the Idaho Nuclear Laboratory (INL) site by rail between 2 July 1986 and April 1990. The 341 canisters that contained the material were placed in a fuel storage pool inside a building designed for nuclear safety. From 1995 to April 2001, canisterswere placed into a horizontal dry storage module at the Independent Spent Fuel Storage Installation (ISFSI) at INL. Importantly, the design of the original canisters was suitable for this purpose, eliminating the need for a new one.

A key part of that project was the vacuum drying of the material inside the canisters, reported in detail in Ref. [34], which discusses aspects of high temperature versus low temperature drying of nuclear fuel and fuel debris. After drying, the TMI-2 shipping cask was used to transport the canisters to the storage modules. The safety aspects of the ISFSI storage are reviewed and licenced by the NRC. The licence was recently renewed; however, corrective actions were first needed to remedy weather related degradation of the concrete modules.

An overview of the campaign is shown in Figs 18 and 19. These four pictures respectively show the storage pool from which the canisters were removed; the loading of a canister into the heated vacuum drying oven; individual fuel debris canisters being loaded into a shielded dry storage over pack that itself stands within a transport cask; and the dry storage modules in which the fuel debris is dry stored.

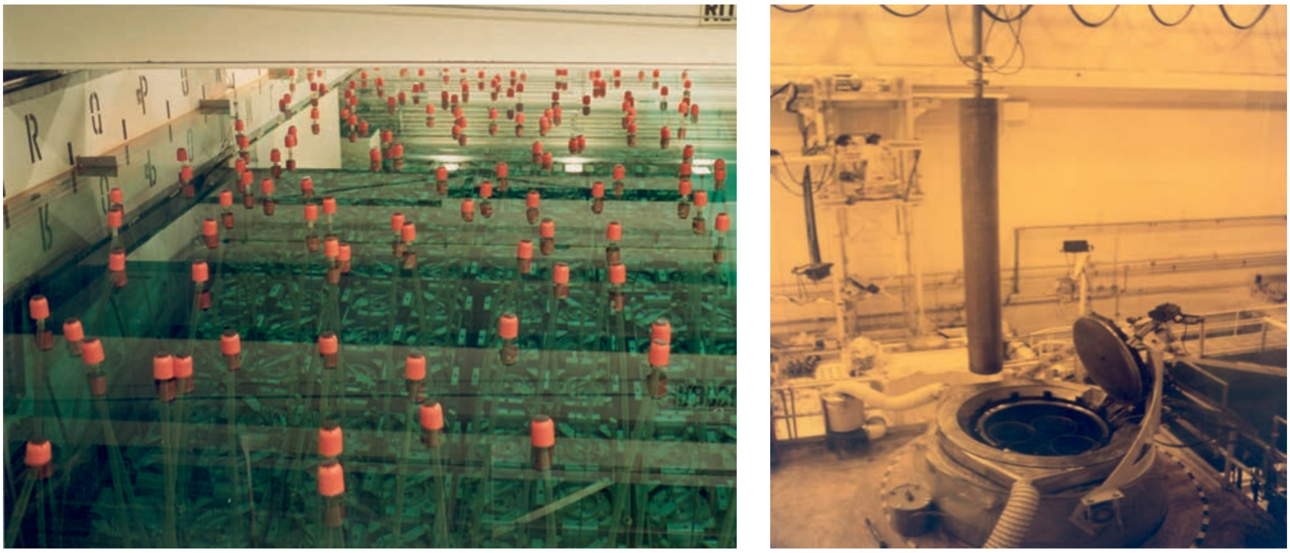

*FIG. 18. On the left, the storage pool at TMI-2; on the right, the loading of a canister into the heated vacuum drying oven.*

*FIG. 19. On the left, TMI-2 fuel debris drying; on the right, placement in dry storage.*

### 6.4.4. Chernobyl

The accident at Chernobyl NPP Unit 4 resulted in total destruction of the reactor core. About 3.5% (by weight) of the fuel originally in the core was ejected. About 50 kg of plutonium, representing 6% (by weight) of the total plutonium in Unit 4, was spread in the European part of the then Union of Soviet Socialist Republics. More than 90% (by weight) of the fuel remains inside the shelter (sarcophagus). At least 11 to 15% (weight) of the fuel inside the shelter is in the form of 'lava', which is a glass like material formed by melting.

Substantial investigations have been conducted on the properties of the lava. The initial mechanical durability of this material was very high. However, a dramatic decrease and even self-destruction of lava matrices was observed in the 1990s, along with observations of the chemical alteration of lava matrices. From these studies, it has been concluded that temperatures greater than 2600°C occurred and that interaction between nuclear fuel and zircaloy cladding took place locally within the reactor core before the explosion. It is likely that active chemical alteration of the lava is ongoing, which means that any future plans for moving this material will require a good understanding of the current conditions at that point.

## 6.5. PROCESSING DAMAGED FUEL AND DEBRIS IN LIEU OF STORAGE AND DISPOSAL

Other than storage and disposal of damaged fuel and fuel debris, the possibility of processing should be considered. There are three possible approaches: aqueous processing, electrochemical dissolution and vitrification. All three options require complex physical chemistry in a highly radioactive environment such as that within medium to large facilities. Processing severely damaged fuel and debris is likely to be at a high unit cost and to require a lengthy schedule. A compensating evaluation factor is the duration of storage if there is no readily available direct disposal pathway.

### 6.5.1. Aqueous processing

Aqueous processing of spent fuel has been conducted for several decades. The Thorp reprocessing plant at Sellafield, UK, combines all the facilities necessary for reprocessing spent oxide fuel under one roof. Thorp's operations are divided into three main areas:

- Fuel receipt and storage;
- Head end plant operations, where spent fuel is chopped up and dissolved in nitric acid;
- Chemical separation, where uranium, plutonium and waste products are separated out.

### 6.5.2. Electrochemical dissolution

The following is a description of electrochemical processing applied to a specific fuel type. The steps in the process are shown in Fig. 20. The description below is for a specific type of fuel processing conducted at the Idaho National laboratory. More complete descriptions can be found on the internet.

Fuel treatment is performed in two hot cells. Spent fuel is transferred into an air-filled hot cell. The elements are separated from the fuel assembly hardware, and then transferred into an argon-filled hot cell. There, the fuel elements are chopped up, placed into steel baskets, and transferred to the electro-refiner. The electro-refiners contain a molten salt medium of LiCl-KCl eutectic and dissolved actinide chlorides, such as $UCl_3$ and $PuCl_3$. There, the spent fuel is electrochemically dissolved from the anode baskets and an equivalent amount of uranium is deposited on a cathode. Uranium is separated from the bulk of the fission products and transuranics, which accumulate in the salt. The cathode products from electro refining operations are further processed to distill adhering salt and recover uranium. The recovered uranium is blended with depleted uranium to produce a product that is less than 20 per cent enriched. The low enriched uranium is then formed into ingots and placed in canisters in interim storage while awaiting final disposition.

The electrometallurgical treatment results in two high level waste forms: ceramic and metal. The ceramic waste form is glass-bonded sodalite produced from the conversion of zeolite A and which, at the end of the process, is consolidated into a monolithic waste form in a furnace at 915˚C. The metal waste form consists of metallic ingots, non-actinide fuel matrix and cladding materials, minor amounts of actinides and added zirconium to improve performance and produce a lower melting point alloy. The composition — usually stainless steel and 15% zirconium (by weight) — is produced in a casting operation at 1600˚C.

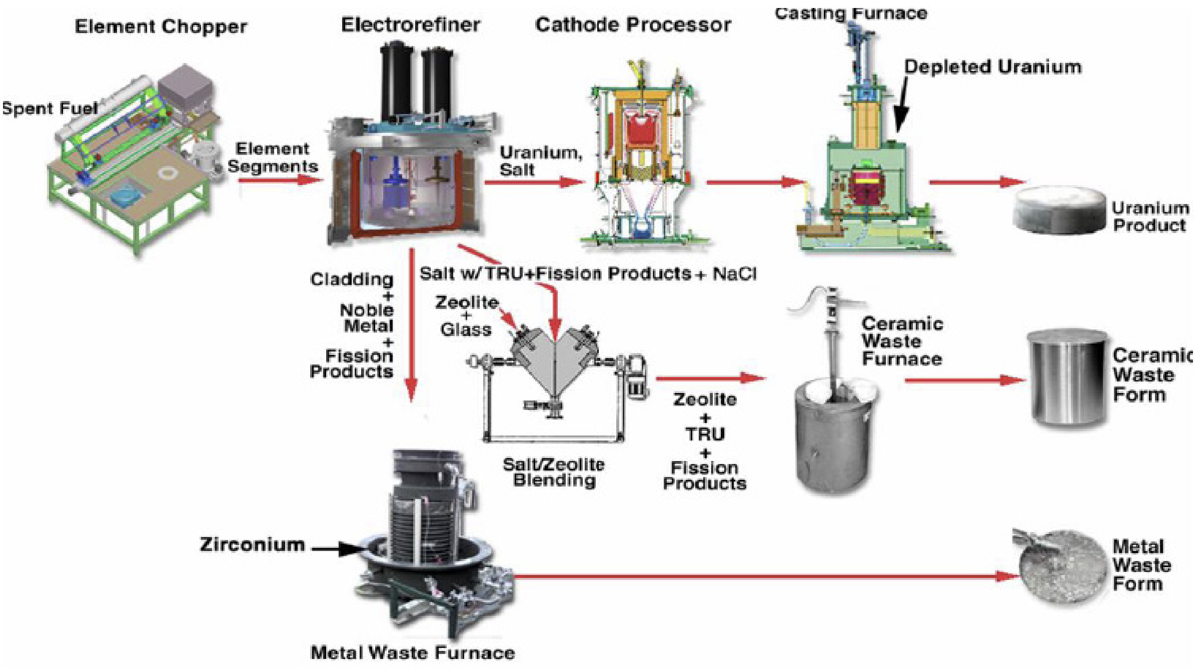

*FIG. 20. Example steps in electrochemical processing.*

### 6.5.3. Vitrification

During the TMI-2 cleanup projects, the contents of three of the spent fuel canisters were vitrified in a hot cell. It was conducted as an experiment to understand the technical feasibility. However, the eventual decision was to opt for long term storage and ultimate direct disposal as described in the previous subsection. Since that time, vitrification has advanced considerably for stabilization for disposal of high activity fission products and reprocessing waste, but not for fuel. Figures 21 and 22 indicate the magnitude and complexity of such facilities [35].

*FIG. 21. Vitrification facility in the USA.*

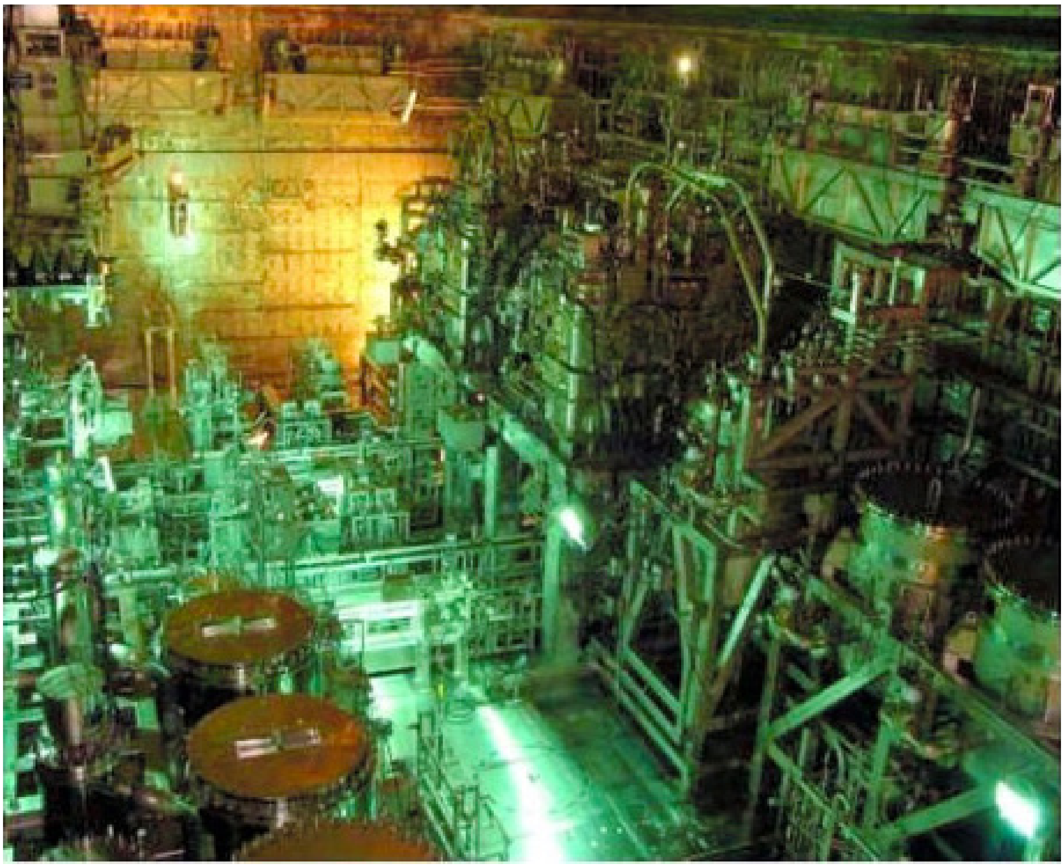

FIG. 22. Interior of a vitrification facility in Japan [35].

# 7. DECOMMISSIONING AND SITE REMEDIATION

**KEY LESSONS LEARNED**

- Very few severe accidents have entered into the decommissioning and site remediation phase; the key learning in this aspect is limited. Deployment of decommissioning techniques for post-accident recovery is also very limited.
- Owing to the time delays associated with decommissioning and site remediation, provisions should be made for knowledge capture of information that will be important when future activities are conducted.
- Many sites opt for a period of safe storage with care and maintenance while operation of other units is continued. An added benefit is reduced exposure rates during decommissioning as a result of radioactive decay.

## 7.1. INTRODUCTION

The purpose of decommissioning, including associated site remediation, is to establish the facility end-of-life disposition and, ultimately, to remediate the site to a safe and acceptable state for the long term. The goals for decommissioning are to reduce risk to on-site personnel and the public and to protect the environment from the distribution of radioactive substances via natural pathways, such as wind and water streams.

This section discusses different strategies for decommissioning and associated site remediation. The current decommissioning and site remediation status of six INES 5–7 nuclear accident cases are addressed. When site circumstances allow, decisions as to which mode to employ to achieve the desired end state is made well in advance, during post-accident cleanup planning.

## 7.2. STRATEGIES FOR DECOMMISSIONING

As already noted in Section 3.4, the definition of interim and final end states for major phases of a post-accident cleanup project is of fundamental importance. The selected final end state for the site will have significant implications for the preceding activities, especially concerning infrastructure requirements for the long term management of waste.

For accident damaged facilities, decommissioning and associated site remediation strategies can be implemented only after an interim end state has been reached in which the potential for an uncontrolled release to the environment no longer exists. As with facilities that have not suffered a severe accident, strategies for decommissioning and associated site remediation are inevitably variants of the following, though it should be borne in mind that timeframes are likely to be significantly longer in the case of facilities that have suffered a severe accident:

*Immediate dismantling (also called DECON).* All radioactive components and structures are cleaned or dismantled, packaged and shipped to a low level waste disposal site, or stored temporarily on-site. Once this task is completed, and the regulatory body terminates the plant licence, that portion of the site can be reused for other purposes.

None of the plants that have experienced a severe accident have been fully decommissioned. In general, this is because of the difficulty and cost of removing the residual radiation hazard.

*Deferred dismantling (also called SAFSTOR or Safe Enclosure).* The nuclear facility is kept intact and placed in protective storage for decades, taking advantage of radioactive decay. This method involves securing that part of the plant containing radioactive materials and monitoring it. On-site security is maintained, as are the facility’s physical conditions.

Technical and safety issues need to be addressed for deferred dismantling as a result of the safety case requirements. Subjects that will need to be addressed include, but are not limited to:

— Estimate of the amount of residual fuel debris or other nuclear materials and assurance that combining these inventories will not lead to a critical mass.
— Requirements for inspection, care and maintenance of any on-site stored wastes and fuel bearing materials.
— Periodic inspection with procedures that specify what is to be inspected, the frequency, criteria for evaluation of conditions, and the walk through path including roof inspections.
— Ability to purge closed areas prior to entries for inspection.
— Prevention of serious spread of contamination by airflow pathways; filtered exhaust ventilation may be necessary.
— Preventing or minimizing in-leakage of storm water and snowmelt; removal and treatment of any such in-leakage.
— Ageing management of passive systems and damaged structure are extremely important. They cannot be abandoned and allowed to fail and collapse.
— Fire detection and response.
— Prevention of intrusion by vermin, birds and other wildlife.
— Security of the site.

The as left configuration needs to address an electrical supply to support the above listed functions. Records and photographic/video information of the as left conditions, along with periodic inspection and repair reports, should be archived in a retrievable manner.

*Entombment (also known as ENTOMB).* This option involves permanently encasing radioactive structures, systems and components in concrete or another durable medium. The encased plant would be appropriately monitored and maintained until final decommissioning is undertaken. Most nuclear facilities will have radionuclide inventories that will prohibit unrestricted use without encasement. Monitoring may be required until this is achieved. At present, there are only a few cases of entombment being selected for final decommissioning; these were not accident cases.

## 7.3. SITE REMEDIATION

When considering specific contaminated sites which are primarily of concern at the local level, the following factors will influence the type of remediation effort undertaken [36]:

- Exposure of the worker, public and environment;
- Economic impact;
- Future end state;
- Local regulations;
- Cleanup or restoration criteria;
- Public concerns.

Significant experience in rehabilitating contaminated sites has been gained worldwide, for which technologies and equipment have been developed. In this regard, the main task of post-accident remediation is the selection of safety criteria, optimum technological solutions and radioactive waste management. These choices are based on the results of radiological surveys suitable to the magnitude of radiation resulting from accidents. Key decisions, planning and strategies for this optimization are:

- Decontamination methods and equipment;
- Dismantling and demolition methods and equipment;
- Radioactive waste management including containers, treatment, transportation, storage and disposal;
- Rehabilitation of contaminated buildings and facilities and environmental remediation.

## 7.4. STATUS OF ACCIDENT SITES

The current status of six sites where severe accidents have occurred is described below. Figure 23 shows the status of each accident on the timeline as covered within the scope of this publication. As Fukushima remains at the very early stages of its recovery, only the status of the other five is described.

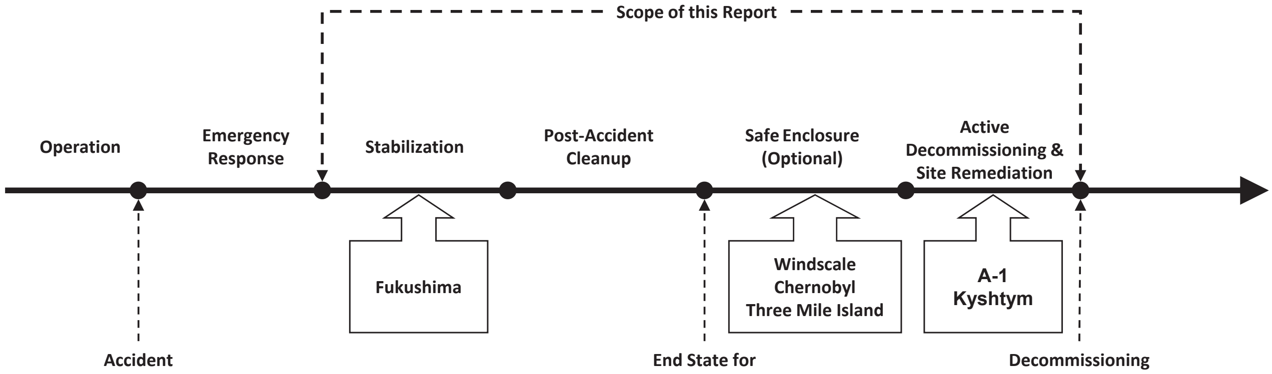

FIG. 23. Current status for six nuclear accident cases.

### 7.4.1. Chernobyl

*Current Status: Deferred Dismantling (SAFSTOR).* More than 25 years after the accident, the Chernobyl plant is still in the phase of stabilization. The law of Ukraine on Chernobyl NPP further operation and decommissioning and transformation of the damaged fourth power unit of this NPP into an environmentally safe system [37] stipulates that the NSC is a protection facility which will contain a complex of process equipment for the removal of fuel containing materials from the destroyed Unit 4, and must achieve a number of goals, including:

- Creating the required conditions to support the physical activities of the shelter object conversion into an ecologically safe system;
- Protecting workers, the public and the environment from the impacts of nuclear and radiation hazard sources inherent in the shelter (sarcophagus);
- Conducting radioactive waste management activities.

One of the major safe confinement functions is the prevention of the transport of radioactive substances and ionizing radiation outside the NSC. This will be achieved under all conditions by the following:

- Ensuring the integrity of the NSC protecting structures over a long period of its operation (at least 100 years);
- Precluding collapse of the unstable structures within the shelter object by means of their deconstruction or strengthening for the period governed by the NSC safety operation conditions;
- Limiting precipitation penetration into the facility;
- Protecting the hydrogeological environment from contamination with radioactive substances located in the NSC;
- Limiting radioactive substances spread inside the NSC.

In 2003, an international consortium developed the NSC conceptual design. According to the project implementation strategy endorsed by the regulatory authorities of Ukraine, the NSC shall be constructed in three stages:

(1) Design and construction of the NSC;
(2) Required tests and NSC commissioning (2008–2015); creation of remote controlled mechanisms, development and approbation of fuel containing material (FCM) retrieval technologies, creation of radioactive waste management infrastructure are also included in this stage.
(3) The dismantling of the original shelter's unstable structures will commence upon the commissioning of the NSC project.

During this third stage, FCM will be removed and transferred in a controllable condition within protective barriers and/or disposed of in radioactive waste geological disposal facilities. Thus, all FCM should be separated according to activity level, compacted and transferred in a safe condition prior to storage. An FCM inventory should be carried out according to the effective legislative requirements.

In order to successfully implement the final stage of the shelter conversion strategy, a geological repository for FCM or other long lived radioactive waste disposal will be arranged under the national programme. Prospecting, estimating, scientific and methodological, research and design works are currently envisaged under the National Ecological Programme for Radioactive Waste Management — in order to select sites that are potentially available for geological repository arrangement. Completion of these efforts is scheduled in 2017. On this basis, the most optimistic date for the mass removal of FCM from the shelter to commence is 2030 [15].

### 7.4.2. Windscale

*Current status: Surveillance and maintenance (SAFSTOR).* An intrusive survey of 52 fuel channels in the fire affected zone (FAZ) within the Windscale Pile 1 Reactor Core was conducted in July and August 2007. This survey was the first time any equipment had been deployed within the FAZ since the core fire in 1957. A second campaign was sanctioned in January 2008, to assess the condition of the core structure and its contents in a further 100 fuel channels within the FAZ.

From the evidence gained during the two surveys, a large proportion of damage to the graphite structure and fuel contained within it is found in the middle third of each channel and varies in severity relative to the centre of the FAZ. Damage to the graphite structure is also at its most severe where shutdown rod, control rod and foil hole penetrations occur adjacent to the fuel channel. The severity of the damage in these areas has hampered the survey, as the endoscope was unable to bridge comparatively large voids caused by significant graphite loss. Because the endoscope probe could not reach far enough into the channel, the condition of fuel beyond the fire damaged area in each channel could not be examined.

It should also be noted that damage to control rods was observed via the fuel channel voids. The observed control rods have undergone severe reduction in diameter and have broken into several pieces within their penetrations; it had previously been assumed that all of these items were completely intact. The CCTV evidence also disproves the previous assumption that the vast majority of channels contained intact fuel elements along their entire length. In the majority of cases, the survey instrument encountered between one to three damaged but complete fuel elements, followed by degraded fuel and debris in various states, ranging from previously molten and re-solidified material to beds of ash.

The results of the intrusive core survey in conjunction with the review of other sources of information have resulted in the increase of the known Pile 1 fuel inventory to 15–20 t of degraded fuel.

The plant is currently in safe enclosure (using the existing structure) based upon the following factors:

- Delay will allow the decay of radioactive isotopes;
- Financial assurance is required to allow the project to commence uninterrupted;
- The Windscale reactor is passively safe;
- It is assumed that new technologies will become available for more safe and efficient decommissioning.

The passively safe condition is based on a balanced risk review across the Sellafield site, and the reactor is approved to remain in its current condition for a significant period of time subject to routine review. Ongoing justification is needed for continuing the operation of the facility under the deferred period, now referred to as ‘surveillance and maintenance’, as opposed to the previously used term ‘care and maintenance’. The use of this terminology signifies recognition that Pile 1 is an operational facility that will be adequately maintained in its present form within an asset care programme to replace worn out or obsolete equipment where necessary.

### 7.4.3. Three Mile Island Unit 2

*Current status: Care and maintenance/SAFSTOR.* The configuration of the TMI-2 facilities was determined using the post-accident cleanup end state specification process described in Section 3.

The estimated amount of fuel debris remaining throughout the plant is summarized in Table 6 [38]. Access to remove this material could not be gained during the post-accident cleanup because it would have involved cutting large components and pipes in high radiation areas.

TABLE 6. LOCATION OF RESDIDUAL FISSILE MATERIAL AT TMI-2

| Building/location | Residual fissile material (kg) |
|---|---|
| Auxiliary and fuel handling buildings | <17 |
| Reactor building (excluding the reactor coolant system) | <75 |
| Reactor coolant system (excluding the reactor vessel) | <133 |
| Reactor vessel | < 900 |
| Total | <1125 |

The decision to place TMI-2 in safe enclosure status was based on four major issues:

(1) Because TMI-1 will continue to operate and be decommissioned for at least 30 years beyond 1990, it would be efficient to remove both facilities as part of a single project. If the licence is renewed, this would be at least 50 years later.
(2) This delay would allow substantial decay of $^{137}$Cs and $^{60}$Co for a range of 30–50 years; the remaining amount of $^{137}$Cs would be 29–50% and $^{60}$Co would be 1.9–13%.
(3) Increased financial assurance by allowing a collection of funding over the 30–50 year time frame for the estimated $869 million (2009 reference year) to decommission TMI-2 .
(4) It is presumed that over this time period, there will be technology development that will make decontamination and demolition safer and more efficient.

The only activities currently conducted at TMI-2 are a few maintenance routines and preventive maintenance for some systems. Routine maintenance includes checking and changing high efficiency particular filters for the air being exhausted from the containment. This flow is passive to ensure no differential pressure conditions develop within the environment. A preventive maintenance procedure verifies that radiation conditions have not changed; the procedure includes a once per year containment walk down and survey.

The control room is operational to the extent needed for monitoring conditions and the few systems in operation. This includes electrical systems and control room ventilation. Preventive maintenance is performed on the motor control centres and ventilation fans and motors. A fire detection system is in place; however, there is no active fire suppression system. This is justified by the elimination of combustibles and minimising ignition sources. If a fire is detected, the fire brigade from the adjacent Unit 1 would respond. The domestic water system is partially operational and is maintained to correct occasional leaks.

### 7.4.4. Bohunice A-1 Reactor

*Current status: decommissioning and site remediation.* The Bohunice A-1 cleanup and decommissioning was initially conducted while the facility had a licence for operation from 1972 to 1998. From 1999 until today it has had a licence for decommissioning [33, 39].

During the period 1980–1995, following shutdown, activities were conducted to improve nuclear safety features and reduce the nuclear fuel inventory. Tasks included:

- Spent fuel management included removal of 439 non-damaged and lightly damaged fuel assemblies that were sent to the USSR/Russian Federation from 1984 to 1991. This was conducted with use of standard procedures. Special procedures were developed for handling the remaining fuel that was damaged and to move it from the cooling canister to the transportation container. This fuel was transported between 1996 and 1999 as a part of Phase I of decommissioning.
- Disassembly of clean or slightly contaminated circuits and equipment began in 1981. This accomplishment required the construction of a facility for low activity decontamination activities. A significant part of the secondary system was dismantled in the 1990s.
- Radioactive waste processing involved the design and construction of a new radioactive waste conditioning facility and near surface repository with the aim to create an integrated system for the management of waste generated at Slovak NPPs. Bituminization, incineration and vitrification facilities were constructed for the processing of the radioactive waste from A-1 NPP. The liquid waste evaporation facility was refurbished and new improved tanks for storing radioactive concentrates were constructed.

In 1993, Slovakia established its Nuclear Regulatory Authority (NRA), which is responsible for oversight of the decommissioning of A-1 NPP. The A-1 operator was required by NRA to prepare and submit for approval a plan for the entire decommissioning process. The conceptual plan for the A-1 decommissioning was issued in 1998, with several decommissioning options, including safe enclosure.

A detailed plan for the first decommissioning phase (1996–2007) was prepared and finalized by 1996. Its focus was on the main safety aspects common for all the decommissioning options. At that time, there was no legal basis for issuing a decommissioning licence. Therefore, some tasks were individually conducted under individual permits. An environmental impact assessment for the first phase of decommissioning was prepared and issued in 1994. Permission for implementing the first phase of decommissioning was issued in 1999, based on evaluation of the plan and the impact assessment, plus other documents required by the Atomic Act.

Planning under the decommissioning licence envisions preparation for major decontamination activities from 2016 to 2023. Activities conducted as part of the first decommissioning phase are ongoing in the following areas:

- Spent fuel management and transfer of remaining spent fuel to the Russian Federation (1996–1999);
- Waste management within the reactor hall;
- Improvement of spent fuel coolant safety features;
- Decontamination and/or dismantling of spent fuel pool inside structures;
- Dismantling part of the heavy water system;
- Conditioning and storage/disposal of the operational waste;
- Decontamination of contaminated facilities outside reactor building.

The following activities are planned for the second decommissioning phase:

- Decontamination and demolition of outer active equipment and objects as well as those in the A-1 main production building;
- Radioactive waste management;
- Contaminated soil management;
- Technical support and environmental protection.

### 7.4.5. Mayak (Kyshtym)

*Current Status: decommissioning and site remediation.* Between 1957 and 1959, over 10 000 t of agricultural products were deemed unfit for human consumption and destroyed. Over 6000 ha of agricultural land were subjected to deep ploughing decontamination, the surface layer of heavily contaminated soil being buried to a depth of over 50 cm, lower than the penetration depth of the roots of many crops. This served to reduce uptake via root systems. From 1958 to 1959, over 20 000 ha were ploughed to reduce uptake of contamination by plants and to decrease the exposure to gamma radiation. In the Chelyabinsk region, 59 000 ha of land were removed from agricultural use, as were 47 000 ha in the Sverdlovsk region. These areas are currently designated as national park areas with restricted access [40].

A range of methods to reduce the transfer of contamination to animals via feed crops were developed and implemented. These included the removal of contaminated soil layers, deep ploughing, the addition of fertilizers and ameliorants designed to reduce the uptake of contaminants, the use of crops which exhibit low uptake of strontium, and the addition of nutrient supplements, mainly calcium, to animal feeds to ensure low assimilation of contaminants in body tissues. The implementation of these methods served to reduce uptake in plant species by factors of 5–15.

# 8. WASTE MANAGEMENT

**KEY LESSONS LEARNED**

- While most post-accident waste types have been managed before, and most treatment methods have been used, the volumes, activity concentrations and radiation levels involved can present new challenges to those managing the cleanup.
- Contamination of reactor coolant with fission products, primarily by $^{137}Cs$ and spent fuel particles, will create high dose rates, prompting an urgent need for process systems and storage of treated water and purification media.
- Damaged nuclear fuel and fuel debris are unique types of waste unlikely to have readily available disposition pathways.
- Where there has been dispersal of fuel particles outside the site facilities, the resulting debris creates an urgent need to find and collect it.
- New facilities will be needed to house systems, store waste, and eventually prepare and package waste for transport to disposal facilities.

## 8.1. INTRODUCTION

This section primarily addresses on-site waste management with regard to types of waste, conditioning, storage and disposal based on experience from the accidents at TMI-2, Chernobyl and Fukushima Daiichi. Management of water and solid waste resulting from an accident was addressed in Ref. [3], which remains current; some information from that publication is repeated here by way of introduction.

While not within the main scope of this publication, it is recognised there can also be major off-site wide area waste management challenges, such as there have been at Chernobyl, Fukushima Daiichi and Mayak (Kyshtym). These are characterized by large volumes of radioactive waste and a wide variation of waste forms, such as soil, concrete, metals, plastic, wood and vegetation. While waste volumes are measured in thousands of cubic metres for normal decommissioning of nuclear power plants, for severe accidents affecting wide areas, the volumes of contaminated material may be significantly larger, in some case reaching tens of millions of cubic metres. Special waste management strategies are needed to address accident and cleanup waste owing to the very large volumes, range of activities and timeframes.

Beyond the experience to date for accident situations presented in various reports and in this section, there are other options for the conditioning of water and waste material. For example, with regard to volume reduction, the principles for waste management for normal operations will have to be revisited for accident cleanup. Volume reduction by means such as compaction and incineration must be assessed in the context of the waste forms and volumes. Because of complexity and facility needs for systems such as incineration or vitrification, these technologies are generally suited to dealing with large and continuous waste streams originating from several sources. In addition to volume, selection of technologies is based on waste properties and the projected timeline for waste arising. It should be borne in mind that waste management at an accident site can last for decades.

As the Fukushima Daiichi project progresses, because of the amount of waste, some of the above technologies may be feasible; only those managing the project can decide the best approach. For less severe situations, TMI-2 is an example in which several large volume processes were evaluated and most of them were decided against. For example, incineration was not cost effective compared with direct disposal, and grouting of ion exchange media was determined to be too complex compared with the option of high integrity containers.

## 8.2. CONDITIONING AND STORAGE OF ACCIDENT WATER

Section 7.1 of Ref. [3] addresses water management. Table 7 summarizes the challenges for post-accident water management.

TABLE 7. WATER MANAGEMENT CHALLENGES

| Need | Problem | Options |
|---|---|---|
| Gaining access to fuel and systems. | — Full tanks and sumps<br>— Flooded floors<br>— Contaminated systems | — In-plant systems<br>— Temporary tanks<br>— Containment sump<br>— Mobile ion exchange systems<br>— Filtration units |
| Establishing and maintaining working conditions for damaged fuel removal or repairs may first require water processing to lower area radiation levels | — Reduce area radiation fields from pipes and sumps<br>— Fission products may continue to be released<br>— Contamination in water | — All of the above plus low flow cleanup system for removing high concentrations of radioisotopes<br>— High flow cleanup system with filters and ion exchangers for removing low concentrations of radioisotopes |
| Storage of processed water | — May not be able to release to the environment, even if within allowed limits | — Use existing tanks and sumps<br>— Use storage tanks not normally used for radioactive water<br>— Build additional storage tanks |
| Release of excess water | — Greater quantities after processing than normally released<br>— Trace radionuclides different and greater than normal release<br>— New flow path may be needed | — Repeated processing<br>— Temporary revision to release limits<br>— Additional control and monitoring equipment |

### 8.2.1. Water management at TMI-2

Meeting these challenges at TMI-2 is well documented in Ref. [10]. The result of meeting these challenges at that site is best summarized by the timeline shown in Fig. 24. Within three years of the accident, the accumulated volume of water was about 4 000 m$^3$. Over the following seven years, this water was recycled via cleanup processing for shielding and cooling. This amount is the smallest encountered at the three accident sites discussed here.

### 8.2.2. Water management at Chernobyl

Approximately 20 000 m$^3$ of water have accumulated at the Chernobyl NPP. Sources of water inside the shelter are both natural and anthropogenic. It is estimated that the current total annual inflow is approximately 2400 m$^3$ from the following sources:

1. Atmospheric precipitations penetrating the object through cracks in the protective constructions represent approximately 50% of the total annual inflow.
2. Condensate formed during the summer due to temperature difference and the humidity content of atmospheric air and air within the bottom levels of the unit.
3. Regular operation of dust suppression systems from solutions sprayed into the space beneath the central hall roof.

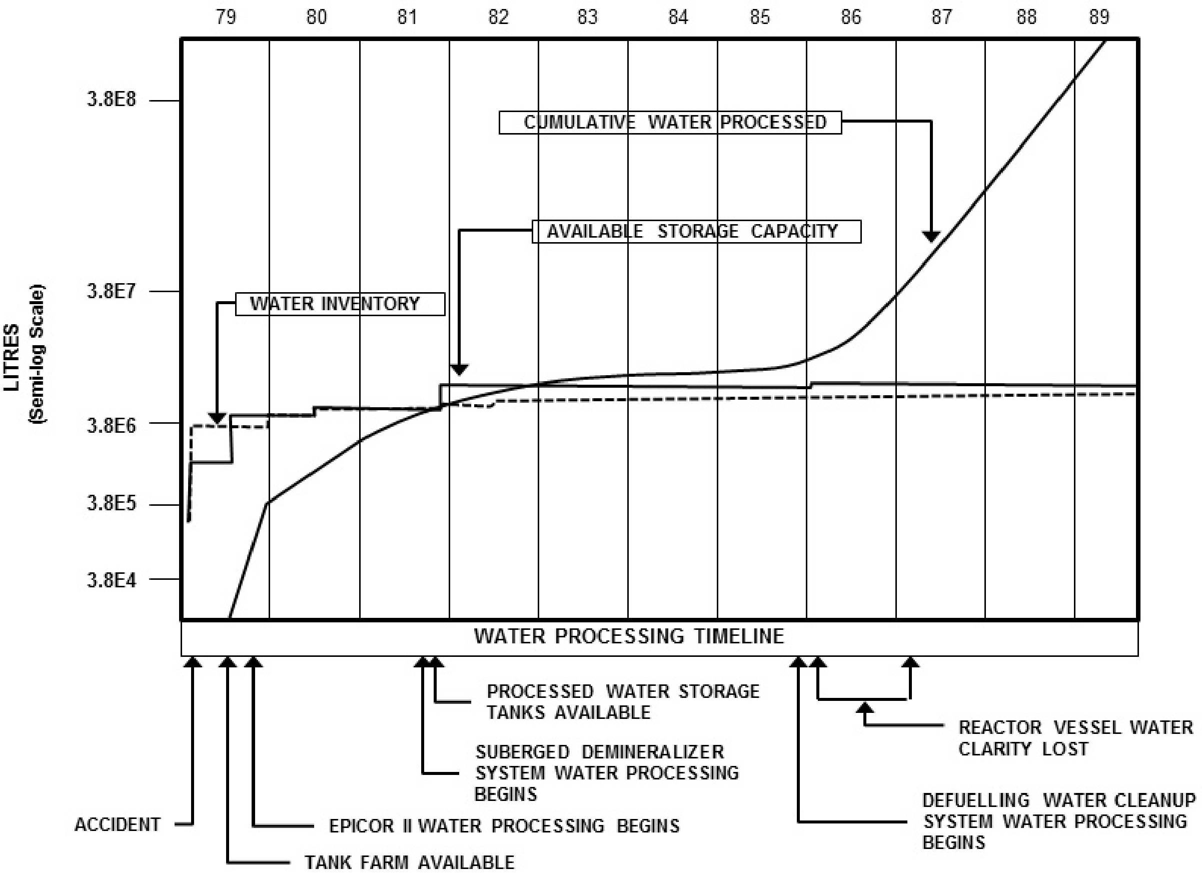

FIG. 24. TMI-2 water processing timeline.

### 8.2.3. Water management at Fukushima Daiichi

As described in Section 4.3, a 4 km loop of treatment and injection cooling system was built at the Fukushima Daiichi site to control the highly contaminated water level in the reactor and turbine buildings of Units 1–3. Since the influx of the groundwater is large, about 400 t per day, as of 2013, the accumulation of treated water excess has been causing a significant challenge. Many tanks for storage have been built to address this challenge — see Fig. 25 [41]. As of June 2013, the total volume of the water excess is over 300 000 t and still rapidly increasing. Further measures, such as building additional decontamination capabilities to make the water excess non-radioactive or bypassing groundwater inflow are under consideration to address this issue. Storage and treatment of the secondary wastes from the decontamination processes is also an important challenge.

Figures 25 and 26 [42] show the storage tank arrays at Fukushima Daiichi. Liquid waste challenges at Fukushima Daiichi include the following:

- Very large volumes of liquid (>100 000 $m^3$);
- Lack of adequate storage capacity;
- Normal waste processing facility is inundated and not available;
- Lack of storage capacities;
- Danger of overflow and leakage;
- High activity ~106 $Bq/cm^3$, totalling several million Ci;
- $^{134}Cs$ and $^{137}Cs$ are the major radio nuclides of concern (as they were at TMI-2);
- Liquids are mixed with sea water (high Na+ concentration);
- The presence of oil.

*FIG. 25. Above ground tanks for storage of fresh water and concentrated salt water. Photograph courtesy of the Tokyo Electric Power Company (TEPCO) [41].*

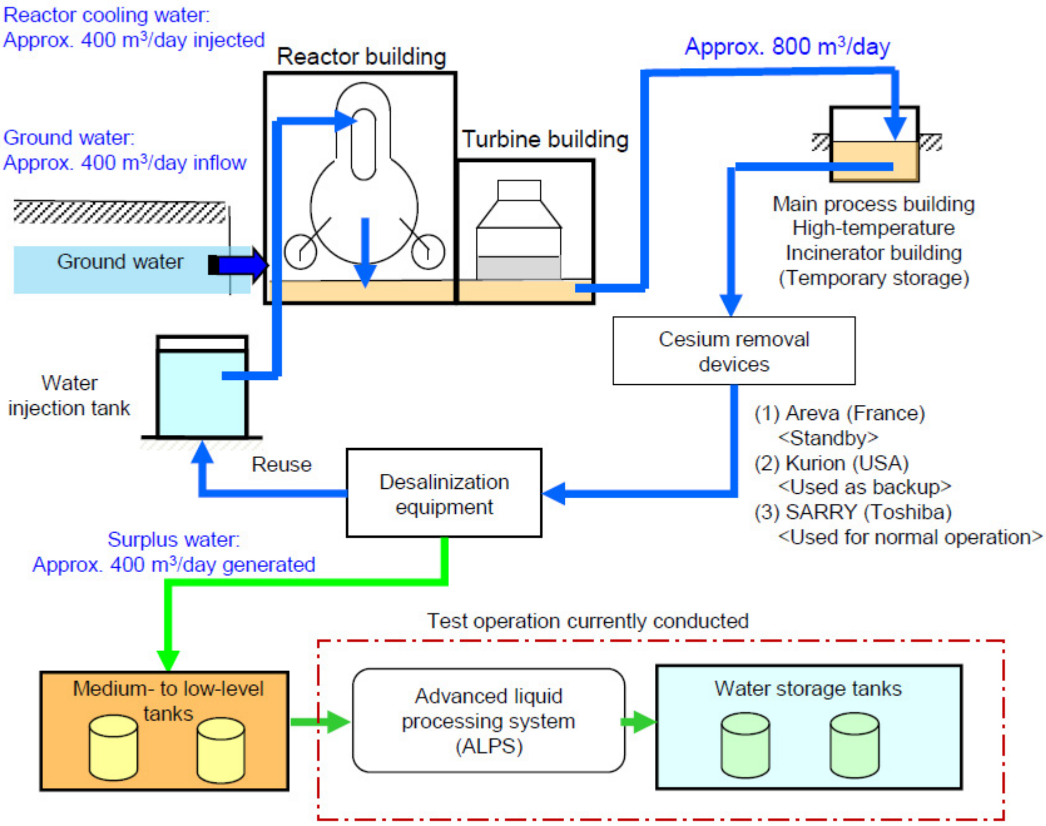

*FIG. 26. Layout of tanks and water capacity (November 2011). Image courtesy of the Tokyo Electric Power Company (TEPCO) [42].*

### 8.2.4. Waste management challenges and decisions

Waste management challenges depend on the scope and severity of an accident. They can vary from the collection and storage of small amounts of wastes in containers without special treatment to the creation of full scale conditioning systems for the capture and stabilization of radionuclides and damaged fuel. Choosing and/or creating a waste management system is dependent upon many factors, such as the amount of wastes, levels of contamination, physical and chemical properties, techniques and resources available, storage requirements and disposal criteria.

Table 8 summarizes the decision making process for several waste conditioning systems at TMI-2. Several processing systems that were rejected included a closed cycle evaporator, an incinerator and a resin grouting system — primarily for reasons of cost and complexity compared with the limited amount of waste that would be treated. The high dose rate characteristic of the accident waste was another significant consideration.

TABLE 8. TMI-2 EXPERIENCE FOR PROCESS SYSTEMS AND FACILITIES

| Consideration | Result | Notes |
|---|---|---|
| Process water demineralization systems | Three systems:<br>— accident water zeolite<br>— accident water organic resin<br>— defuelling water resin and filtration | Studied and rejected centrifuges and hydrocylones |
| Closed cycle process water evaporator | Rejected | High cost, at least 18 months to commission, too complex requiring maintenance and personnel exposure |
| Process water storage tanks | Built two tanks,<br>1 900 000 L each | Augmented other tanks, spent fuel pools and other water storage locations |
| Open cycle evaporator | Small, low temperature evaporator with system to solidify the residue | Needed because political considerations prevented discharge of water that was well within discharge criteria. |

## 8.3. SOLID WASTE MANAGEMENT EXAMPLES

As shown in Fig. 27, management of solid wastes takes place throughout stabilization and cleanup. Furthermore, finding an ultimate disposal location for waste forms that are not encountered during normal operations may require special efforts. As a result, they may remain on-site beyond the completion of cleanup activities, as illustrated.

Section 10 of IAEA TECDOC No. 935 [3] addresses solid waste management. Table 9 repeats the lists of materials introduced in that section; additional types have been added that reflect the Chernobyl and Fukushima Daiichi challenges.

At the beginning of 2013, the amount of solid radioactive waste estimated to have been accumulated at Chernobyl was 2.8 million $m^3$, of which 400 000 $m^3$ were located in the shelter and 1.74 million $m^3$ on the site [43]. The Chernobyl waste represents approximately 90% of the total incidence of radioactive waste in Ukraine.

The quantity of fuel containing nuclear materials present as solids at Chernobyl is approximately 185 t. As of October 2012, it has been estimated that about 95% of fuel that was in the reactor at the time of the accident remains. It is further estimated that its total activity is about 16 million Ci (about 600 000 TBq). The irradiated nuclear fuel inside the shelter is in the form of core fragments, lava-like FCMs, finely dispersed fuel (dust), small fuel particles and secondary uranium minerals generated from FCM solutions as new types of crystal formations.

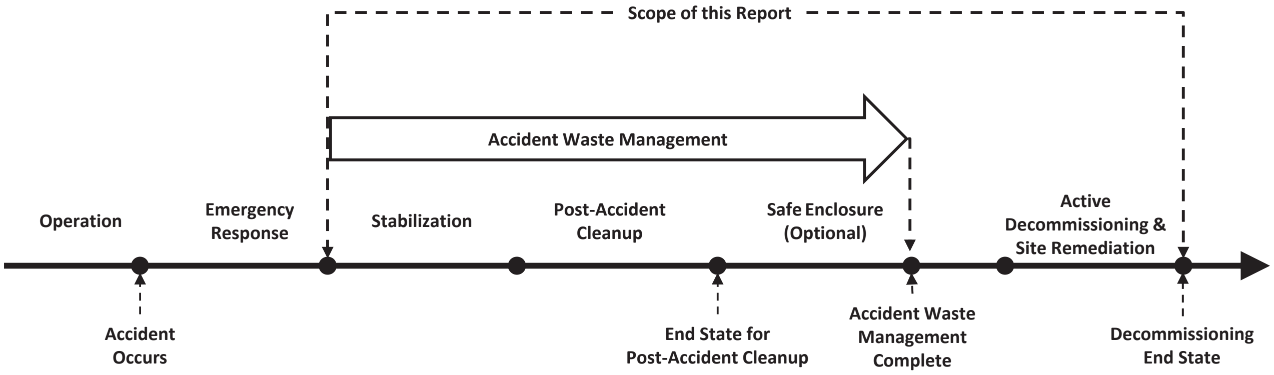

*FIG. 27. Focus of solid waste management.*

TABLE 9. SOLID WASTE MANAGEMENT EXAMPLES

| Waste type and origin | Physical form | Chemical properties | Waste type |
|---|---|---|---|
| Core components that are primarily accident wastes (excluding fuel) | Dry solids; non-compactable | Metal | Metal neutron activated components; high levels of radioactivity; possibly contaminated with fuel and transuranics. |
| Special tools for handling damaged fuel during removal | Dry solids; non-compactable | Metal | Surface contamination. Intermediate level wastes; possibly contaminated with fuel and transuranics. |
| Spent ion exchange material and evaporation concentrates from water processing | Wet solids | Organic and inorganic beads, particles, sludges. Chemistry can include ion exchange groups, dissolved minerals and salts, and inactive solids. | Intermediate and high activity contaminated with fission products. Presence of transuranic nuclides may be substantial. Possibility of combustible gas generation from radiolysis; corrosive; presence of chelating agents. |
| Slurries and sludge from water processing and decontamination | Wet solids | Chemical compounds with various properties | Intermediate level wastes; possibly contaminated with transuranics. |
| Spent filters from water processing | Wet or dry solids | Charcoal, metal, fabric, or paper media | Intermediate level wastes; possibly contaminated with transuranics. |
| Spent protective clothing, cleaning materials from cleanup and fuel removal activities | Dry solids; combustible, compactable | Various plastics, textiles, rags, paper, PVC, etc. | Large volumes of low level waste possibly contaminated with transuranics. |
| Spent filters from ventilation systems operating during the accident | Dry solids; combustible, compactable | Charcoal, wooden or metal frames, paper | Intermediate level wastes possibly contaminated with fuel and transuranics |
| Rubble from surface removal | Dry solids; non-combustible, somewhat compactable | Spalled and scoured concrete | Low activity wastes |
| Reagents from decontamination processes | Concentrated liquids | May contain variety of organic and inorganic chemicals such as citric acid, permanganate, nitric acid | High activity waste |

TABLE 9. SOLID WASTE MANAGEMENT EXAMPLES (cont.)

| Waste type and origin | Physical form | Chemical properties | Waste type |
|---|---|---|---|
| Building structure and rubble | Steel, wood and building materials | Metal and organic, various paper, plastic and other composite materials | Low activity wastes |
| Trees | Wood and leaves | Organic matter and inorganic typical of ash residue | Low activity wastes |
| Soil | Soil | Organic matter and inorganic minerals | Low activity wastes |

The following is a summary of solids at Fukushima Daiichi in 2011:

- Small volume, high activity solids; concentrates from processing of contaminated water and filtration of contaminated gases;
- Large volumes of relatively low contamination solids, such as soil, wood, etc.;
- Structural debris;
- 700 freight containers full of debris collected;
- ~2000 t of spent nuclear fuel on-site, including in damaged reactors and storage pools.

Figures 28 [44] and 29 indicate the magnitude of solid waste that must be managed at the Fukushima Daiichi site.

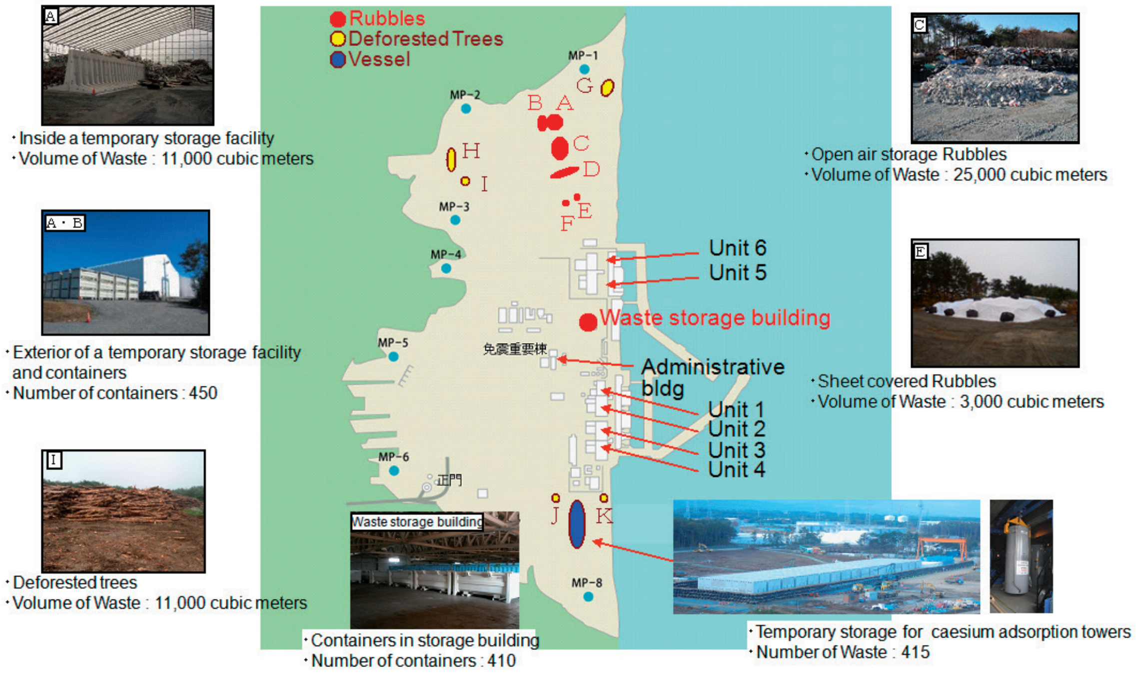

*FIG. 28. Layout and volume of waste at Fukushima Daiichi, May 2012. Images courtesy of the Tokyo Electric Power Company (TEPCO) [44].*

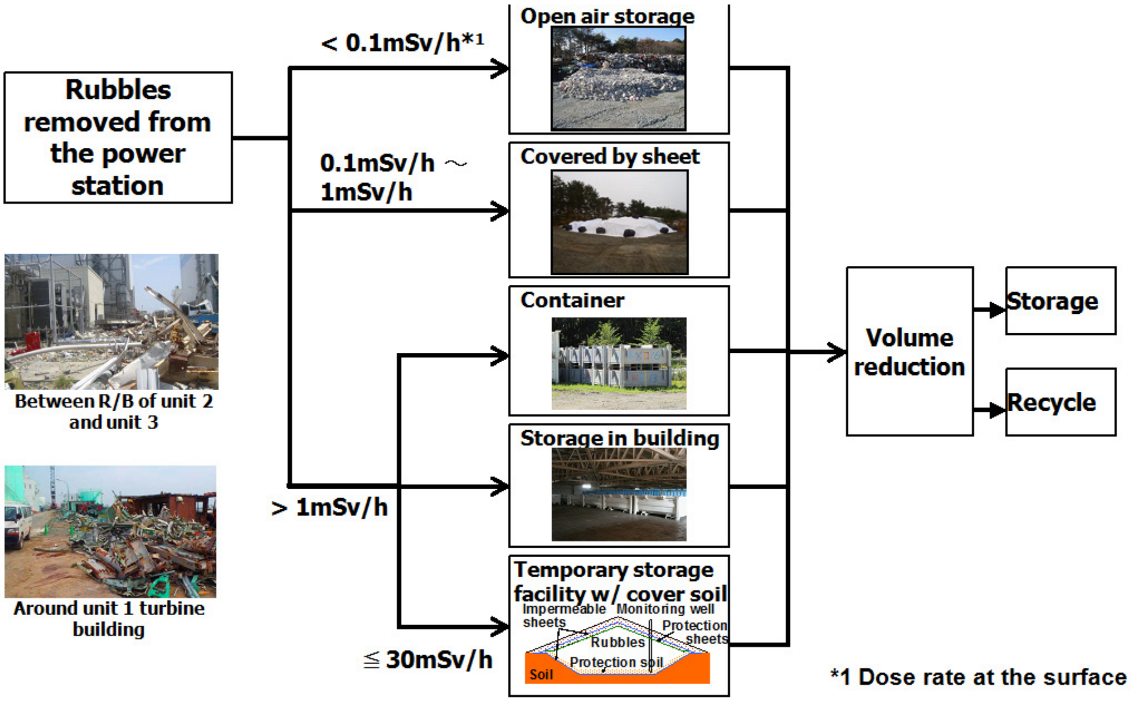

*FIG. 29. Flow of rubble removed from the power station at Fukushima Daiichi, May 2012.*

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# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ALARA | as low as reasonably achievable |
| CCTV | closed circuit television |
| FAZ | fire affected zone |
| FCM | fuel containing material |
| GPS | geospatial positioning system |
| INES | International Nuclear Event Scale |
| ISFSI | Independent Spent Fuel Storage Installation |
| NSC | NSC (Chernobyl) |
| PCV | primary containment vessel |
| RPV | reactor pressure vessel |
| SSC | structures, systems and components |
| TMI-2 | Three Mile Island reactor 2 |

# Annex

# CHARACTERIZATION

This Annex describes a number of advanced technologies that have potential use for post-accident characterization. It should be understood that the mention of a particular vendor or supplier does not constitute a specific recommendation or endorsement.

## A–1. AIRBORNE MEASUREMENTS

Remote gamma sensing from aircraft has been an effective way of rapidly locating, monitoring and mapping gamma activity on the ground. Helicopters or aeroplanes can be used as platforms for sensitive NaI or germanium detectors to measure total gamma count rate or gamma spectra. Recently, unmanned flying platforms that are remote controlled and can be equipped with lighter measurement devices has become available. Figure A–1 shows the loading bay of a German helicopter routinely used for airborne gamma spectrometry and dose rate measurements.

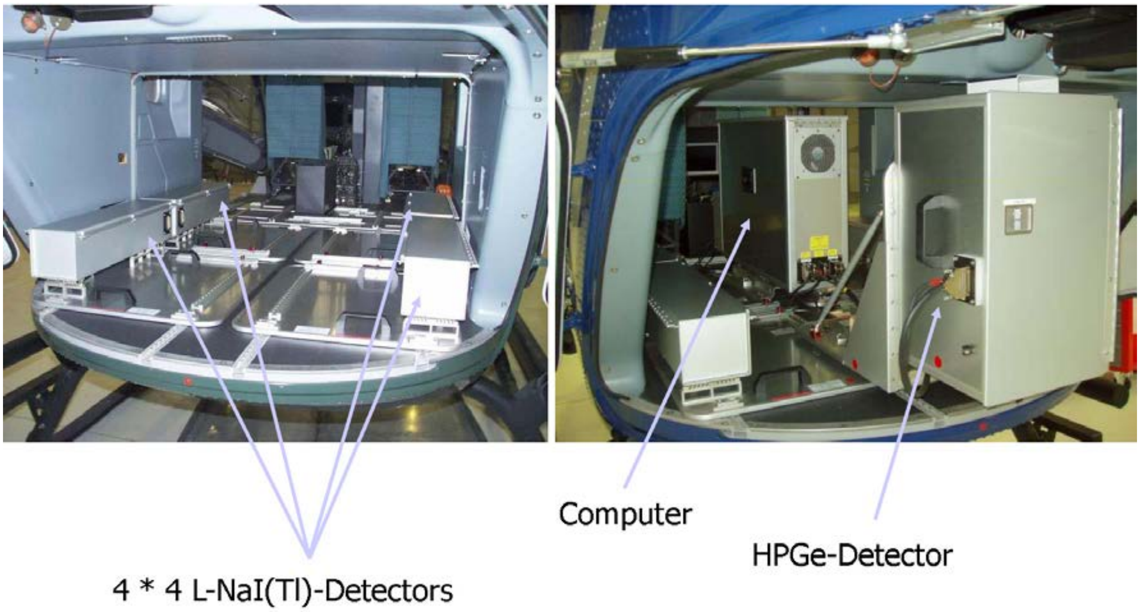

*FIG. A–1. Equipment on a helicopter used for airborne gamma spectrometry and dose rate measurements.*

The results of such measurements can be plotted on an aerial map of the area showing the distribution of dose rates or of the certain radionuclides if spectrometric measurements are evaluated. Figure A–2 shows a sample map with colour-coded dose rate contours.

## A–2. VEHICLE BASED MEASUREMENTS

Similar measurement equipment can be attached to manned and remote-controlled vehicles to be moved across the site or — to a limited extent — inside buildings. Figure A–3 shows a vehicle equipped with a gamma detector.

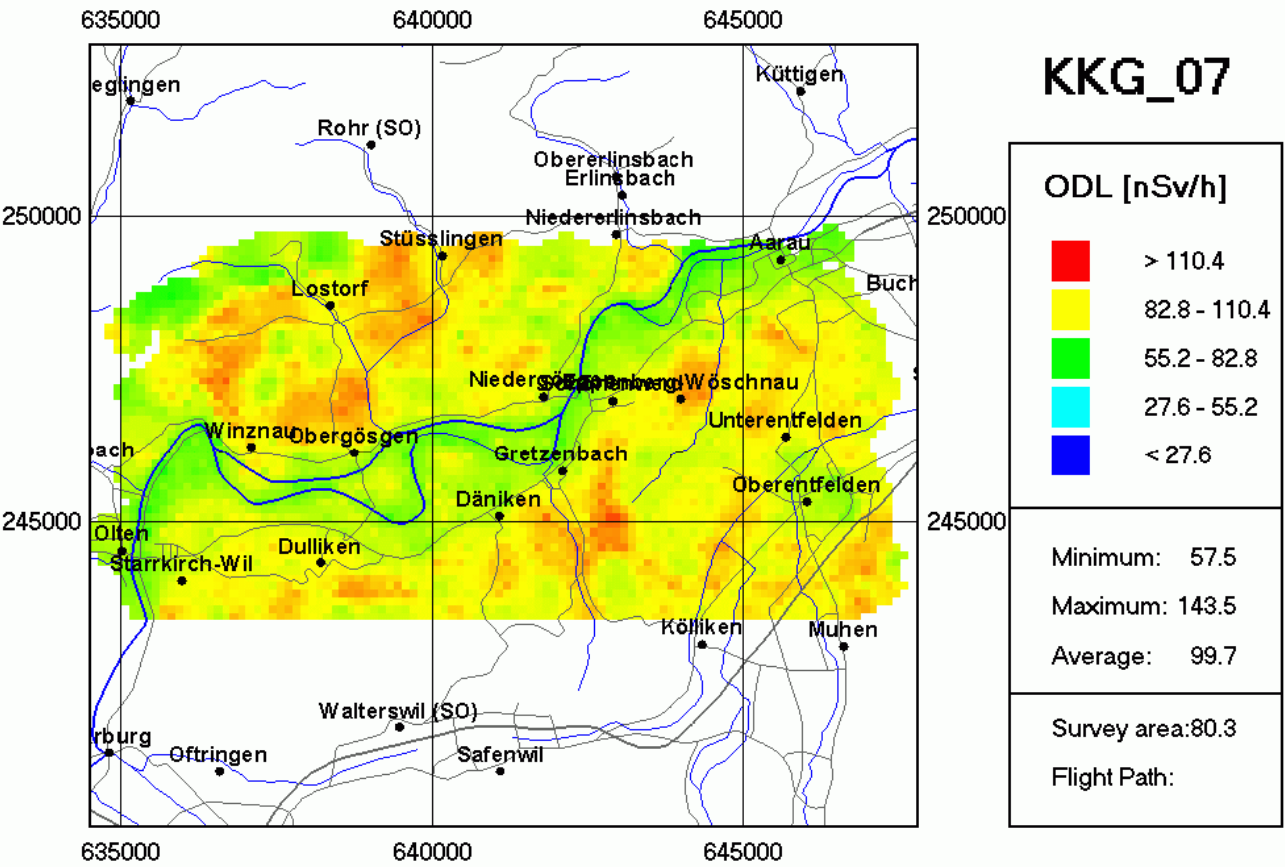

*FIG. A–2. Example of the plotting of airborne gamma spectrometry and airborne dose measurements.*

*FIG. A–3. A vehicle equipped with a gamma detector.*

## A–3. NUCLEAR EMERGENCY RESPONSE TEAMS USING SIMILAR EQUIPMENT

The measurement techniques presented above are in use by various nuclear emergency response teams, and the relevant equipment kept operable for emergency situations. Various organizations have vehicles ranging from large radio-controlled excavators to small radio-controlled inspection devices. The latter are very compact, making them useful for reconnaissance, inspection and for performing measurements in very confined locations within a nuclear facility. The large and heavy manipulator vehicles can be operated in contaminated areas, both inside and outside of buildings, for inspection and measurement, clearing and recovery, and for decontamination, and assembly. Figure 4 shows an overview of the vehicles of the Kerntechnische Hilfsdienst and of a small vehicle capable of making radiological measurements inside pipes with diameters of 150 mm and above.

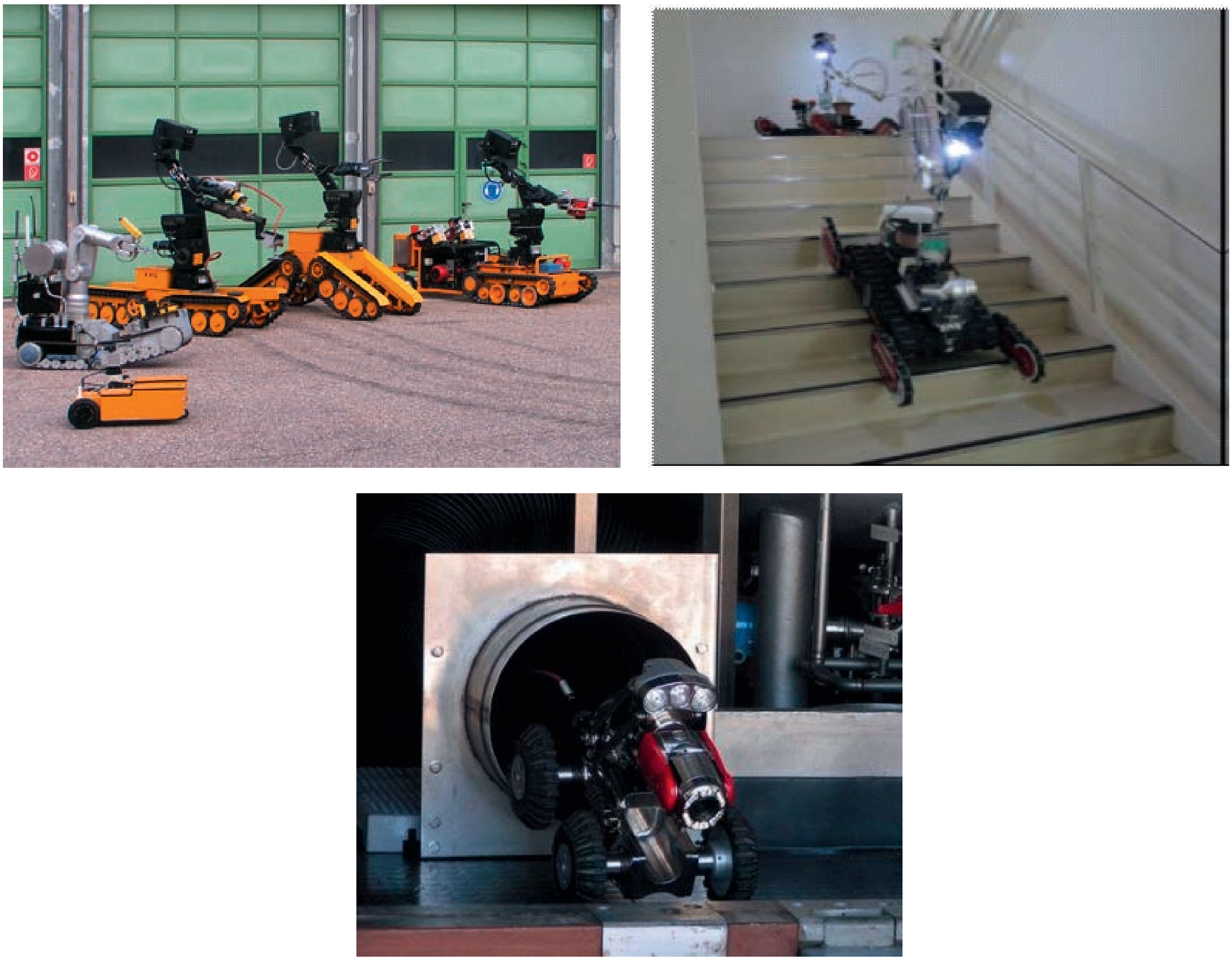

*FIG. A–4. Remote-controlled vehicles.*

The vehicles above have been designed for a broad range of applications. Other such vehicles are designed for a single purpose, such as the Pioneer remote reconnaissance system configured for structural analysis of the Chernobyl Unit 4 reactor building. This remote operated mobile robot is for deploying sensors and sampling payloads. In Fig. A–5, the system is shown during cold tests outside the Chernobyl NPP before its deployment inside the plant. Its major components include:

- A mapping system for creating photorealistic 3-D models of the building interior,
- A core borer for cutting and retrieving samples of structural materials,
- A suite of radiation and other environmental sensors.

*FIG. A–5. The Pioneer remote reconnaissance system.*

## A–4. RADIATION SCANNING

A technology that combines a highly collimated NaI detector and a conventional camera provides a fast overview of the gamma component of contamination on areas inside and outside nuclear facilities. It can measure gamma dose rates and gamma spectra from large distances. Areas are scanned with an automated pan and tilt unit on which the detector is mounted. Images of the measured gamma dose rate distribution are overlaid on a conventional optical image, showing the distribution of dose rates; by using selected gamma energy spectra channels, the activity of specific radionuclides can be imaged. The resolution of the gamma measurements is mainly determined by the steps in both angular motions, while the minimum detectable activity depends on the measurement time in each position.

Figure A–6 show the RadScan 800 device on the left and images of $^{137}$Cs contamination in a nuclear facility on the right.

*FIG. A–6. The RadScan 800 device (left) and images of $^{137}$Cs contamination in a nuclear facility (right).*

Recent developments in radiation scanners have seen the deployment of smaller and more versatile scanners. Some smaller units based on pinhole (Canberra Cartogam) or coded aperture principles (DynasilRadCam) are available, and these are generally more suitable for remote deployment, including on remote-controlled vehicles. However, they can have drawbacks, such as limited field of view, sensitivity to out-of-images sources and lack of spectrometry.

For challenging applications, a recently developed system, the N-Visage scanner (first figure below), combines the flexibility and robustness of a mechanically scanned system with the low weight and small (110 mm operational distance) cylindrical format of the pinhole/coded aperture systems and a high dose tolerance of up to 1 Sv/hr. This system can be deployed on a remote-controlled vehicle or on a passive deployment system such as poles and beams. The output is a spherical image (Fig. A–8) of the dose environment that can be used to calculate the dose at the scanner due to any of the visible sources. This is contrasted with a conventional image, shown in Fig. A–9. The system also produces a spherical optical image and (optionally) a full 3-D laser scan of the environment, providing a comprehensive characterization in a single sweep.

*FIG. A–7. The N-Visage scanner (cylindrical component) mounted on a deployment tool. OD is 110 mm.*

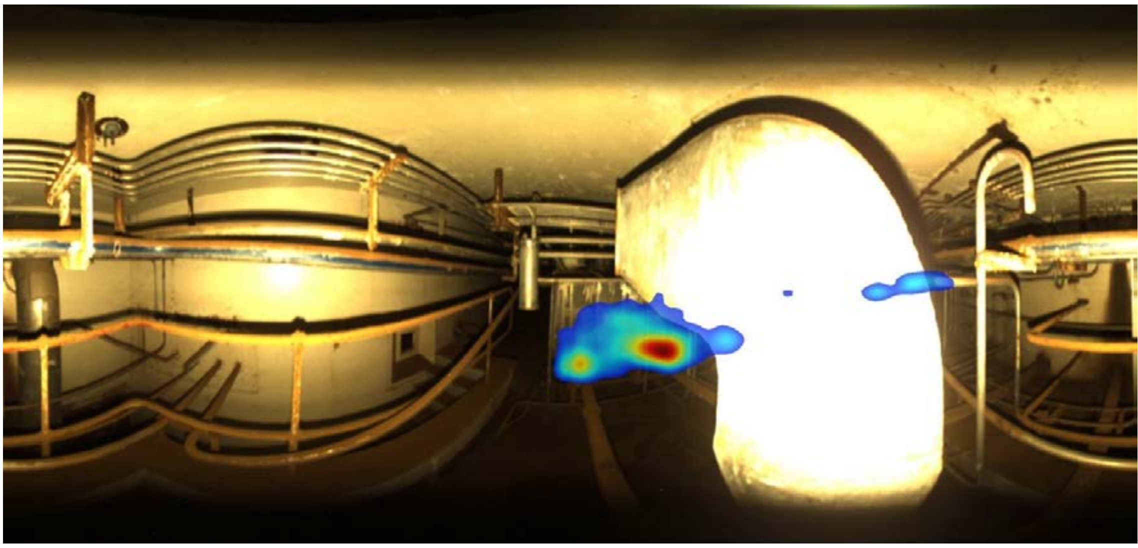

*FIG. A–8. A spherical optical image with gamma overlay rendered as a 360 degree panorama.*

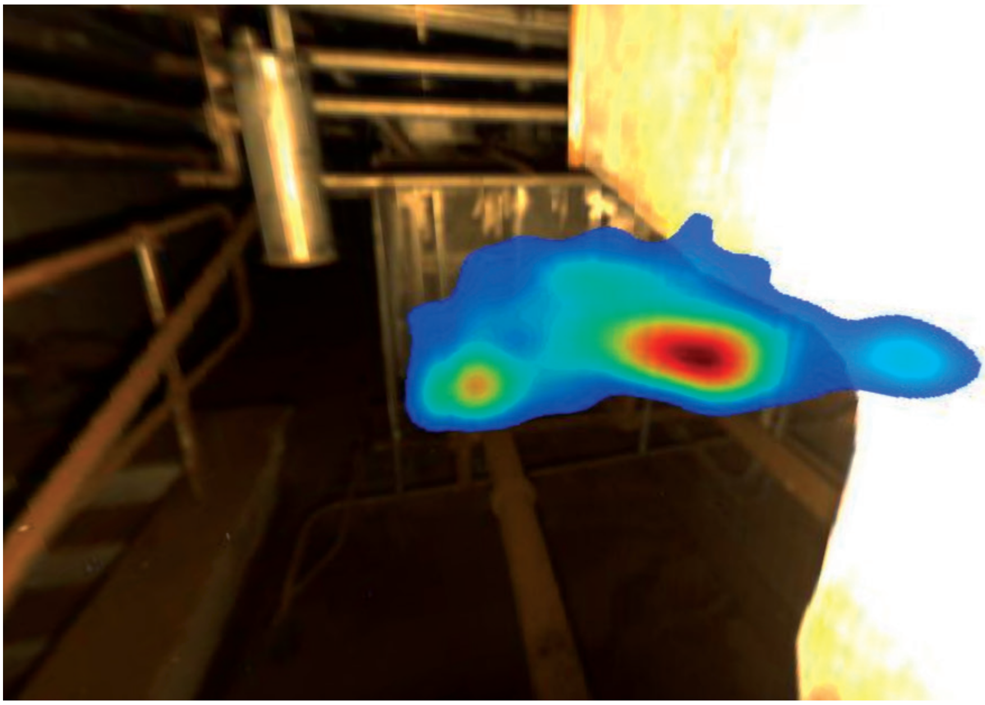

*FIG. A–9. A conventional view of Fig. 1–8.*

## A–5. INVERSE RADIATION MODELLING

The techniques described above are limited by knowledge of the radiation environment. In complex environments with multiple source terms, this knowledge can be gained using inverse radiation modelling tools. Inverse modelling is the process of calculating the distribution of radiation source material from the observed radiation field. Taken to its ultimate limit, inverse radiation modelling can produce image-like 3-D maps of radioactive materials. While some modelling packages provide a basic capability, dedicated packages such as N-Visage Source Mapping enable source distributions of arbitrary complexity to be calculated from a finite number of dosimeter or spectrometer readings, as shown in Fig. A–10.

The technique can be used to extract additional information from existing radiometric data or as an alternative to radiation scanning for characterizing complex environments. Once the source distribution has been calculated, simulations can be performed to estimate the dose benefit of planned interventions.

## A–6. TECHNIQUES FOR RAPID GEOMETRY ACQUISITION

Three dimensional laser images of structures, equipment and piping are routinely available. Using modelling software, scaling and material take-offs can be generated to support planning for area access and for waste management. It is noted that radiation fields may limit the use of this equipment without modification for radiological hardening. Illustrations of this technology are shown in Fig. A–11.

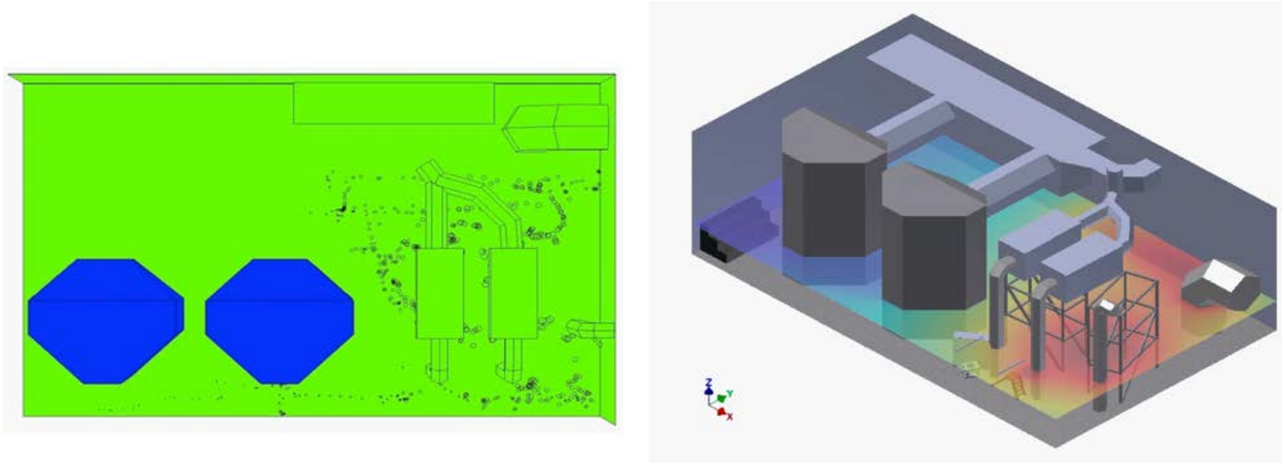

FIG. A–10. Raw survey data (left) and N-Visage model showing an estimated waist height dose plane (right). Data was recorded using the Eberline LARADS system.

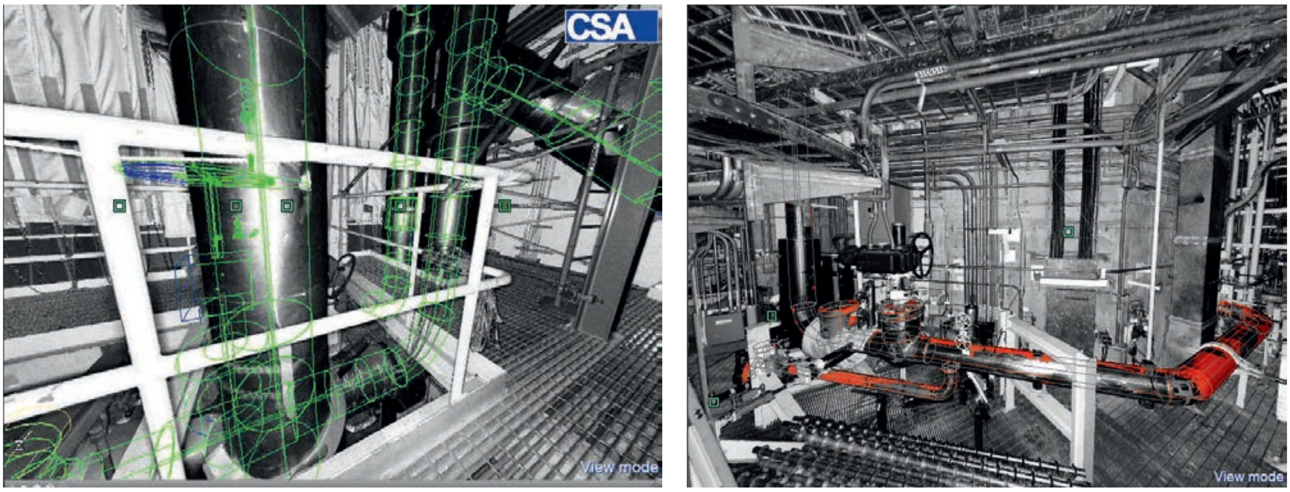

FIG. A–11. Technology for rapid geometry acquisition.

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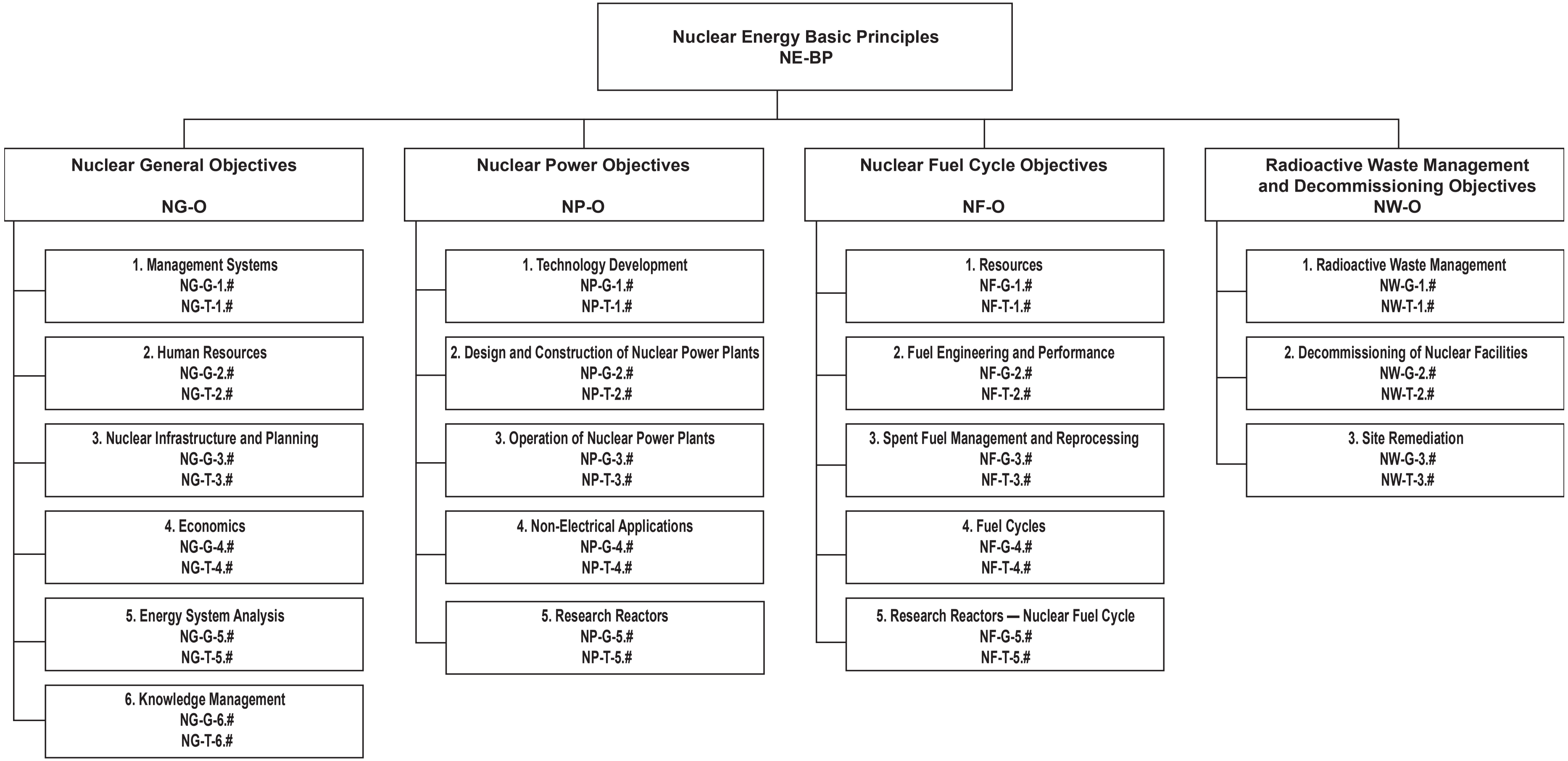

*Key*

| | |
|---|---|
| **BP:** | Basic Principles |
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| **G:** | Guides |
| **T:** | Technical Reports |
| **Nos 1-6:** | Topic designations |
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*Examples*

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