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Global Status of Decommissioning of Nuclear Installations

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GLOBAL STATUS OF DECOMMISSIONING OF NUCLEAR INSTALLATIONS

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IAEA NUCLEAR ENERGY SERIES NW-T-2.16

GLOBAL STATUS OF DECOMMISSIONING OF NUCLEAR INSTALLATIONS

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2023

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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the IAEA is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

The Global Status of Decommissioning project was launched in August 2019 and involved collecting and analysing authoritative information on the current status and future evolution of nuclear decommissioning activities around the world. Such information is currently not generally available and therefore this publication addresses this knowledge gap.

The project was coordinated by a steering group comprising experts from a range of IAEA Member States: M. Guy (United Kingdom, Chair), S. Carroll, (Sweden), B. Rehs (Germany), P. Imielski (Germany), J. McCafferty (Canada), T. Kukan (Slovakia), H. Hänggi (Switzerland), T. Rakitskaya (Russian Federation) and R. Quintiliani (Italy). The involvement of and support received from M. Brandauer (OECD Nuclear Energy Agency) and J.-P. Guisset (European Commission) are also gratefully acknowledged.

The IAEA officers responsible for this publication were P.J. O'Sullivan and T. Kilochytska of the Division of Nuclear Fuel Cycle and Waste Technology.

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SUMMARY

This publication presents the outcomes of a project that aimed to analyse the status of nuclear decommissioning activity around the world, as of 2020, and its future evolution. The information presented is based on responses to a questionnaire distributed to organizations with responsibility for planning, implementation and oversight of decommissioning programmes. Baseline information on the numbers and current operational status of nuclear facilities was extracted from the various online nuclear facilities databases maintained by the IAEA. Analysis of the collected data was undertaken at global and regional levels, rather than at the level of individual Member States or sites. Given the unavoidable limitations introduced by such an extensive data collection exercise, this publication is a ‘first of a kind’ and has a pilot nature, with the intention being to develop further editions in due course, taking benefit of the experience gained from the project.

Many of the issues that have led to the shutdown of nuclear facilities over the past decade — political and economic factors, maintenance and/or refurbishment costs and electricity market conditions — may be expected to continue to apply in the future, and indeed it is likely that the rate of shutdowns will accelerate over the next one to two decades due to the age profile of the nuclear power reactors and other facilities currently in operation. This is particularly the case for nuclear power reactors, as a significant proportion of these have been in operation for more than 40 years. Nonetheless, it should also be noted that there is no simple relationship between the age of a facility and the timing of permanent closure, with multiple factors influencing decisions on when a particular facility may be permanently shut down.

Considering all main types of nuclear facility, it is evident that decommissioning activities are likely to continue for the remainder of this century and even beyond. The questionnaire responses suggest that, despite the substantial amount of decommissioning undertaken over the past two to three decades, decommissioning funding and workforce needs will increase significantly in the future.

Subject to the availability of appropriate waste management infrastructure and funding, the responses indicate that immediate dismantling is the preferred decommissioning strategy for all main facility types. Even in the case of graphite moderated reactors, for which deferred dismantling was historically often the selected strategy, the study findings suggest that immediate dismantling approaches are increasingly being selected. National policy, often linked to sustainability considerations, is an important driver for all facility types, together with an increasing tendency among plant owners to seek to discharge liabilities sooner rather than later.

The analysis of factors impacting on project delivery showed regional differences but again generally emphasized the importance of the availability of waste and spent fuel management systems, funding and access to appropriate technology. The latter issue received greatest emphasis in the more advanced programmes, suggesting a perceived need to take greater advantage of technological developments. Licensing and regulatory issues were noted as important considerations for fuel cycle facility decommissioning programmes in particular.

The study respondents indicated a number of technical challenges for which it was anticipated that further technological developments will be required, such as for the dismantling of large components and concrete structures present in graphite moderated reactors, and for improved characterization techniques in poorly accessible locations. Accordingly, despite the technical maturity of current routine decommissioning activities, respondents envisaged that ongoing research and development work will lead to improved levels of safety and of efficiency of implementation.

1. INTRODUCTION

1.1. BACKGROUND

‘Decommissioning’ is the term generally used in the nuclear industry to delineate the final stage in the lifetime of an authorized nuclear facility, the preceding stages being ‘siting’, ‘design’, ‘construction’, ‘commissioning’ and ‘operation’. It is defined in the following terms in the IAEA Safety Standards Series, Decommissioning of Facilities, No. GSR Part 6 [1]:

> “The term ‘decommissioning’ refers to the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (except for the part of a disposal facility in which the radioactive waste is emplaced, for which the term ‘closure’ instead of ‘decommissioning’ is used). Aspects of decommissioning have to be considered throughout the other five major stages.”

In accordance with this definition, decommissioning is a planned activity, undertaken in accordance with strict radiological safety criteria appropriate to such activities [2], to ensure the safety of the workforce and the public, as well as of the surrounding environment.

Decommissioning activities have been ongoing for several decades in the nuclear industry and, as of the end of 2020, substantial experience has already been gained in several countries, particularly those with long running nuclear power or nuclear fuel cycle programmes. Given that many such programmes have typically been in existence for more than half a century, an increasing number of nuclear facilities are reaching the end of their useful lives and are being withdrawn from service. It is therefore inevitable that the number of facilities requiring decommissioning will increase substantially in the coming decades.

In 2019 IAEA launched an international collaborative project to collect relevant data and analyse the current global status and future prospects for decommissioning of nuclear facilities (Technical Meeting, 26–30 August 2019, Vienna International Centre), following which the terms of reference for the project were finalized by a steering group comprising representatives from IAEA Member States with significant decommissioning programmes. The terms of reference were issued to Member States in February 2020, together with details of an online questionnaire to collect data on decommissioning plans.

The collected national level information is not being published, but is being used to inform a global and regional level analysis of current practice in decommissioning and future plans, as presented in this publication. The baseline information required for this analysis — for example, regarding the age and current operational status of facilities — was obtained from the IAEA’s online databases for nuclear facility information, such as the Power Reactor Information System (PRIS), the Research Reactor Database (RRDB)[1] and the Integrated Nuclear Fuel Cycle Information System (iNFCIS). A summary description of these databases is provided in Appendix I.

The data collection exercise, based around the online questionnaire, began in February 2020 and continued throughout that year. The questionnaire focused on individual nuclear sites and requested up to date information on current activities and future plans relating to facility decommissioning. The data request was issued to the organizations best placed to provide this information, with this typically being the facility owner, except in limited cases where a specialist decommissioning entity has this responsibility.

The requested information included decommissioning plan dates for individual facilities, together with envisaged personnel and funding requirements. Information was requested on the factors impacting on the selection of decommissioning strategies and on the implementation of those strategies. The questionnaire also sought information on the technologies being used to implement

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[1] A list of the abbreviations used in the text is given at the end of the publication.

decommissioning, including perceived needs for further technological development, whether to enhance the implementation of ongoing decommissioning programmes or to address needs specific to future programmes. The questionnaire results were stored on a Microsoft Excel spreadsheet to facilitate data processing and analysis.

Information of this type is required by persons with policy responsibilities for decommissioning and associated waste management activities, including government officials, managers of nuclear facility operating organizations, regulators, and managers of waste management organizations and industrial organizations offering decommissioning and waste management services. The information is also useful to the general public, the media and environmental advocacy groups.

1.2. OBJECTIVE

This publication documents the outcomes of the Global Status of Decommissioning project, the goal of which was the collection and analysis of authoritative information on the current status and likely future evolution of nuclear decommissioning activities around the world. Such information is currently not generally available and therefore the publication addresses a current knowledge gap.

The project considered decommissioning strategies, time frames and milestones; the status of programmes, including important drivers or restraints on implementation; and strategic issues, including resource needs, in terms of human resources and technological developments necessary for effective implementation of future programmes. The project aimed to provide benefits in a number of key areas:

(a) Supporting benchmarking, planning and decision making;
(b) Facilitating collaboration to address similar challenges and opportunities;
(c) Making data available to support further analysis.

This publication aims to provide a comprehensive global overview of the status of decommissioning of nuclear facilities, based on relevant data collected from Member States. It aims to provide information at global and regional levels, rather than nationally. Given the unavoidable limitations introduced by the such an extensive data collection exercise, the report is a first of a kind and has a pilot nature. The IAEA Secretariat intends to develop further editions of this publication, taking benefit of the experience gained from the current project, at a frequency still to be decided.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3. SCOPE

This publication presents information on decommissioning activities involving the following installations:

(a) Nuclear power plant (NPP) reactors;
(b) Research reactors (RRs);
(c) Fuel cycle facilities (FCFs), including fuel fabrication, enrichment and reprocessing facilities, and waste treatment and storage facilities.

Waste disposal facilities and small facilities involving practices relevant to the use of radioactive substances, including medical, industrial and research facilities, are excluded from this publication. Facilities associated with the mining and milling of uranium ores are also excluded.

1.4. STRUCTURE

This publication has the following structure. Section 1 is the introduction, while Section 2 provides a brief global overview of the nuclear facilities included in this project and baseline information from the IAEA's online databases for nuclear facility information — PRIS, RRDB and iNFCIS. In doing so it presents a summary of the numbers of different types of facilities, their distribution and their current status. It also compares the number of facilities in questionnaire responses with the number of installations listed in the relevant IAEA database.

Section 3 describes the policy and institutional arrangements and the legal and regulatory frameworks for decommissioning. It provides a summary analysis of currently existing frameworks in different Member States and regions, considering policies, strategies, institutions, implementing organizations, legal frameworks, allocation of roles and responsibilities, and financing arrangements.

Section 4 provides an overview and analysis of current decommissioning strategies and associated timelines for the implementation of programmes (including for different phases of decommissioning), drivers for strategy selection and current major trends in strategy definition for decommissioning programmes, based on questionnaire responses.

Section 5 discusses the main factors impacting on the implementation of decommissioning programmes, based on questionnaire responses. An analysis of strengths, weaknesses, opportunities and threats (SWOT) of current decommissioning programmes is also presented. This section further includes a discussion of major current trends in programme implementation.

Section 6 provides a review of resources that have been used and will be needed to deliver decommissioning projects and programmes, based on questionnaire responses obtained in this project. Specifically, it reviews the information provided in questionnaire responses on the size of the workforce, for both past activities and those planned in the future, together with the costs incurred to date, as well as estimates of liabilities for future work.

Section 7 presents an analysis of the technologies needed to deliver decommissioning projects, primarily based on questionnaire responses. The technologies addressed are characterization, decontamination, segmentation and dismantling, cleanup and environmental monitoring, and material and waste management.

Section 8 presents the overall conclusions of the project.

This publication includes four appendices that provide additional information on the IAEA databases used in this project, examples of national and facility specific decommissioning strategies, and a tabulation of national financing schemes and funding mechanisms for spent fuel, radioactive waste and decommissioning.

2. THE CONTEXT FOR DECOMMISSIONING AND BASELINE INFORMATION

2.1. DECOMMISSIONING OF NUCLEAR INSTALLATIONS

While nuclear facility decommissioning is the focus of this present report, it is worth noting that management of assets at the end of the operating life is a growing challenge across all energy sectors. Recent research confirms that policies have largely focused on the planning, design and building of energy production infrastructure rather than on its decommissioning [3]. Consequently, a significant quantity of ageing energy production infrastructure will need to be decommissioned, while policies, experience and capabilities are limited within the sector to perform this effectively and efficiently [4]. The World Energy Council has highlighted a growing need to ensure that operators meet their responsibilities to manage decommissioning effectively, and that this requires awareness of the associated challenges, careful planning, strategic decision making, coordination between industry and regulators and early action [5].

Nuclear facilities, similar to all industrial facilities, have a finite operating lifetime. Even if operation is extended through careful maintenance, refurbishment and modernization, at some point it becomes impractical or not desirable to continue to operate the facility. After permanent shutdown and withdrawal of a nuclear facility from service, it will need to be decommissioned and any radioactive waste and other hazardous materials managed safely.

There are many different types of nuclear facilities and the specific decommissioning activities to be undertaken will vary accordingly. Nonetheless, there are common elements and nuclear decommissioning typically involves activities such as removal of nuclear materials, emptying of systems and process tanks, dismantling of plant and equipment, decontamination of structures and components, demolition of buildings and cleanup of contaminated ground, and ultimately release of the site and any remaining uncontaminated structures. Increasing consideration is being given to exploring the potential reuse of components and the recycling of uncontaminated or decontaminated materials in order to reduce the environmental footprint of decommissioning and improve the sustainability of the nuclear life cycle.

Planning and preparation for these activities typically starts well before a facility is shut down[2], and adequate management needs to be ensured throughout the decommissioning implementation, until the approved end state is attained and the facility is delicensed (licence termination). Indeed, removal of regulatory controls (either with conditions or unconditionally) that apply to a nuclear site is a central goal of decommissioning, and is achieved through the progressive and systematic reduction of radiological and other hazards.

2.2. NUCLEAR POWER REACTORS

The PRIS database[3] provides information on nuclear power reactors that are currently under construction, operational or have been permanently shut down. PRIS subdivides power reactors currently in operation into six main types or categories, which are the main types of power reactors used in this publication. These are:

(1) Pressurized light-water moderated and cooled reactors (PWRs);
(2) Boiling light-water cooled and moderated reactors (BWRs);
(3) Pressurized heavy-water moderated and cooled reactors (PHWRs);
(4) Gas cooled, graphite moderated reactors (GCRs);
(5) Light-water cooled, graphite moderated reactors (LWGRs);
(6) Fast breeder reactors (FBRs).

PRIS also includes a number of additional categories for other types of nuclear power reactors, which are mainly older designs from the early years of development of nuclear power.[4] For the purposes of this publication, we have allocated each of these into one of the above mentioned principal categories.

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[2] IAEA Safety Standards emphasize that for a new facility, planning for decommissioning should begin early in the design stage. See Refs [1, 6].

[3] See Appendix I for a more detailed description of the PRIS database.

[4] These are: high temperature gas cooled reactors (HTGRs); heavy-water moderated, gas cooled reactors (HWGCRs); heavy-water moderated, boiling light-water cooled reactors (HWLWRs); and steam generating heavy-water reactors (SGHWRs).

There are a small number that cannot be readily classified in the six principal groups, and therefore the PRIS category 'Others' has been retained.

The PRIS database divides countries into seven geographical regions: America — Northern; America — Latin; Europe — Western; Europe — Central and Eastern; Africa; Asia — Middle East and South; and Asia — Far East. For the purposes of this publication, information is presented using the PRIS regional breakdown so as to have the same regions used throughout.

2.2.1. Global overview of nuclear power reactors

At the end of 2020, globally there were a total of 686 nuclear power reactors at various stages of their life cycles, including 52 under construction, 442 that were operational, 172 that had been permanently shut down and 20 that had been fully decommissioned. This global overview is presented in Fig. 1. Figure 2 indicates the age profile of nuclear power reactors currently in operation.

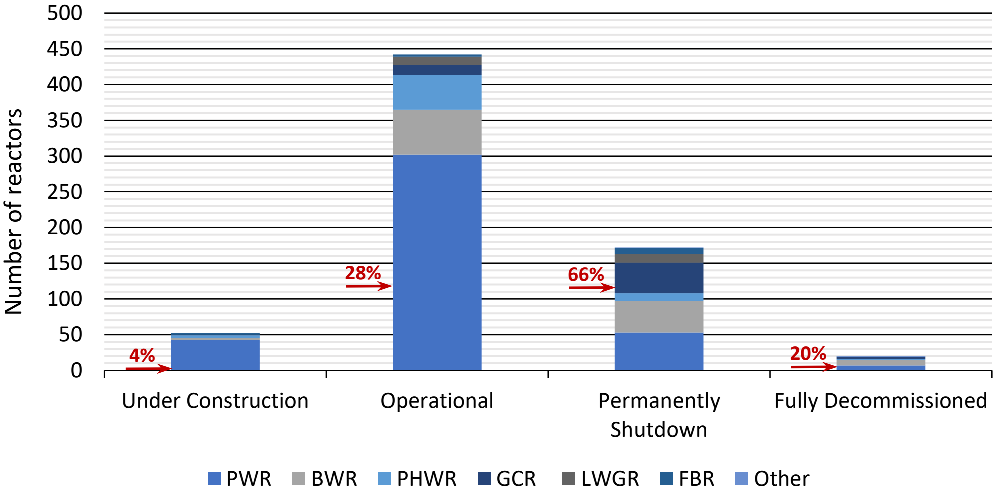

FIG. 1. Number of nuclear power reactors by stages and reactor types. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from PRIS, status at year end 2020.

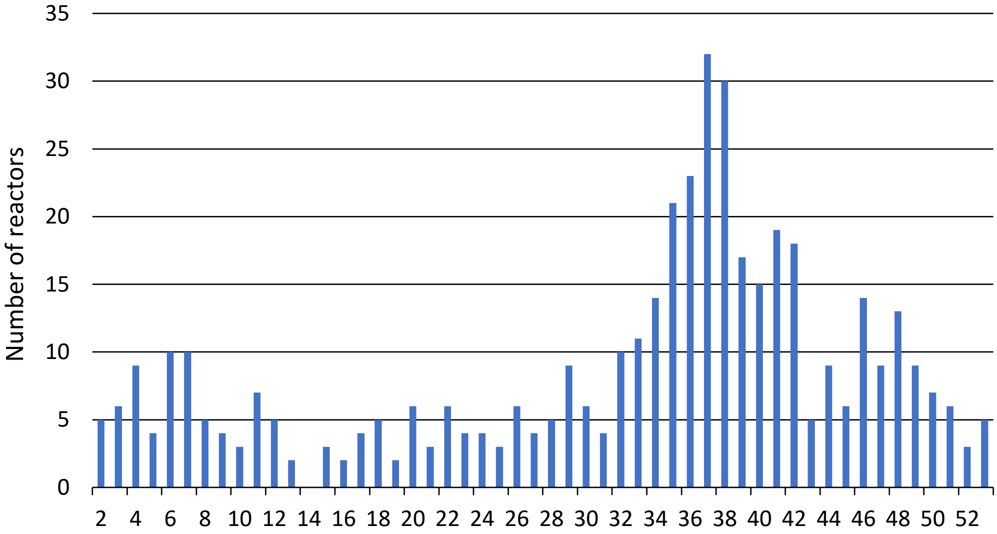

FIG. 2. Age profile of nuclear power reactors in operation by number. Data from PRIS, status at year end 2020.

A large proportion of nuclear power reactors currently in operation around the world are more than 30 years old, as shown in Fig. 2. Although many of these will reach the end of their original design lives within the next one to two decades, it is not straightforward to forecast with any precision when a particular reactor will be retired from service, as the reasons for deciding to permanently shut down a power reactor are not solely related to the original design life.[5] Experience shows that the reasons for deciding to permanently shut down a power reactor are often a combination of political and economic factors, maintenance and/or refurbishment costs and electricity market conditions. There are many examples of the design lifetime having been extended.

Overall, the questionnaire responses represent just over a third of nuclear power reactors globally (242 responses, a response rate of ~35%). However, the extent of coverage of questionnaire responses varies quite widely between the various stages of their life cycles, as indicated by the red arrows in Fig. 1. The questionnaire responses included 122 nuclear power reactors in operation, and a further 2 under construction. There were also responses from 114 nuclear power reactors that have been permanently shut down and 4 power reactors that have been fully decommissioned.

The subgroup of permanently shutdown nuclear power reactors has the highest proportion of questionnaire responses (114 responses, a response rate of ~66%). This is of significance, as this subgroup comprises the nuclear power reactors currently undergoing decommissioning or in a safe enclosure phase.

The subgroup of fully decommissioned nuclear power reactors has a relatively low proportion of questionnaire responses (four responses, a response rate of 20%). This is the category for which a complete overview of decommissioning is possible, since they have fully completed the decommissioning process. This is significant in that the analysis presented here does not have information from the majority of completed NPP decommissioning projects.

Overall, the responses from operational power reactors were less extensive (a response rate of under 28%). This low questionnaire response rate is significant for our analysis as currently operational reactors comprise by far the largest proportion of the total, and represent the bulk of future decommissioning.

In addition to the above considerations, a number of additional observations can be made from the global data for nuclear power reactors:

(a) The data from PRIS indicate that the majority of operational nuclear power reactors have currently been in operation for more than three decades, with the NPP reactor age distribution currently having a peak at approximately 38 years (see Fig. 2). The link between duration of operation and date of permanent shutdown is not a simple one; age is an important though not an exclusive factor determining the timing for the end of reactor operation. Nonetheless, it can be inferred that an increasing number of the operational reactors will be permanently shut down in the coming years.

(b) There are relatively few nuclear power reactors that have fully completed decommissioning — 20 in total, <3% of the total number of nuclear power reactors ever constructed — see also Table 1 in Appendix II.

2.2.2. Regional distribution of nuclear power reactors at different stages of the life cycle

2.2.2.1. Nuclear power reactors in operation

The PRIS data indicate that the majority of operating nuclear power reactors are fairly evenly divided between the PRIS regions of America — Northern (26%), Asia — Far East (25%) and Europe — Western (24%), followed by Europe — Central and Eastern with a smaller proportion (17%), as shown in Fig. 3.

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[5] The relationship between the age of a facility and the timing of permanent shutdown is also not straightforward for research reactors and fuel cycle facilities.

PWRs are the dominant type of NPP reactor currently in operation (68%)[6], while BWRs (15%) and PHWRs (11%) are the two next largest categories.

The questionnaire responses comprised <28% of the nuclear power reactors currently in operation. The red arrows in Fig. 3 show that the geographical distribution of questionnaire responses differs significantly from the geographical distribution of the nuclear power reactors in operation. The majority of questionnaire responses are from the Europe — Central and Eastern region, and the next largest grouping is Europe — Western , followed by Asia — Far East. Proportionally, the region of America — Northern is significantly underrepresented in the questionnaire responses.

Although the region Europe — Central and Eastern is proportionally overrepresented in the questionnaire responses, it is actually the most representative of the regions, with 86% of the region's NPP reactors in operation being covered by the responses.

The distribution of responses within responses is not representative of the types of power reactors in operation. In the questionnaire responses for power reactors in operation, the less common types of reactor are overrepresented (GCRs, LWGRs, FBRs) and the most common types of power reactor are significantly underrepresented (PWRs, BWRs, PHWRs). Specifically:

- PWRs are the largest group of nuclear power reactors in the questionnaire responses (61% of the total responses). However, PWRs are significantly overrepresented in responses as they represent <25% of the PWRs currently in operation.
- The questionnaire responses only include 22% of the total BWRs in operation. This reflects the relatively small number of responses from the regions America — Northern and from Europe — Western.
- PHWRs are also underrepresented in the questionnaire responses. This is because of the relatively small number of responses from the regions America — Northern and Asia — Middle East and South.

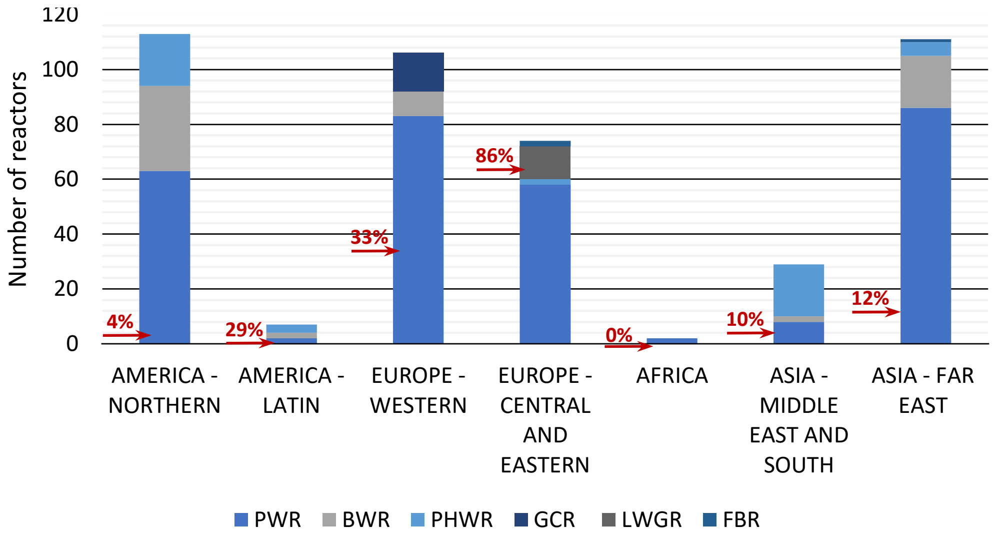

FIG. 3. Number of nuclear power reactors in operation by reactor type and region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. The red arrows indicate the relative proportion of questionnaire responses in each region. Data from PRIS, status at year end 2020.

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[6] This dominance of PWRs increases further for reactors currently under construction, where PWRs amount to nearly 83% of the total of all NPP types under construction.

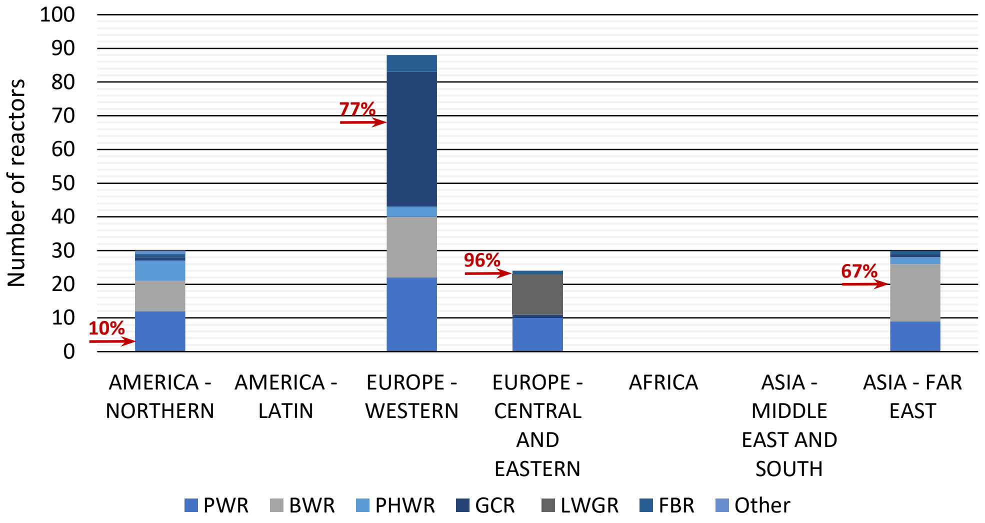

FIG. 4. Nuclear power reactors that have been permanently shut down by type of reactor and region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from PRIS, status at year end 2020.

2.2.2.2. *Nuclear power reactors that have permanently shut down, including nuclear power reactors under decommissioning*

The PRIS database shows that there are 172 NPP reactors that have entered into permanent shutdown[7], including those that are currently undergoing decommissioning, as shown in Fig. 4. The majority of the nuclear power reactors that have been permanently shut down are found in the PRIS region of Europe — Western (51%). Equal numbers of permanently shutdown reactors are found in America — Northern and Asia — Far East (both 17%), followed by Europe — Central and Eastern (14%). Of the reactor types that have been permanently shut down, PWRs are the most common (31%), followed by BWRs (26%) and GCRs (25%).

The questionnaire responses comprise two thirds (66%) of the permanently shutdown power reactors. The largest number of questionnaire responses come from the region Europe — Western, followed by Europe — Central and Eastern and Asia — Far East. The region Europe — Central and Eastern is proportionally overrepresented in the questionnaire responses, and the region of America — Northern is significantly underrepresented in the questionnaire responses. The proportion of questionnaire responses from the region Europe — Western is roughly in proportion to the total number of permanently shutdown reactors from the region.

Although the region Europe — Central and Eastern is not the region with the greatest number of responses, it is overrepresented in the questionnaire responses. However, it is the most representative of the individual regions, with questionnaire responses covering almost all (96%) of the region's permanently shutdown power reactors.

In the questionnaire responses for permanently shutdown power reactors, PWRs and GCRs are somewhat overrepresented and BWRs and PHWRs are underrepresented.

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[7] In PRIS, 'permanent shutdown' means that the reactor has officially been declared by the owner to have been taken out of commercial operation and has been shut down permanently without any intention to restart the unit. It includes reactors in a post-shutdown phase, preparing for decommissioning, in a deferral period, or undergoing decommissioning.

2.2.2.3. *Fully decommissioned nuclear power reactors*

There are relatively few power reactors that have completed decommissioning, in relatively few regions. Currently, there are 20 power reactors that have been fully decommissioned, as shown in Fig. 5 and listed in Table 1 in Appendix II. The majority of these NPP reactors were decommissioned in the region America — Northern (75%). Of the reactor types that have been fully decommissioned, the most common are BWRs (40%) and PWRs (35%).

The questionnaire responses comprise one fifth of the total (20%) number of fully decommissioned nuclear power reactors.

The geographical distribution of questionnaire responses differs significantly from the geographical distribution of fully decommissioned nuclear power reactors. There were no responses from the region America — Northern. The only responses came from the region Europe — Western.

The distribution of responses is not representative of the types of power reactors that have been fully decommissioned, comprising two BWR and two GCR decommissioning projects.

The questionnaire responses do not include information from the majority of completed NPP decommissioning projects. Moreover, as the total number of responses is very small and not representative, caution needs to be exercised in drawing any general conclusions from the data received for this category.

2.3. RESEARCH REACTORS

Research reactor facilities are used for a variety of purposes, including training, radioisotope production, irradiation of materials and industrial processing of material. There are many different types of reactors, and the range of power ratings varies from several watts up to hundreds of megawatts. The complexity varies from relatively simple constructions of critical and subcritical assemblies to a complexity comparable with power reactors.

The RRDB provides information on research reactors that are currently planned or under construction, operational, permanent shut down, under decommissioning and decommissioned.[8]

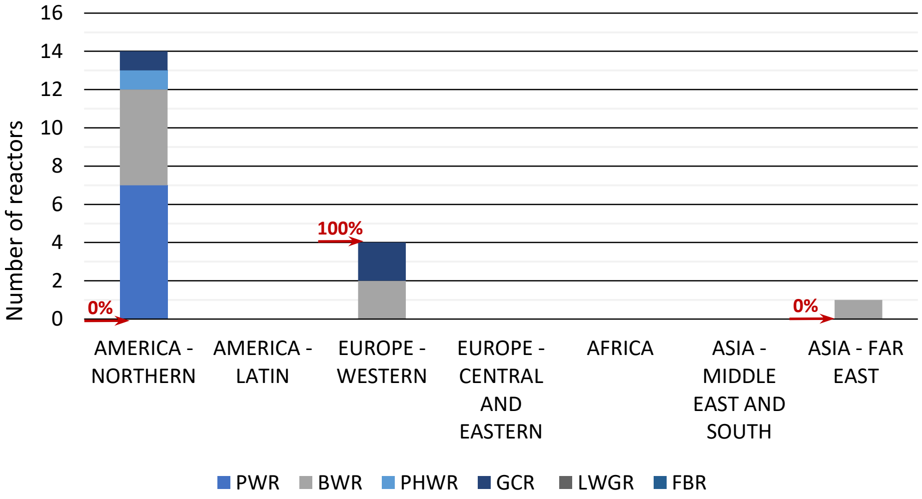

FIG. 5. Nuclear power reactors that have been fully decommissioned by type of reactor and region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from PRIS, status at year end 2020.

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[8] See Appendix I for a more detailed description of the RRDB.

For the purposes of this publication, research reactors are treated as one class of facilities. However, information in the RRDB includes general categories or main types of research reactors. These are:

- Open pool reactors (of which TRIGA[9] and SLOWPOKE[10] are specific types);
- Tank reactors[11];
- Argonaut[12] reactors;
- Homogeneous liquid reactors;
- Fast reactors;
- Graphite reactors and others, including critical and subcritical assemblies and homogeneous solid reactors.

The RRDB uses a slightly different regional breakdown from PRIS, with eight regions instead of seven. For the purposes of this publication, RRDB information is presented using the PRIS regional breakdown so as to have the same regions used throughout the report.

The RRDB collects and presents data at the level of individual research reactors. While much of the research reactor facility information from questionnaire responses can also be presented at the level of individual research reactors, there are a number of large sites with several research reactors where it was not possible to break down the data to the level of individual facilities. For the purposes of facilitating comparison with the RRDB data, these large multifacility sites are excluded from the research reactor analysis presented in this section. This has the effect of underestimating the questionnaire response rate for research reactors in comparison to the RRDB. However, the information from these multifacility sites is presented in other sections of this report.

2.3.1. Global overview of research reactors

The RRDB lists 833 research reactors globally in the phases: planned and under construction; in operation or temporary shutdown; permanent shutdown; under decommissioning; and decommissioned[13]. The largest grouping is those research reactors that have been fully decommissioned (446), comprising 54% of the total. The second largest category is research reactors in operation or temporary shutdown (237), comprising 28% of the total. There are 123 research reactors that have been permanently shut down, including those currently in decommissioning (15%).[14] A further 27 research reactors are planned or under construction (3%). This global overview is shown in Fig. 6.

There were questionnaire responses from 77 research reactors. Of these, the largest category is research reactors that have been fully decommissioned (35 reactors). The second largest grouping is research reactors that have been permanently shut down, including those currently under decommissioning (31 reactors). The questionnaire response sample has 11 operational research reactors. There were no responses from research reactors planned or under construction.

As previously noted, in order to facilitate comparison with the RRDB, a number of large multifacility sites are excluded from the research reactor analysis in Section 2. The excluded multifacility sites are one each in the regions Europe — Western, Europe — Central and Eastern, America — Northern and Asia — Far East.

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[9] TRIGA is an acronym for the Training, Research, Isotopes, General Atomics reactors from the USA.

[10] SLOWPOKE is an acronym for the Safe LOW-POwer Kritical Experiment reactors from Canada.

[11] Tank reactors, including WWRs (water-water reactors), pool in tank reactors of Soviet design.

[12] ARGONAUT is an acronym for the Argonne Nuclear Assembly for University Training reactors from the USA.

[13] RRDB, accessed 1 June 2021.

[14] The RRDB further subdivides this into 'permanent shutdown' (58 reactors or 7%) and 'under decommissioning' (65 reactors or 8%).

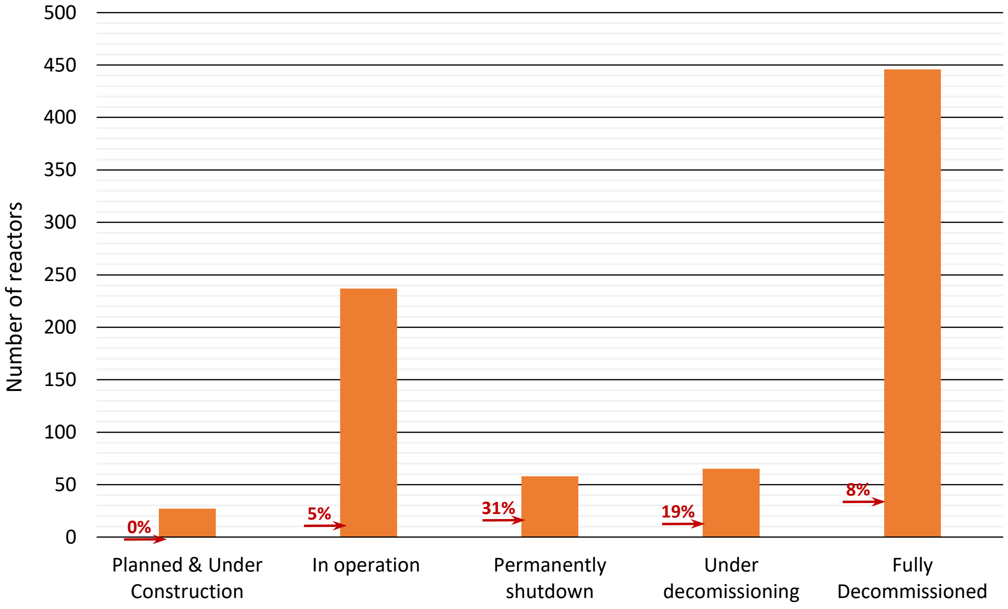

FIG. 6. Research reactors by phase. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from RRDB, accessed 1 June 2021.

A number of observations can be made from the above global data for research reactors:

- The questionnaire responses represent a small proportion of research reactors (a response rate of 9%), and are unlikely to be representative of the global picture for research reactors. This calculated response rate excludes a number of multifacility sites, but even with these factored in the overall response rate would be low compared to the overall numbers of research reactors.
- There is considerable experience with research reactor decommissioning, as demonstrated by 54% of research reactors having been fully decommissioned. However, the total number of questionnaire responses for fully decommissioned research reactors was small (35 responses), and means that the analysis is based on only a small portion of completed research reactor decommissioning projects. Nonetheless, as a proportion of the overall questionnaire responses the number of fully decommissioned research reactors in the responses is broadly in line with the research reactors globally (45% fully decommissioned in responses, compared with 54% globally).
- Just over a quarter of the research reactors are currently in operation (28%), meaning that a significant amount of decommissioning is still to be undertaken. For these, there is considerable decommissioning experience to draw upon, although it should be noted that this grouping is significantly underrepresented in the questionnaire responses.
- A total of 31 permanently shutdown research reactors are represented in responses, a response rate of 25%. This is of significance, as this group is the category that includes the research reactors currently undergoing decommissioning or in a deferral phase. Permanently shutdown research reactors are significantly overrepresented in the questionnaire responses (40% in responses, compared with 15% of research reactors globally).
- A relatively small proportion of research reactors globally are currently planned or under construction (27 research reactors). This group is not represented in the questionnaire responses (0 responses).

2.3.2. Regional distribution of research reactors at different stages of the life cycle

2.3.2.1. Research reactors in operation and in temporary shutdown

The RRDB currently lists 237 research reactors as being operational, representing just over a quarter of research reactors globally (28%).[15] This category includes research reactors currently in operation and in temporary shutdown pending restart. Operational research reactors are found in all of the regions, although the numbers are spread unevenly. The majority of the operational research reactors are found in in the regions of Europe — Central and Eastern (32%) and America — Northern (23%), as shown in Fig. 7.

There were few questionnaire responses for research reactors in operation (11 in total). This group is underrepresented in the overall questionnaire responses.

Within the group of operational research reactors, the Europe — Central and Eastern region had the highest number of responses (over half), which is a significantly greater proportion than its actual share of the operational research reactors globally.

As the total number of responses is small and not representative, caution needs to be exercised in drawing any general conclusions from the data received.

2.3.2.2. Research reactors that are permanently shut down, including research reactors under decommissioning

The RRDB lists 123 research reactors that have been permanently shut down, including those currently in decommissioning (15% of all research reactors globally). It further subdivides 'permanent shutdown' into 'permanent shutdown but not under decommissioning' and 'under decommissioning'.

The RRDB subgroup of research reactors in permanent shutdown but not under decommissioning comprises 58 reactors (47% of the permanently shutdown reactors and 7% of all research reactors). The

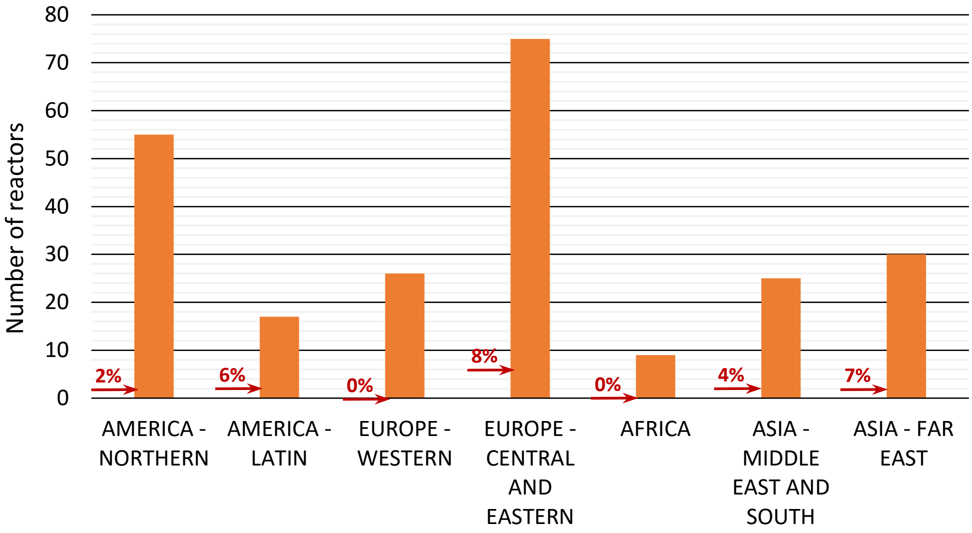

FIG. 7. Research reactors in operation and temporary shutdown by region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from RRDB, accessed 1 June 2021.

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[15] For the purposes of this publication, 'research reactors globally' includes those reactors under construction and those already fully decommissioned.

region with the highest number of these is America — Northern, followed by Europe — Western and then Europe — Central and Eastern, as shown in Fig. 8.

There are 18 questionnaire responses from the subgroup of research reactors that are in permanent shutdown but not currently under decommissioning — a response rate of 31%. The region with the highest number of these is Europe — Western, followed by Europe — Central and Eastern. The region America — Northern is underrepresented in this subgroup and the region Europe — Western is overrepresented, in comparison to the same subgroup of the research reactors globally.

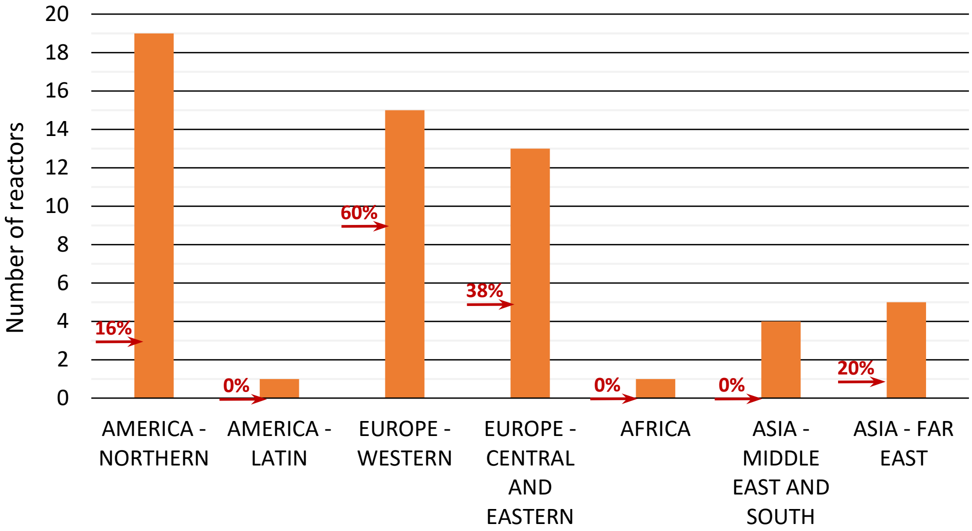

FIG. 8. *Research reactors in permanent shutdown but not under decommissioning by region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from RRDB, accessed 1 June 2021.*

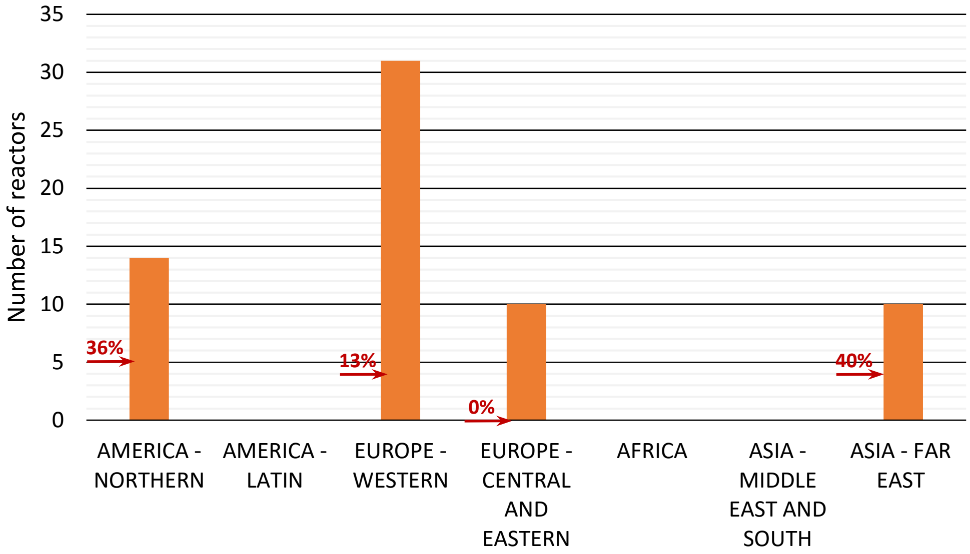

FIG. 9. *Research reactors currently under decommissioning by region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from RRDB, accessed 1 June 2021.*

RRDB identifies a subgroup of 65 research reactors as being under decommissioning (53% of the permanently shut down reactors, and 8% of all research reactors globally). The region with the highest number of these is Europe — Western, as shown in Fig. 9.

There are 13 questionnaire responses from the subgroup of research reactors that are in permanent shutdown and currently under decommissioning — a response rate of 20%. The region with the highest number of these is America — Northern, followed by Europe — Western and Asia — Far East. No responses in this subgroup were received from the region Europe — Central and Eastern.

A number of observations can be made from the above data for permanently shutdown research reactors:

- The relative proportion of research reactors that are in permanent shutdown, including under decommissioning, in the questionnaire responses is significantly higher than in the research reactors globally (40% in responses, compared with 15% of research reactors globally).
- The distribution of responses for research reactors that are in permanent shutdown and not undergoing decommissioning is not representative; the region America — Northern is underrepresented in responses and the region Europe — Western is overrepresented in responses.
- The distribution of responses for permanently shutdown research reactors that are undergoing decommissioning is not representative; the regions America — Northern and Asia — Far East are overrepresented in responses, and the region Europe — Western is underrepresented. The region Europe — Central and Eastern is not represented in responses.

2.3.2.3. Fully decommissioned research reactors

The RRDB lists 446 research reactors that have been fully decommissioned, which is 54% of the research reactors globally. This is a significant body of experience that should provide a pool of knowledge for those preparing for and currently undertaking decommissioning of research reactors. It is noteworthy that there is some experience with fully completed decommissioning of research reactors in every region, although this experience is spread unevenly between the regions. By far the highest number of fully decommissioned research reactors is in the region America — Northern (over half of the total), followed by Europe — Western. The regions with the fewest fully decommissioned research reactors are America — Latin and Africa. The regional distribution of fully decommissioned research reactors is shown in Fig. 10.

The total number of questionnaire responses for fully decommissioned research reactors was small (35 reactors or a response rate of 8%), and means that the analysis is only based on a small portion of completed research reactor decommissioning projects. Nonetheless, as a proportion of the overall questionnaire responses the number of fully decommissioned research reactors in responses is lower than in the research reactors globally (45% fully decommissioned in responses, compared with 54% of all research reactors globally). The regional distribution in responses differs significantly from that in the research reactor fleet.

A number of observations can be made from the above data for fully decommissioned research reactors:

- A large number of research reactors have been fully decommissioned, 446 reactors in total, comprising 54% of all research reactors globally. This is a valuable pool of knowledge and experience for research reactor decommissioning.
- All regions have some experience with fully decommissioning research reactors, although this experience is not spread evenly between them. Most experience is in the regions America — Northern, Europe — Western and Europe — Central and Eastern; the least experience is in America — Latin and Africa.

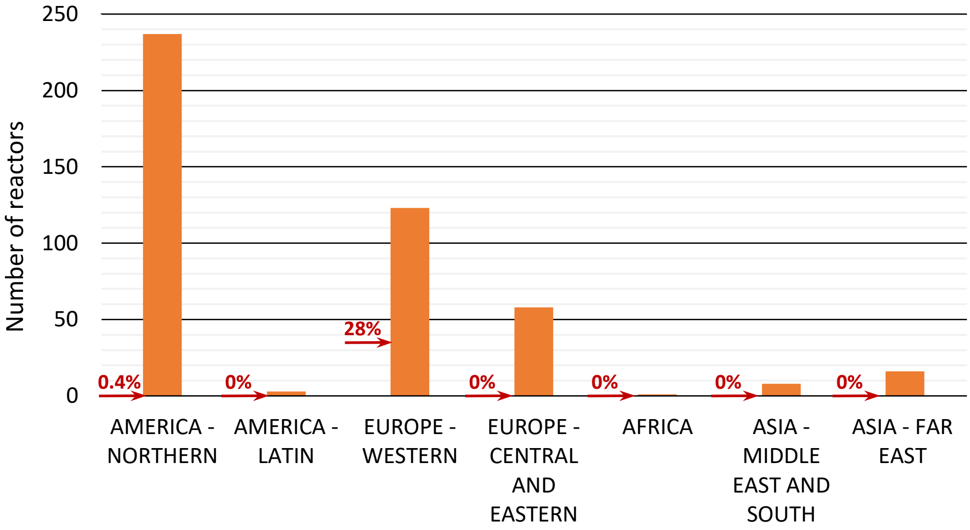

FIG. 10. Research reactors that have been decommissioned by region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from RRDB, accessed 1 June 2021.

- The relatively small number of questionnaire responses from fully decommissioned research reactors means that the analysis is only based on a small portion of completed research reactor decommissioning projects.
- Fully decommissioned research reactors are underrepresented as a proportion of overall research reactors (45% fully decommissioned responses, compared with 54% of all research reactors globally), but the regional distribution in the responses differs significantly from that for research reactors globally. In particular, the region Europe — Western is significantly overrepresented in responses, whereas the region America — Northern is significantly underrepresented.

2.4. NUCLEAR FUEL CYCLE FACILITIES

The iNFCIS database provides information on FCFs that are currently planned or under construction, operational, permanently shut down, under decommissioning and decommissioned.[16]

For the purposes of this publication, FCFs are being treated as one class of facilities. However, information in the iNFCIS database includes 11 categories or main types of FCF. From these, uranium mining and milling facilities have been excluded from consideration.[17] Therefore, the subset of FCFs considered in this analysis comprises facilities for:

- Uranium conversion;
- Uranium enrichment;
- Uranium fuel fabrication;
- Spent fuel storage;
- Spent fuel reprocessing and recycling[18];

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[16] See Appendix I for a more detailed description of the iNFCIS database.

[17] Uranium and milling facilities are a major category in the iNFCIS database. They comprise a total of 235 facilities. Of these, 74 are in operation or standby, 7 are planned and 15 are under construction, 52 are permanently shut down and 75 are under decommissioning or decommissioned.

[18] This category includes mixed oxide (MOX) fuel fabrication.

— Spent fuel conditioning;
— Related industrial activities.

It should be noted that FCFs, as represented here, comprise several different classes of nuclear facility, with a diverse range of characteristics and presenting different decommissioning challenges. One consequence is that experience is less readily shared within this grouping. For the purposes of this publication, iNFCIS information is presented using the PRIS regional breakdown so as to have the same regions used throughout the report.

iNFCIS collects and presents data at the level of individual FCFs. While much of the fuel cycle facility information from questionnaire responses can also be presented at the level of individual FCFs, there are a number of large sites with multiple FCFs where it was not possible to break down the data to the level of individual facilities. For the purposes of facilitating comparison with the iNFCIS data, these large multifacility sites are excluded from the fuel cycle facility analysis in this section. This has the effect of underestimating the questionnaire response rate for FCFs in comparison to the iNFCIS database. However, the information from these multifacility sites is incorporated into the analysis presented in other sections of this report.

2.4.1. Global overview of nuclear fuel cycle facilities

The subset of iNFCIS facilities considered by this project comprises 473 facilities in total, as shown in Fig. 11. It can be seen that the majority of these facilities are still in operation (290, or 61%), and that a significant number of facilities are already in permanent shutdown, including decommissioning (96, or 20%), or have already been fully decommissioned (66, or 14%). A further 21 (4%) of FCFs are under construction.[19]

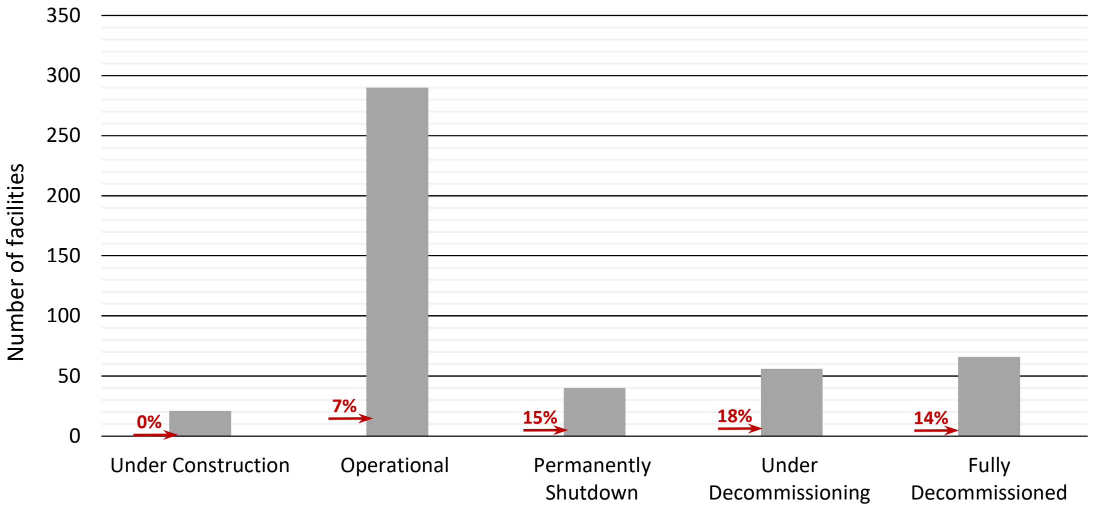

FIG. 11. Number of facilities in the iNFCIS nuclear FCFs (excluding uranium mining and milling) by phases. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from iNFCIS, accessed 1 June 2021.

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[19] This category includes facilities that are being planned, are under construction or are in the process of being commissioned.

There were questionnaire responses from 45 individual FCFs. Of these, the largest category is operational FCFs (20 facilities). The second largest grouping is FCFs that have been permanently shut down, including those currently under decommissioning (16 facilities). The questionnaire responses had nine fully decommissioned FCFs. There were no responses from FCFs planned or under construction.

As previously noted, in order to facilitate comparison with the iNFCIS database, a number of large multifacility sites are excluded from the fuel cycle facility analysis in Section 2. The excluded multifacility sites comprise four located in the region Europe — Western and nine located in the region Europe — Central and Eastern.

A number of observations can be made from the above global data for FCFs:

- The questionnaire responses from individual FCFs represent a small proportion of all FCFs considered in this project (a response rate of <10%), and are therefore unlikely to be representative of the global picture for FCFs. This calculated response rate excludes a number of multifacility sites but, even with these factored in, the overall response rate would be low compared to the total number of FCFs globally.
- There is some experience with fuel cycle facility decommissioning, as demonstrated by 14% of all FCFs globally having been fully decommissioned. The overall number of questionnaire responses for fully decommissioned FCFs was small (nine facilities), representing a response rate of 14%. Fully decommissioned FCFs are somewhat overrepresented in the questionnaire responses. It needs to be borne in mind that there is a large diversity of facility types within the FCF grouping, which complicates the process of identifying general lessons that may be applicable to future decommissioning projects.
- Currently operational FCFs comprise the largest proportion of all FCFs considered in this project (61%), and represent the bulk of future FCF decommissioning. Although this is the largest group in the questionnaire response sample, it is nonetheless underrepresented in comparison to the total number of FCFs considered in this project.
- A total of 16 permanently shutdown FCFs, including facilities currently undergoing decommissioning, are represented in responses, a response rate of 17%. The proportion of permanently shutdown FCFs is somewhat overrepresented in the questionnaire responses.
- A relatively small proportion of all FCFs considered in this project are currently planned or under construction (21 facilities). This group is not represented in the questionnaire response sample (0 responses).

2.4.2. Regional distribution of nuclear fuel cycle facilities at different stages of the life cycle

2.4.2.1. Fuel cycle facilities in operation and in temporary shutdown

There are a total of 290 operational FCFs, constituting 61% of all FCFs globally. This category includes both facilities in operation and those on standby. Operational FCFs are found in all of the regions, although the numbers are spread unevenly. The regions with the greatest number of operational FCFs are America — Northern (94 facilities, or 32%) and Europe — Western (76 facilities, or 26%). The regions with the fewest number of operational FCFs are Africa (3 facilities, or 1%) and America — Latin (18 facilities, or 6%). The regional distribution of operational FCFs is shown in Fig. 12.

There were questionnaire responses from 20 operational FCFs, a response rate of 7%. Within the group of responses for operational FCFs, the region Europe — Western had the highest number of responses (75% of the sample). There were no responses from the region America — Northern.

A number of observations can be made from the above data for operational FCFs:

- Operational FCFs are the largest proportion (61%) of all FCFs globally and are found in all of the regions, although the numbers are distributed unevenly.

- Although operational FCFs comprise the largest portion of the overall fuel cycle facility responses, the overall questionnaire response rate was low (7%) and operational facilities comprised only 44% of the overall questionnaire response sample. As a result, operational FCFs are underrepresented in the sample in comparison to all FCFs globally.
- The distribution of questionnaire responses for operational FCFs is unrepresentative of FCFs globally. Within the group of responses for operational FCFs, the region Europe — Western had the highest number of responses (75% of the sample), which is a significantly greater proportion than its share of FCFs globally. Conversely, there were no responses from the region America — Northern, meaning that this region is unrepresented, despite being the region with the greatest number of FCFs globally.

2.4.2.2. Fuel cycle facilities that have been permanently shut down, including facilities under decommissioning

There are 96 FCFs that have been permanently shut down, including FCFs under decommissioning (22% of all FCFs globally). iNFCIS further subdivides this into ‘permanent shutdown’ and ‘under decommissioning’.

The iNFCIS subgroup of FCFs in permanent shutdown but not under decommissioning comprises 40 facilities (8% of all FCFs globally). The region with the greatest number of permanently shutdown FCFs not under decommissioning is Asia — Far East (15 facilities). The next largest numbers are in the regions America — Latin (six facilities) and America — Northern (five facilities). The regional distribution of permanently shutdown FCFs is shown in Fig. 13.

The questionnaire response sample has a total of six in permanent shutdown but not under decommissioning, a response rate of 15%. Within the group of responses for permanently shutdown FCFs, the region Europe — Western had the highest number of responses (five facilities), and the only other response came from the region Asia — Far East.

The iNFCIS subgroup of FCFs currently undergoing decommissioning comprises 56 facilities (12% of all FCFs globally). The region with the highest number of these is Europe — Western, as shown in Fig. 14.

The questionnaire response sample has a total of ten FCFs currently under decommissioning, a response rate of 18%. Within the group of responses for FCFs currently under decommissioning, all of the responses came from the region Europe — Western.

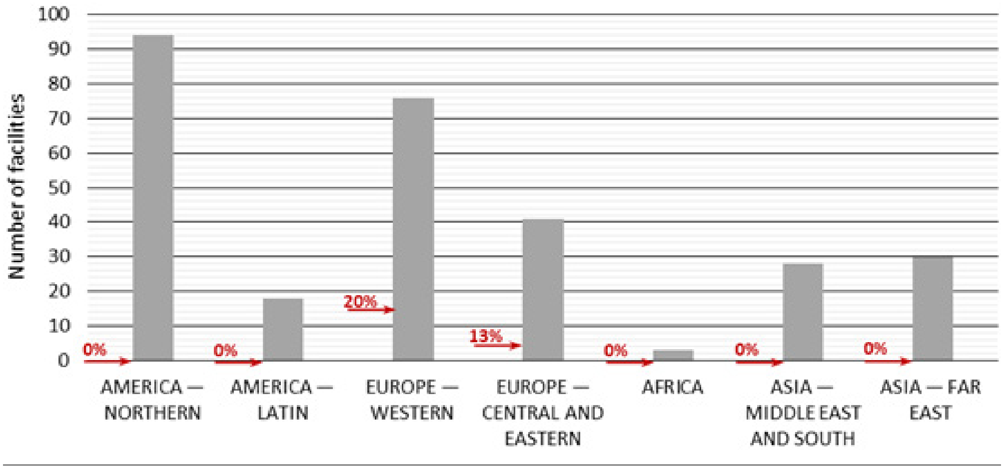

FIG. 12. Operational FCFs by region. The red arrows indicate the relative proportion of questionnaire responses in each region. Data from iNFCIS, accessed 1 June 2021.

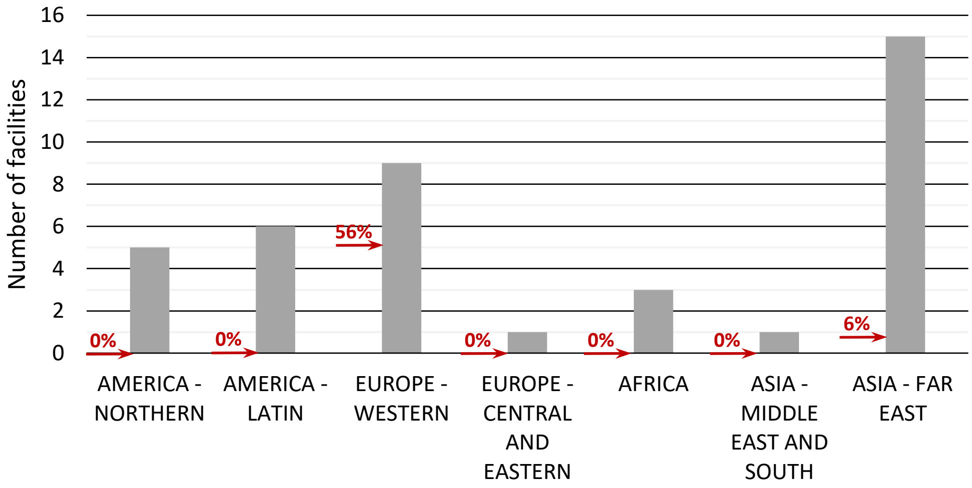

FIG. 13. Nuclear FCFs that have permanently shut down, excluding FCFs under decommissioning, by region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from iNFCIS, accessed 1 June 2021.

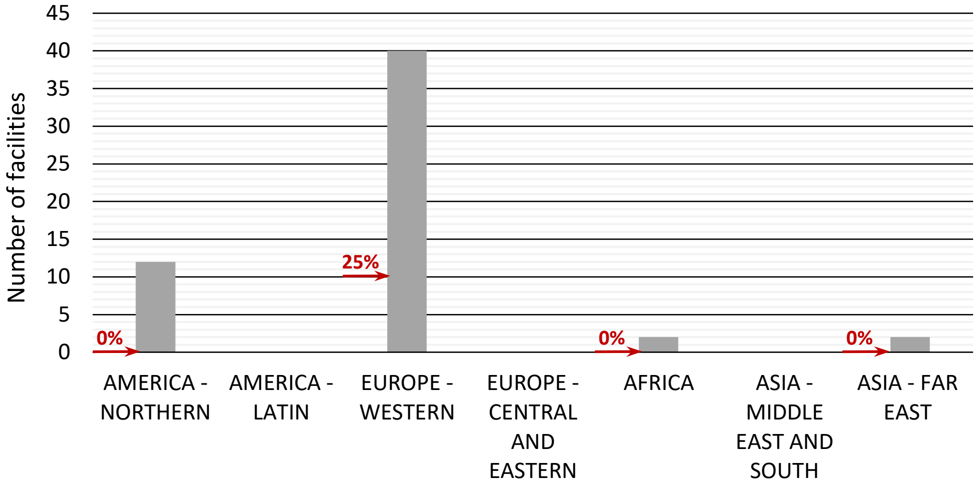

FIG. 14. Nuclear FCFs currently under decommissioning by region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from iNFCIS, accessed 1 June 2021.

A number of observations can be made from the above data for permanently shutdown FCFs:

- Permanently shutdown FCFs, including FCFs under decommissioning, comprise the second largest proportion (22%) of all FCFs globally and are found in all of the PRIS regions, although the numbers are spread unevenly.
- There is a different geographical distribution of permanently shutdown FCFs and FCFs under decommissioning.
- The questionnaire response rate for permanently shutdown FCFs, including FCFs under decommissioning, is relatively low. However, it is overrepresented in the questionnaire response sample (36% in the sample, compared with 20% of all FCFs globally).

- The distribution of questionnaire responses for permanently shutdown FCFs, including FCFs under decommissioning, is unrepresentative of permanently shutdown fuel cycle facilities globally. The region Europe — Western is overrepresented in the questionnaire response sample.

2.4.2.3. Fully decommissioned fuel cycle facilities

There are 66 individual FCFs that have been fully decommissioned, constituting 14% of all FCFs globally. Fully decommissioned FCFs are found in most PRIS regions, although there is significant variation between the regions. The regions with the greatest number of fully decommissioned FCFs are Europe — Western (36 facilities) and America — Northern (21 facilities). Two regions have no fully decommissioned FCFs: Africa and Europe — Central and Eastern. The regional distribution of fully decommissioned FCFs is shown in Fig. 15.

The overall number of questionnaire responses for fully decommissioned FCFs is small (nine facilities). The only region represented in the questionnaire response sample is Europe — Western.

A number of observations can be made from the above data for fully decommissioned FCFs:

- Permanently shutdown FCFs comprise the second largest proportion (22%) of all FCFs globally and are found in all of the regions, although the numbers are spread unevenly.
- The overall number of questionnaire responses for fully decommissioned FCFs is small (nine facilities). There may be additional individual FCFs that have been fully decommissioned on large multifacility sites that are excluded from this comparison with the iNFCIS database.
- Fully decommissioned FCFs are somewhat overrepresented in the questionnaire response sample.
- The distribution of questionnaire responses for fully decommissioned FCFs is unrepresentative. The only region with questionnaire responses for fully decommissioned FCFs is Europe — Western.

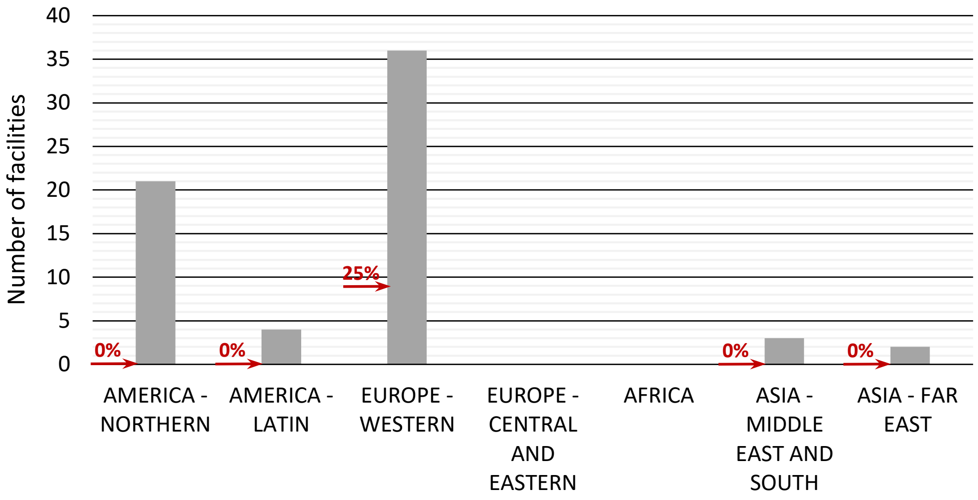

FIG. 15. Nuclear FCFs that have been fully decommissioned by region. The red arrows indicate the number of questionnaire responses as a proportion of the total number of facilities in each category. Data from iNFCIS, accessed 1 June 2021.

2.5. CONCLUSIONS

For NPP reactors, the information from the PRIS database and the questionnaire responses indicates that:

- The majority of NPP reactors are currently still in operation, and this will represent the bulk of decommissioning over the coming decades. The majority of these reactors are in the latter half of their planned operating periods. This group is underrepresented in the overall questionnaire response sample, and within it the sample the region Europe — Central and Eastern is overrepresented.
- NPP reactors that have been permanently shut down comprise the second largest grouping, and the one that is best represented in the questionnaire responses. This is significant, as this group is the category that includes the reactors currently undergoing decommissioning or in a deferral phase, and it thus reflects the current approach to decommissioning. Within the questionnaire responses for permanently shutdown reactors, there is particularly comprehensive coverage from the region Europe — Central and Eastern, although this means that the region is overrepresented in the sample.
- There are relatively few NPP reactors that have fully completed decommissioning and this group is significantly underrepresented in the questionnaire responses. The questionnaire responses are not representative, with no responses received from the region America — Northern. Moreover, as the total number of responses are very small and not representative, caution needs to be exercised in drawing any general conclusions from the data received for this group of reactors.
- Although there are a significant number of power reactors currently under construction, these are not represented in the questionnaire responses.
- Overall, the questionnaire responses represent approximately one third of all NPP reactors. However the distribution of questionnaire responses for NPP reactors differed significantly from the overall NPP reactor distribution, and they are unlikely to be representative of the global picture.

For research reactors, the information from the RRDB and the questionnaire responses indicates that:

- Just over a quarter of research reactors are currently in operation or temporary shutdown, meaning that there is a significant amount of decommissioning to come. However, this grouping is significantly underrepresented in the questionnaire response sample.
- Permanently shutdown research reactors, including those undergoing decommissioning, comprise 15% of the global research reactors. This group is overrepresented in the questionnaire responses. The distribution of responses means that the information received from the questionnaire responses may not be representative.
- A large number of research reactors have been fully decommissioned, 446 reactors in total, comprising over half of all research reactors. All regions have some experience with fully decommissioning research reactors, although this experience is not spread evenly between the regions. However, the relatively small number of questionnaire responses from fully decommissioned research reactors means that the analysis only has information from a small portion of completed research reactor decommissioning projects.
- A relatively small proportion of research reactors is currently planned or under construction, and this group is not represented in the questionnaire response sample.
- Overall, the questionnaire responses represent a small proportion of research reactors, and they are unlikely to be representative of the global picture. This section excludes a number of multifacility sites, but even with these factored in, the overall response rate would be low compared to the global research reactor fleet.

For FCFs, the information from the iNFCIS database and the questionnaire responses indicates that:

- Currently operational FCFs comprise the largest proportion of all FCFs (60%), and represent the bulk of future FCF decommissioning. Although this is the largest group in the questionnaire response sample, the response rate is low and it is underrepresented in comparison to FCFs globally. The questionnaire response sample for operational FCFs is not representative of the global fuel cycle facility fleet.
- Permanently shutdown FCFs represent 22% of FCFs, which is significant, as this includes FCFs currently undergoing decommissioning or in a deferral phase. Permanently shutdown FCFs are somewhat overrepresented in the questionnaire response sample. The distribution of questionnaire responses is unrepresentative of permanently shutdown FCFs globally.
- There is some experience with fuel cycle facility decommissioning, as demonstrated by 14% of FCFs globally having been fully decommissioned. The total number of questionnaire responses for fully decommissioned FCFs was small. Fully decommissioned FCFs are overrepresented in the questionnaire response sample. There may be additional individual FCFs that have been fully decommissioned on large multifacility sites that are excluded from this comparison with the iNFCIS database. The distribution of questionnaire responses is unrepresentative of fully decommissioned FCFs globally.
- A relatively small proportion of FCFs globally are currently planned or under construction. This group is not represented in the questionnaire responses.
- The questionnaire responses from individual FCFs represent a small proportion of all FCFs (a response rate of 9%), and they are not representative of the global distribution of FCFs. This excludes a number of multifacility sites, but even with these factored in, the overall response rate would be low compared to FCFs globally.

3. INSTITUTIONAL AND LEGAL FRAMEWORKS FOR DECOMMISSIONING

3.1. POLICIES AND INSTITUTIONAL ARRANGEMENTS

The prime responsibility for ensuring the safety of decommissioning and radioactive waste management rests with the licence holder, usually the operator or owner of the facility. This is reflected in international Safety Standards [7], international agreements [8] and European Union (EU) law [9], as well as in national laws. The ultimate responsibility rests with the States in which the facilities are located, and these have established legislation and regulations setting out the roles and responsibilities of the relevant organizations.

The specific details of the national arrangements for ensuring that decommissioning of nuclear facilities is safely managed vary from country to country, although there are some common features. The national legislative assembly is usually responsible for approving legislation to cover the safe decommissioning of nuclear facilities. This legislation generally includes the establishment of a regulatory body as well as defining the essential elements of the national policy for the management of decommissioning, the management of radioactive wastes and other related governance. In many cases, it also includes the establishment of a national organization for radioactive waste management. In addition,

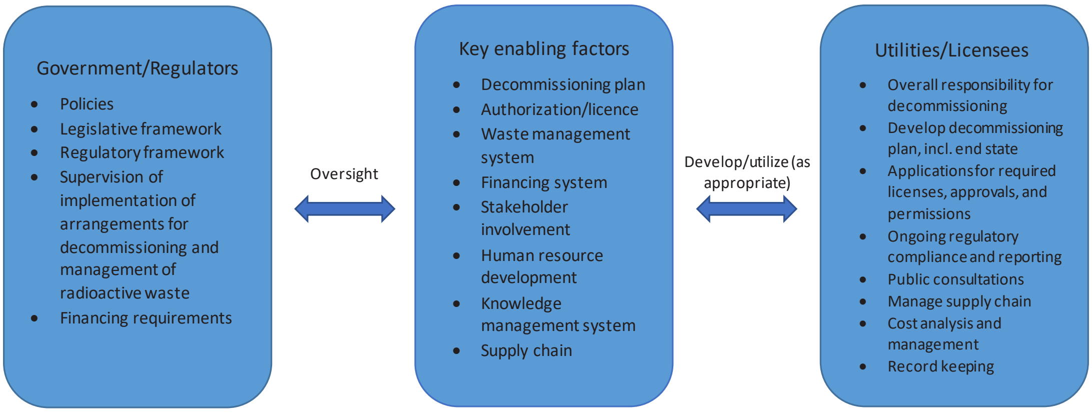

FIG. 16. Generic illustration of allocation of roles and responsibilities for decommissioning (adapted from Ref. [10] with permission).

some countries have established a national decommissioning organization. As an alternative to legislation, national policy can be set out separately by governmental decree or ministerial directives.

Figure 16 illustrates a general allocation of roles and responsibilities in the context of implementing decommissioning programmes. Specific national frameworks will vary according to the specific institutional and legal arrangements in each country.

National policy typically addresses the following:

(a) Responsibilities within the country for decommissioning;
(b) Arrangements for financing decommissioning;
(c) Decommissioning of nuclear facilities;
(d) Preferred management options for radioactive wastes arising from decommissioning;
(e) Public information and public involvement in related decisions.

To implement the national policy, strategies have to be developed for the decommissioning of facilities, which is generally the responsibility of the operators of nuclear facilities. Operators are also responsible for the detailed planning of the work and its execution. Some States have national strategies for implementing decommissioning, and include, for example, plans for implementing national policy, the development of the requisite facilities, the identification of roles and the setting of targets. The Euratom Waste Directive [9] requires that each EU Member State prepares a strategy expressed as a national programme for managing and disposing of all kinds of radioactive waste, including that arising from decommissioning. Generally, the development of the specific plan for facility decommissioning and its implementation is the responsibility of the operators of nuclear facilities and is to be undertaken within the overarching national legal and policy framework.

3.2. LEGAL AND REGULATORY FRAMEWORKS

National laws and regulations provide the legal framework for the management of liabilities from retired nuclear facilities, as well as for nuclear waste generated during their operation and decommissioning. Such frameworks are required to ensure that policies and strategies are set out and implemented effectively, and that financial and non-financial responsibilities are clearly defined and suitably allocated to those responsible for discharging the liabilities. The extent to which the specific legal and regulatory framework for nuclear decommissioning has been developed varies somewhat with the degree to which nuclear programmes have developed and the time frame for decommissioning activities.

History, institutional arrangements, the size and role of the nuclear industry and other factors all play a role in determining both the current and future forms of legal and regulatory arrangements.

National legal and regulatory systems ensure the safety of decommissioning in different ways. Variability of regulation can emerge in many ways, from the basic structure of the legislative framework, to the interaction between various legal and regulatory instruments, to the degree of detail, and the definition of boundaries and constraints in the laws, ordinances and regulations. Laws can, for instance, define general guidelines or main principles, based on a goal setting approach, or can prescribe very specific requirements that have to be met in full.

3.2.1. Legal frameworks

While the specific details of legal instruments vary from country to country, the national legal frameworks typically assign roles and responsibilities for nuclear activities, including radioactive waste management, to operating organizations, ministries and other governmental organizations. IAEA Safety Standards Series, No. GSR Part 1 (Rev. 1), Governmental, Legal and Regulatory Framework for Safety describe the basic requirement for a safety framework as follows [11]:

> “**Requirement 2: Establishment of a framework for safety**
>
> “**The government shall establish and maintain an appropriate governmental, legal and regulatory framework for safety within which responsibilities are clearly allocated.**”

More specifically, Article 19(2) of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (‘Joint Convention’) [8][20] states inter alia that the legislative and regulatory framework provides for:

> “(i) the establishment of applicable national safety requirements and regulations for radiation safety …
>
> (iv) a system of appropriate institutional control, regulatory inspection and documentation and reporting;
>
> (v) the enforcement of applicable regulations and of the terms of the licences;
>
> (vi) a clear allocation of responsibilities of the bodies involved in the different steps of … radioactive waste management.”

At the national level, decommissioning and radioactive waste management are typically covered in either special statutes or general nuclear energy laws. In the latter case, specialization of regulation occurs at a lower level of legislation and/or in administrative regulatory provisions. This legislative and regulatory framework may be subject to regular revisions and can also be changed in cases where the boundary conditions change. The national legislation can set constraints on decisions regarding the basic strategic options for decommissioning (i.e. immediate or deferred dismantling) or leave the decision to the operators, provided that specific requirements, set in national regulatory frameworks, are enforced.

Countries with well established nuclear programmes tend to have comprehensive provisions on decommissioning in their legal and regulatory frameworks (laws, acts, decrees, ordinances, codes, etc.). However, in some cases provisions on decommissioning have only recently been enacted or are otherwise being modified as actual decommissioning of facilities comes closer in time. For some countries, initial legal and institutional arrangements for decommissioning have been further modified in light of

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[20] Similar requirements are given for EU Member States in the Euratom Waste Directive [9].

actual practical experience with decommissioning, changes to the national organization and policies for the nuclear sector, or as new entities seek to enter the decommissioning market. In some countries, a general legal and regulatory framework is in place but is oriented towards operational activities, with decommissioning activities not yet considered in detail [12].

3.2.2. Regulatory framework, role and responsibilities

Nuclear decommissioning entails a high level of engagement and oversight by the nuclear regulatory authorities through a series of authorizations or licences, and inspections. Requirements 3 and 4 of No. GSR Part 1 (Rev. 1) [11] set out the essential elements of a regulatory framework for nuclear safety:

> "**Requirement 3: Establishment of a regulatory body**
>
> **The government, through the legal system, shall establish and maintain a regulatory body, and shall confer on it the legal authority and provide it with the competence and the resources necessary to fulfil its statutory obligation for the regulatory control of facilities and activities.**
>
> "**Requirement 4: Independence of the regulatory body**
>
> **The government shall ensure that the regulatory body is effectively independent in its safety related decision making and that it has functional separation from entities having responsibilities or interests that could unduly influence its decision making.**"

The IAEA Safety Standards establish the general safety requirements to be met for decommissioning [1]. These are applicable to the decommissioning of nuclear power reactors, research reactors, other nuclear FCFs, including predisposal waste management facilities, facilities for processing naturally occurring radioactive material, former military sites, and relevant medical facilities, industrial facilities, and research and development facilities. The general safety requirements for decommissioning address all aspects of decommissioning throughout the life cycle of a facility, from the siting and design stage through to the termination of the authorization for decommissioning. The general safety requirements also elaborate on the various responsibilities for decommissioning of governments, the regulatory body and the licensees.

The IAEA has also published Safety Guides to assist Member States in meeting the safety requirements applicable to decommissioning. One such Specific Safety Guide addresses decommissioning considerations and actions for the safe decommissioning of nuclear power reactors, research reactors and other nuclear FCFs [6]. Another Specific Safety Guide addresses decommissioning considerations and actions for safe decommissioning of medical, industrial and non-reactor research facilities in which radioactive materials and sources are produced, used or stored [13].

The ultimate role of the nuclear regulator is to provide adequate oversight to ensure that nuclear activities are performed in a safe manner and in accordance with existing laws and regulations. Regulators are usually responsible for establishing regulations and guidance appropriate for ensuring the safety of decommissioning and radioactive waste management and for supervising, monitoring and enforcing the regulations. The independence of the regulatory body is important, and it is also emphasized in Article 20(2) of the Joint Convention [8].

Often a number of different regulatory bodies are involved in the regulatory oversight of nuclear activities in general, including decommissioning. For example, there may be differing regulatory arrangements for nuclear safety and radiological protection, conventional health and safety of personnel, and protection of the environment. Historically, statutory aspects related specifically to financing for decommissioning tend to be regulated separately from the technical and safety aspects of regulation relating to operation of nuclear facilities.

The IAEA has developed model regulations for decommissioning [12], providing information on an appropriate set of regulations covering all aspects of decommissioning. They are intended to be of assistance to States in both appraising the adequacy of their existing regulations and regulatory guides, and also serve as a reference for those States developing regulations for the first time. They include a brief explanation of the process for establishing the necessary legal and regulatory framework and of the regulatory process applicable to decommissioning.

The Western European Nuclear Regulators Association (WENRA) is an international body with representatives from the nuclear regulatory bodies of European countries with nuclear power reactors. In 2015 WENRA published its evaluation in the area of regulation of the decommissioning of nuclear installations in its member countries [14]. WENRA has developed safety reference levels (SRLs) for decommissioning activities, which are based on the corresponding IAEA safety requirements and guidance for decommissioning. The evaluation process is centred on the national benchmarking of legislation and regulations and how the implementation of these in each country meets the requirements of the decommissioning SRLs.

3.3. RESPONSIBILITIES FOR DECOMMISSIONING

Decommissioning of disused nuclear facilities is the responsibility of the licensee for that facility. This responsibility, which is typically established in national legislation, includes the provision of funds to cover the decommissioning costs. In the case of commercial nuclear power reactors and other income generating facilities, funds for decommissioning and long term waste management need to be set aside during the operating phase of the facility. Facilities used for research into the development and uses of nuclear energy are normally owned by the State or region in which the facility is located, in which case the decommissioning financing is likely to come from State resources, without the establishment of a fund during the operating lifetime.

In general, following permanent shutdown of a nuclear facility, the licensee implements decommissioning, using a management team drawn from its own staff, or employing a specialist contractor to oversee the project implementation. In some cases, responsibility for decommissioning is transferred from an operator to a dedicated State owned organization to implement the decommissioning; for example, Spain has a national decommissioning organization (Enresa) that implements the decommissioning of all nuclear facilities in Spain using funds that have been set aside during the operating period. Broadly similar arrangements apply in Italy (SOGIN) and in Slovakia (JAVYS).

Such arrangements are not limited to countries with extensive nuclear programmes. For example, a specialist state enterprise (Dansk Dekommissionering, DD) was established in 2003 to dismantle the six original nuclear research facilities in Denmark, and a similar organization (Norsk Nukleær Dekommisjonering, NND) was created in 2018 to undertake the decommissioning of the research reactors and other nuclear infrastructure in Norway.

In the United Kingdom, the Nuclear Decommissioning Authority (NDA) was established in 2004. The NDA's responsibilities currently include decommissioning and cleaning up of nuclear facilities at multiple sites, ranging from research facilities, through first generation gas cooled reactors, to large FCFs. The NDA's role is strategic rather than operational, in that it establishes the overall approach, allocates budgets, sets targets and monitors progress, but it does not have a hands-on role in cleaning up the facilities.

An emerging trend in the United States of America has been to transfer nuclear power reactors after permanent shutdown to specialist decommissioning enterprises, together with the funds that were set aside to implement decommissioning. The three entities to emerge in recent years are based on varying combinations of expertise and experience, with the aim of completing projects at lower overall costs than were envisaged for decommissioning under the original licensee.

There is an extensive supply chain of organizations and specialized companies involved in effecting different aspects of nuclear decommissioning, including contractors, equipment manufacturers and suppliers, personnel, management and consultancy services. These operate at different scales, with a number offering specialized services and products at the international level, while more are primarily active at regional or national level.

3.3.1. Human resource considerations

Human resource considerations, including the training of personnel, are crucial for the decommissioning of nuclear facilities [15]. The satisfactory performance of decommissioning programmes depends on various levels of involvement from all personnel, whatever the type of nuclear facility and the management procedures that are implemented. It should be noted that the national nuclear landscape, together with other ongoing infrastructure projects within each country and the organizational approach to project implementation, will have a significant influence on the main human resource (HR) activities impacting on decommissioning. The operating organization may have to recruit new personnel and establish new teams throughout the duration of the programme.

The transition from operations to decommissioning may bring some particular HR management challenges into focus, in terms of skills, recruitment, leadership, training and performance management, and even psychosocial factors. In this context, the IAEA has highlighted the importance of and provided guidance on the application of the systematic approach to training (SAT) methodology for training of nuclear facility personnel, including contractors [15, 16]. SAT methodology is now being applied to all types of nuclear facilities for various phases of a nuclear facility life cycle, including the operational phase and the decommissioning phase. The technologies being used in decommissioning have also advanced over this period, driven in particular by innovations in the use of digitalization and robotics. This changing landscape of technologies and how these are deployed in decommissioning also need to be considered in the HR management and training contexts.

3.3.2. Knowledge management for decommissioning organizations

Knowledge management (KM) has been defined as “An integrated, systematic approach to identifying, acquiring, transforming, developing, disseminating, using, sharing, and preserving knowledge, relevant to achieving specified objectives” [17]. For the purposes of this publication, the focus is on KM in decommissioning projects and for organizations undertaking decommissioning. However, it should be noted that there are other contexts for KM, and a thorough consideration of the topic would need to examine KM in decommissioning in these wider contexts.

The KM programme for decommissioning will include decommissioning strategies and plans for project management and control, through to decommissioning technologies, waste treatment, packaging and interim storage. Significant differences between facility operation and decommissioning entail that with the change from operation to decommissioning, it will also be necessary to adapt the KM programme. This process needs consideration well in advance of the start of decommissioning and will ideally be an integral element of decommissioning planning. During preparation for decommissioning it is necessary to define the critical knowledge, skills and competences to be transferred from operation, with these to be generated internally or acquired externally. This process also needs to consider the critical knowledge required for the subsequent steps, such as waste treatment, storage and disposal.

At an organizational level, a significant amount of new knowledge will be created during decommissioning and therefore the management system will ideally provide the basis for the KM programme by ensuring that knowledge preservation and knowledge transfer are properly organized and controlled. The management system needs to ensure that the processes for the identification, acquisition or generation, application and deployment of the knowledge necessary for decommissioning and the subsequent steps are also properly set up, executed and controlled. Changes in the management system itself (i.e. vision, mission, policies, aims) will be initiated during the transition from operations to decommissioning, and these changes may also influence the KM programme.

There is a wide range of recent and emerging technologies and tools, including advances in digitalization and data visualization, that could be integrated into KM programmes to support planning, management and execution of decommissioning. Section 7.6 provides a summary description of these and their relevance to decommissioning.

3.4. FINANCING ARRANGEMENTS FOR DECOMMISSIONING

The IAEA general safety requirements require national legislation to set out responsibilities in respect of financial provisions for decommissioning [1]. These provisions need to establish a mechanism to provide adequate financial resources to cover the costs associated with safe decommissioning, including management of the resulting waste.

A range of financing arrangements have been put in place for nuclear decommissioning in countries with established nuclear activities. The details of these financing arrangements vary considerably between countries, reflecting their diverse histories and institutional arrangements, the size and role of their nuclear industries, and expectations for future developments. Moreover, these arrangements continue to evolve, as countries review the arrangements and adapt them to be suitable to meet future decommissioning liabilities.

Operators of nuclear power reactors and other commercial facilities are typically responsible for the financing of all activities connected to the decommissioning of the facilities, and these costs are then passed on to customers. Generally speaking, the financial means to cover the costs of future decommissioning are accumulated while the nuclear facilities are productive and earning money. Where decommissioning is deferred, these costs may appear long after the nuclear power reactors have ceased to operate and at a time when funds are no longer being created from commercial operation.

Even where an immediate decommissioning strategy is followed, the accumulated funds will need to be managed throughout the operating period. It is therefore necessary to make arrangements to ensure long term funding. For this purpose, a special fund has been established in many countries to cover the costs of decommissioning and the associated radioactive waste management and disposal. In some countries (e.g. Finland and Sweden), combined funds cover the costs for decommissioning, spent fuel management and radioactive waste disposal. In other countries (e.g. Belgium, Germany, Switzerland, the United States of America), separate funding arrangements have been established for decommissioning and the costs of radioactive waste disposal.

A range of national strategies are applied by States to the management of the accumulated funds, and fund ownership or control also varies. In some countries, the operators may accumulate and manage their own decommissioning funds that remain in their own accounts (e.g. Belgium, France, Germany). In other countries, the funds are collected from the operators or via the electricity market system, and are managed by separate, independent bodies (e.g. Japan, the Republic of Korea, Sweden, Switzerland, the United States of America). Both management approaches have the same goal; namely, to cover the expected costs of decommissioning and to have the finances available at the time the costs are incurred. The funding scheme in Canada is characterized by the sharing of responsibilities between the national level, the provincial level and the licence holders, and relies primarily on a set of financial guarantees. For non-commercial facilities, such as government owned research facilities, decommissioning financing is typically through government funding, although the exact details vary widely. In countries where there are decommissioning liabilities arising from earlier nuclear activities, the State retains the responsibility for the decommissioning and the necessary resources are typically provided through government funding.

Examples of national financing schemes and funding mechanisms for spent fuel, radioactive waste and decommissioning are provided in Appendix III (Table 2). This information is drawn from Ref. [18].

A recent report by the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) examines funding arrangements for decommissioning and radioactive waste management in NEA member countries [19]. This report presents 12 detailed national case studies of funding arrangements for decommissioning and radioactive waste management.[21] An earlier NEA report specifically reviews nuclear power plant reactor decommissioning costs and funding practices adopted across NEA member countries [10].

A study on the risk profile of the funds allocated to finance the back end activities of the nuclear fuel cycle in the EU was published by the European Commission in 2019, and includes descriptions of the funding arrangements in EU member states [20].

3.5. ADDITIONAL SOURCES OF INFORMATION ON INSTITUTIONAL AND LEGAL FRAMEWORKS

This chapter provides a brief overview of institutional and legal frameworks for decommissioning, highlighting the principal features and more typical arrangements. However, there is considerable variation in the specific national arrangements, and these details are outside the scope of this project and publication. The following sources provide additional details on national institutional and legal frameworks:

(a) Summaries of national regulatory and institutional frameworks governing nuclear activities have been published for OECD and NEA member countries, as well as for India and China, on the NEA website: https://www.oecd-nea.org/law/legislation/

(b) Information on the waste management and decommissioning programmes of individual NEA member countries are also available on the NEA website, presented as country profiles and country reports. Both include information about the sources, types and quantities of waste, as well as how and by whom they are managed. **Country profiles** provide abridged information that allows for rapid familiarization with the country situation. **Country reports** provide detailed information for in-depth understanding. This information is available at: https://www.oecd-nea.org/rwm/profiles/

(c) Parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management provide national reports on how they meet their obligations under the Convention, including for decommissioning. A number of these reports have been made public: https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste/documents

4. DECOMMISSIONING STRATEGIES AND END STATES

4.1. GENERAL APPROACH

Decommissioning strategy denotes the sequence and timing of activities that facilitate achievement of the designated end state of a decommissioning project. Two main decommissioning strategies are recognized in the IAEA Safety Standards — immediate dismantling and deferred dismantling [1]. The former signifies that decommissioning begins shortly after permanent shutdown of the facility, whereas deferred dismantling envisages a delay after permanent shutdown during which the facility is maintained

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[21] The case studies are for: Belgium, Canada, Finland, France, Germany, Japan, the Republic of Korea, Spain, Sweden, Switzerland, the United Kingdom and the United States of America.

in a safe state (generally known as 'safe enclosure'), pending its later dismantling. For both strategies, the structures, systems and components of a facility containing radioactive material are eventually removed and/or are decontaminated to a level that permits the release of the facility from nuclear regulatory control, either for unrestricted use or with restrictions on its future use. Related decommissioning timelines are discussed in Section 4.2 in more detail.

The Safety Standards recognize that, in exceptional circumstances, there may be situations (e.g. after a severe accident) when part or all of a facility is encased — or 'entombed' — in a long lived structural material, further to which the facility remains under regulatory control for an extended period and is not released for other uses. Case study examples of different decommissioning strategies, including examples of the entombment approach, are presented in Appendix IV.

The selection of a decommissioning strategy may be influenced by several factors, and there are examples of where the initially selected strategy was subsequently changed [21]. The decommissioning strategy for Magnox nuclear power stations in the UK was recently changed from one in which all facilities were placed in an extended period of quiescence (deferred dismantling), to one based on site specific decommissioning approaches, which may result in some sites being decommissioned earlier than anticipated (i.e. the deferral duration is shortened) [22]. Decay storage of large components (e.g. steam generators), with later segmentation — as practised at some facilities in Germany — has elements of both strategies. The extent and spread of on-site contamination (and/or off-site contamination) can also influence the urgency of implementation of cleanup actions on the site and can influence the decommissioning timeline [23]. There are also many cases involving facilities that, although following an immediate dismantling approach, remain in a quiescent state for several years before active dismantling begins.

In cases of interdependences between facilities located on sites having more than one facility (multifacility sites), the decommissioning strategy for individual facilities can be coupled with a decommissioning strategy for the site as a whole, aiming at overall optimization of the use of resources and of supporting and waste facilities.

The intended future use of the site after completion of decommissioning has an impact on the selection of the decommissioning strategy, which is typically considered in the strategy selection process. Decommissioning actions are completed when the foreseen end state of the facility has been reached, and has been demonstrated to the satisfaction of the nuclear regulatory authorities. Release from nuclear regulatory control, with or without restrictions on the future use of the site and remaining structures or further utilization of the site for another nuclear facility, are possible end states that will have a major impact [24]. The questionnaire responses indicate that most facilities aspire to an end state involving the potential reuse of the site for non-nuclear purposes, in contrast to an end state involving ongoing institutional control — with the latter being more associated with research reactors than nuclear power reactors (see Fig. 17).

In many cases, permanent shutdown is followed by a phase of transformation of the organizational structure and of safety systems, pending the commencement of decommissioning actions. During this post-operational phase[22] — sometimes referred to as a 'transition period' — spent fuel and process fluids are typically removed from the facility [6]. The duration of this phase can vary significantly, depending, inter alia, on the reasons for permanent shutdown (planned or unforeseen) and the extent of preparatory work undertaken before final shutdown. The questionnaire responses indicate that most facilities are permanently shut down according to a time frame determined by the operator ('planned procedure'), although political interventions have also gained in importance during the past decade (see Fig. 18).

The selection of a decommissioning strategy is generally the responsibility of the licensee for that facility. The process of strategy selection depends on multiple factors, including the national regulatory frameworks, safety or environmental requirements, local conditions, financial considerations and solutions for storage or disposal of radioactive waste, as well as the type of facility and its radiological inventory.

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[22] There are various terms in common use to refer to the phase of activity immediately following the shutdown of the facility, including 'transition', 'deactivation' and 'post-operational clean out' (POCO).

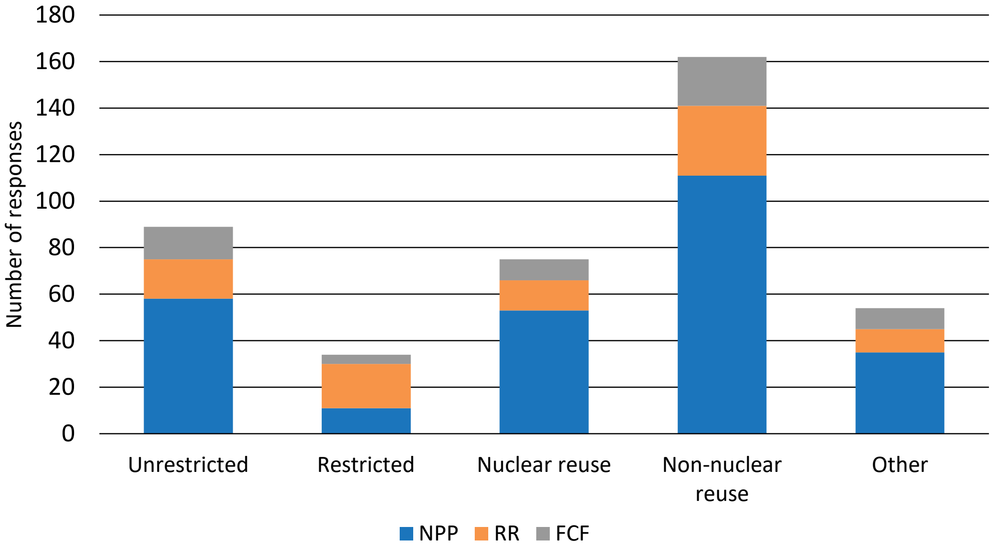

FIG. 17. Predicted end state by type of facility.

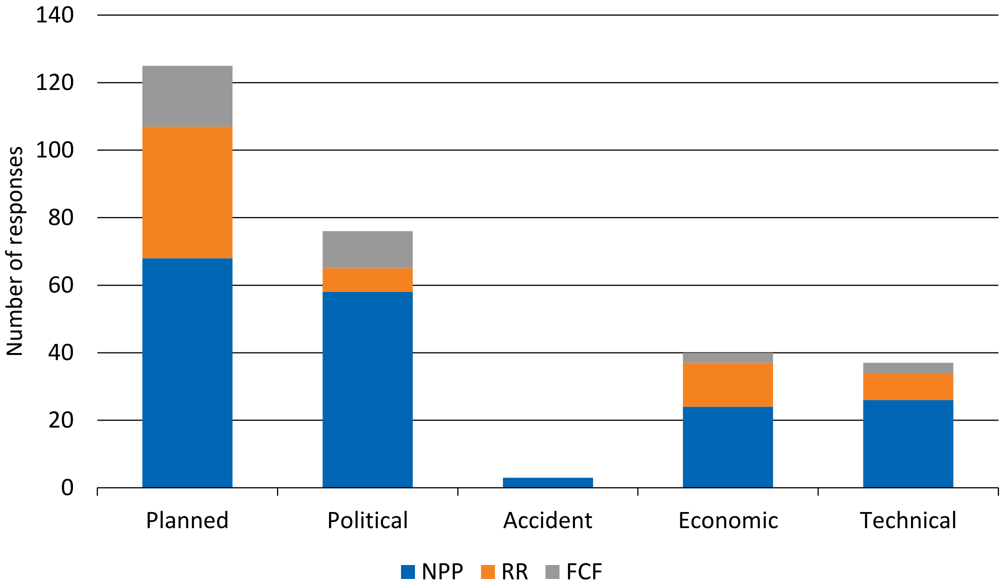

FIG. 18. Reasons for shutdown of nuclear facilities (NPPs, RRs, FCFs).

The weighting of such factors in the strategy selection process depends on the relevant national, political and cultural background — see Section 4.3.

In contrast to other existing studies [25] examining the future of nuclear decommissioning by means of desk based data research extrapolated from existing data sets such as the PRIS database, the results presented here are based solely on analysis of questionnaire responses received over the course of the project, comprising data for past activities and planning values for future activities.

4.2. DECOMMISSIONING TIMELINE

For the purposes of this publication, the following main phases of activity were assumed to occur following permanent shutdown of a nuclear facility:

(a) Post-operation — during which spent fuel (where present) and highly active process fluids and operational waste are removed and safety systems are reconfigured to support the active dismantling phase.
(b) Safe enclosure (where applicable) — during which the installation is maintained in a safe state with minimal interventions over a period of years or decades.
(c) Dismantling — during which the structures, systems and components of a facility are taken down and disassembled, and removed. In this phase, radioactively contaminated plant and equipment are decontaminated and processed either to radioactive waste or released, depending on the levels of residual radioactive contamination.
(d) Demolition — during which the remaining structures are taken down following the dismantling phase and residual contamination is removed so that the approved end state is achieved.

The maximum duration of certain phases or the dismantling process as a whole may be stipulated in national regulations; for example, the regulations of the US Nuclear Regulatory Commission (NRC) require NPP reactor decommissioning to be completed within 60 years of permanent closure of a power reactor and limit safe enclosure periods[23] to 50 years to allow up to 10 years for project completion. Immediate dismantling[24] is the main alternative strategy adopted in the United States of America [26]. Decommissioning projects in Germany have typically been implemented following a phased approach, but general requirements for the duration of phases do not exist in the regulatory framework. Questionnaire responses indicate long time spans between permanent shutdown and achievement of the approved end state — more than 30 years for many facilities (dominated by NPPs). Shorter time spans, of less than 10 years, are typical for research reactors (see Fig. 19).

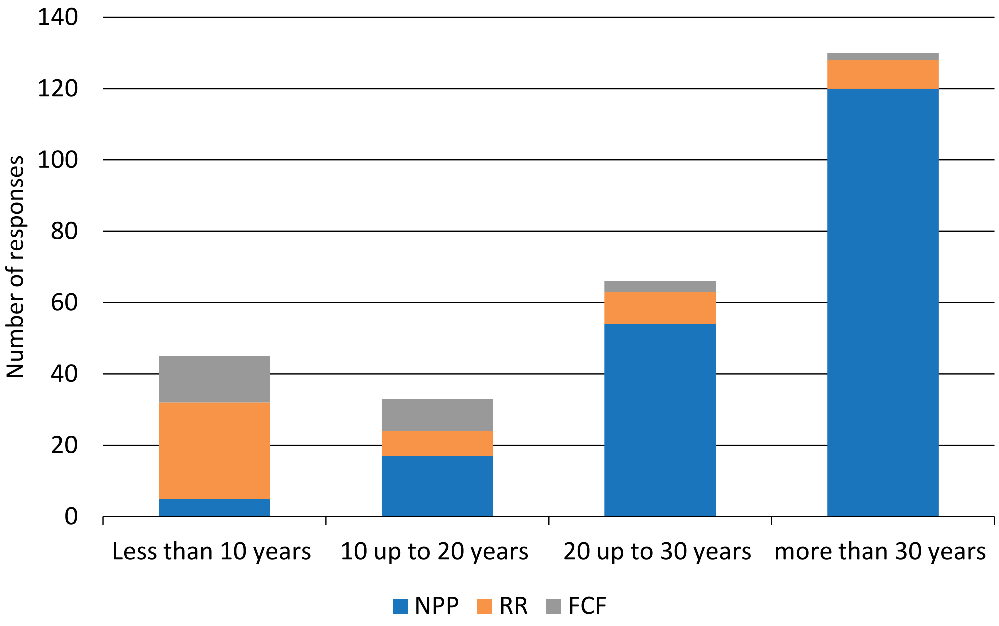

FIG. 19. Time elapsed between end of operation and achievement of end state.

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[23] Often referred to as SAFSTOR in the United States of America.

[24] Often referred to as DECON in the United States of America.

For NPPs and research reactors, the progress of defuelling has a significant influence on the timing of the main dismantling activities. For the majority of programmes 'defuelling' implies that spent fuel (fuel assemblies and defective rods) is completely removed from the reactor and the spent fuel pool and is shipped to an external storage facility, such that no spent fuel remains in the facility to be decommissioned. Based on information requested subsequent to the initial questionnaire responses, completion of defuelling is a condition for commencing decommissioning in some countries (e.g. Czech Republic); that is, the decommissioning licence is not granted until this has been achieved.

Notwithstanding the above, the questionnaire responses indicate that ~21% of nuclear power reactors (2% in the case of research reactors) with a decommissioning strategy based on immediate dismantling begin active dismantling while spent fuel remains in the reactor or spent fuel pool. For example, in Germany removal of spent fuel is not a precondition for granting a decommissioning licence and there are several examples in which dismantling is proceeding with spent fuel remaining in the facility. Where spent fuel assemblies and defective rods remain in the facility, the safety implications are addressed in the safety analysis supporting the application to proceed with decommissioning. Even in situations where a deferred dismantling strategy is being followed, there are examples — approximately 5% of NPPs — where the safe enclosure phase begins while fuel in still present in the facility.

Questionnaire respondents were requested to indicate the actual or planned duration of the period between permanent shutdown of a facility and the commencement of active dismantling (in the case of immediate dismantling) or safe enclosure (in the case of deferred dismantling). A summary of the results for nuclear power reactors, research reactors and FCFs following an immediate dismantling strategy is shown in Fig. 20.

In Fig. 20 and similar figures in this section, box chart graphs are used to indicate the spread in the data. The 25th and 75th percentile values and the median are shown within a box on the figure, with the median (hereafter referred to as 'MED') being represented as a horizontal line inside the box. Additional bars (outside the box) indicate the 5th and 95th percentile values. The responses represented in this figure indicate a median period of approximately nine years from permanent closure until the start of dismantling in the case of nuclear power reactors, a median period of six years in the case of research reactors and a median period of approximately two years in the case of nuclear FCFs.

The questionnaire responses concerning the durations of different decommissioning phases are based partly on assumptions associated with a high level of confidence (i.e. the information is historical

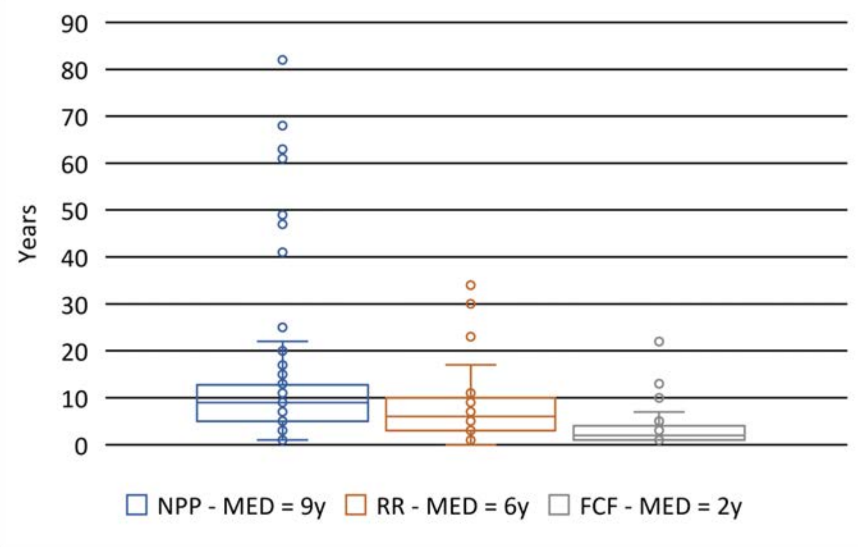

FIG. 20. Duration between shutdown and start of dismantling (transition period) for facilities without safe enclosure (118 NPPs, 51 RRs, 36 FCFs). Horizontal lines represent the median, vertical lines represent spreading, dots represent values and rectangles represent the third and first quartiles. MED, median.

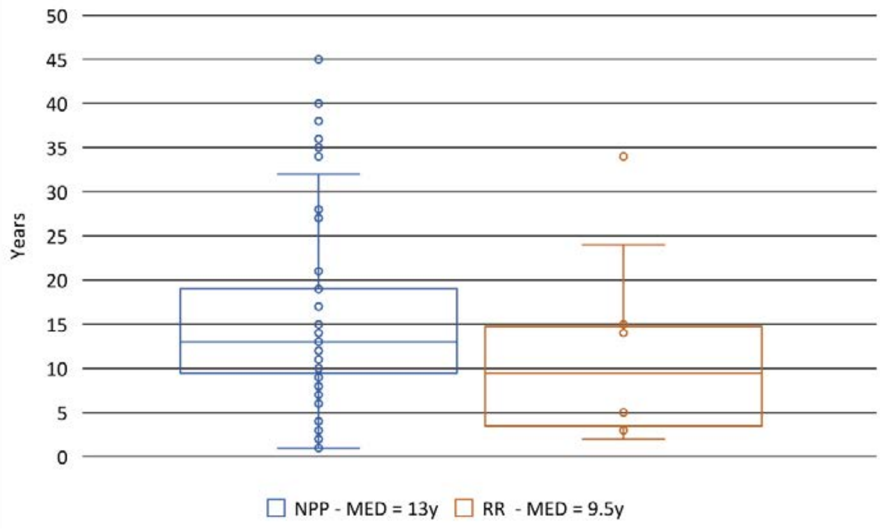

FIG. 21. Duration between shutdown and start of safe enclosure (87 NPPs, 10 RRs, 0 FCFs). Horizontal lines represent the median, vertical lines represent spreading, dots represent values and rectangles represent the third and first quartiles. MED, median.

or relates to the near future), and partly provide estimated dates in the longer term, for which confidence levels are necessarily lower. It appears that some facilities have post-operational (or transition) periods significantly greater than 10 years (see Appendix IV, e.g. Latina NPP in Italy), with two NPP outliers indicating delays of more than 40 years as a result of an extended defuelling phase due to damaged fuel elements. In such cases, although an immediate dismantling approach may have been adopted, the strategy being followed in practice also incorporates elements of deferred dismantling.

The questionnaire responses suggest that the median duration of the period between permanent shutdown and the start of safe enclosure (Fig. 21) is typically longer than the period between permanent shutdown and the start of immediate dismantling (Fig. 20), with a very large range of durations in the case of NPPs (i.e. 13 year MED delay prior to safe enclosure as compared to 9 years prior to active dismantling).

Considering questionnaire responses for facilities undergoing immediate dismantling without previous safe enclosure (Fig. 22) shows significantly longer median dismantling phases for NPPs (15 years) compared to research reactors (2 years), indicating that many research reactor decommissioning projects are small projects. The questionnaire responses addressing the duration of safe enclosure (where applicable) — as shown in Fig. 23 — suggest a very wide range of current practice, particularly in the case of NPPs, where the majority of data are within a range of two to six decades, with a median of approximately three decades. In the case of research reactors the range is somewhat narrower, with a median of 25 years.

The median duration of the dismantling phase for NPPs after safe enclosure of ~9 years (deferred dismantling, see Fig. 24) is shorter than the average duration of the dismantling phase for NPPs without safe enclosure of ~15 years (immediate dismantling, see Fig. 22), suggesting a significant reduction in the duration of the subsequent decommissioning. This project did not explore the underlying reasons for this difference in duration or other important factors in the choice between the two strategies. In the case of deferred dismantling, the median safe enclosure phase is 30 years for nuclear power reactors and ~25 years for research reactors (Fig. 23).

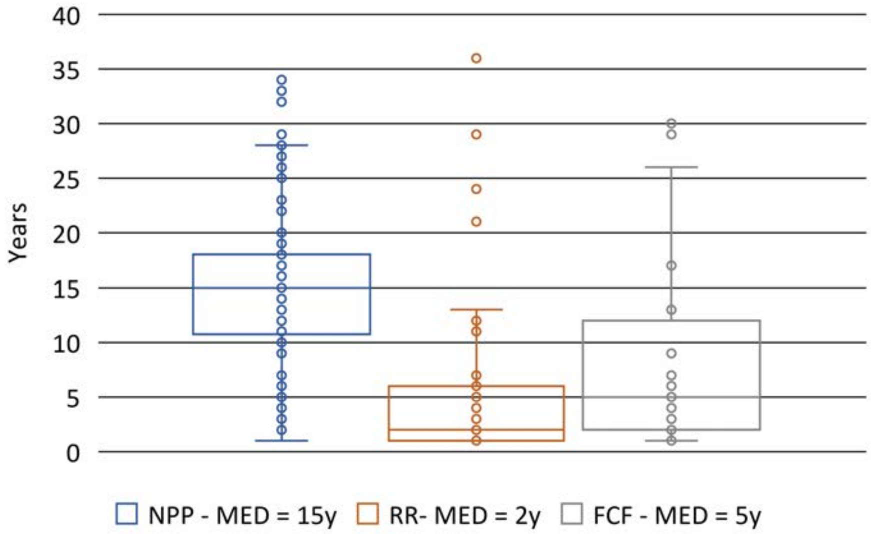

FIG. 22. Duration of dismantling phase without safe enclosure (96 NPPs, 48 RRs, 30 FCFs). Horizontal lines represent the median, vertical lines represent spreading, dots represent values and rectangles represent the third and first quartiles. MED, median.

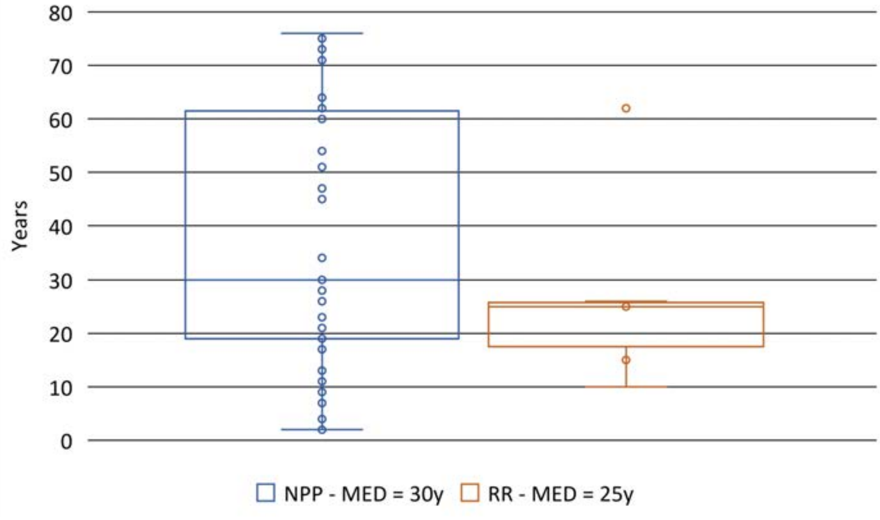

FIG. 23. Duration of safe enclosure phase (87 NPPs, 6 RRs, 0 FCFs). Horizontal lines represent the median, vertical lines represent spreading, dots represent values and rectangles represent the third and first quartiles. MED, median.

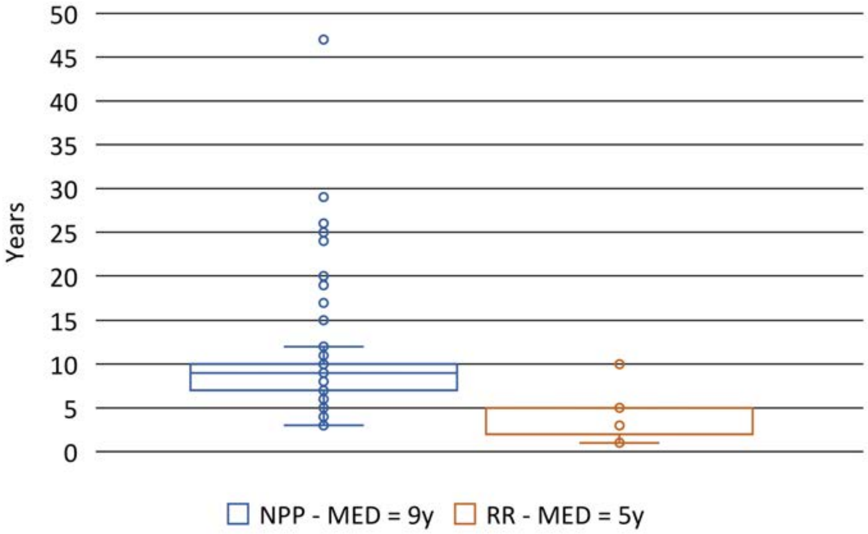

FIG. 24. Duration of dismantling phase for facilities with safe enclosure (85 NPPs, 7 RRs, 0 FCFs). Horizontal lines represent the median, vertical lines represent spreading, dots represent values and rectangles represent the third and first quartiles. MED, median.

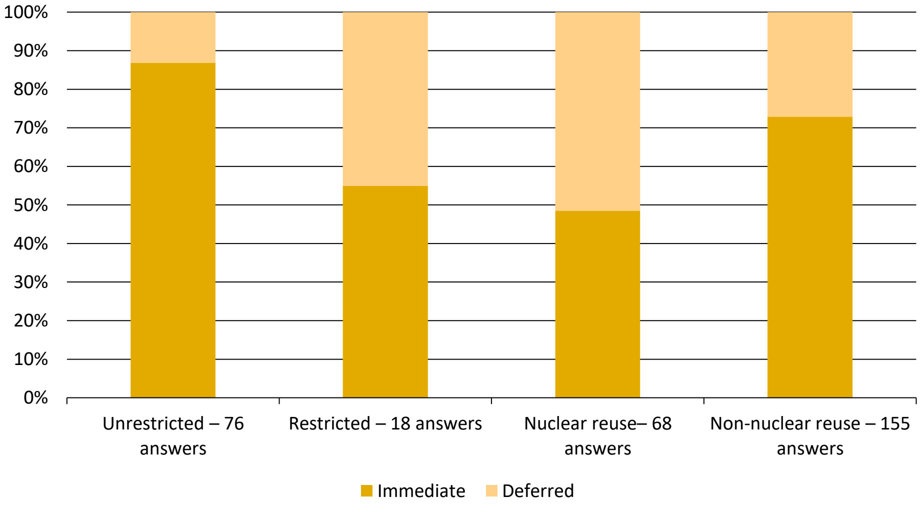

FIG. 25. Influence of end state on decommissioning strategy for the end states unrestricted release, release with restrictions, release with intended nuclear reuse and release for a specific non-nuclear reuse.

The data suggest that the median durations of all major phases (post-operational period, safe enclosure and dismantling) are often sufficiently long that regulators may require periodic safety reviews in order to ensure safety during the whole process.

The questionnaire responses suggest a preference for immediate dismantling strategies in cases where the end state is unrestricted release or the planned future use is industrial (non-nuclear) reuse, as shown in Fig. 25.

Figures 26–28 show the durations of dismantling phases by end state for nuclear power reactors, research reactors and FCFs, including both types of decommissioning strategies. Relatively few responses were received and these are not considered large enough to draw firm conclusions as to the implications of different end states for the duration of the dismantling phases. It is worth noting that the majority of the data results indicate durations of the dismantling phase in the range of 10–15 years for nuclear power reactors. The data for research reactors suggest a wide range of results, including very short dismantling ranges of approximately one year. The results for nuclear FCFs are too sparse to draw firm conclusions.

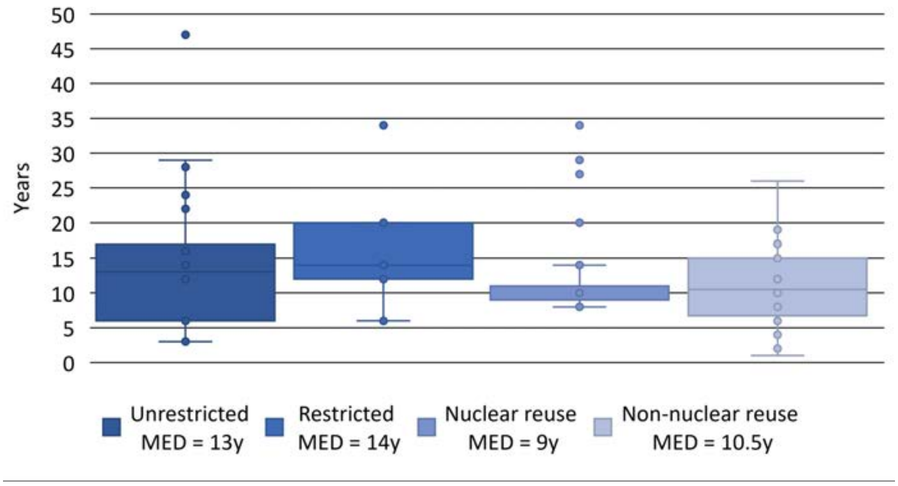

FIG. 26. Duration of dismantling phase for NPPs by end state (33 unrestricted, 9 restricted, 46 nuclear reuse, 87 non-nuclear reuse). Horizontal lines represent the median, vertical lines represent spreading, dots represent values and rectangles represent the third and first quartiles. MED, median.

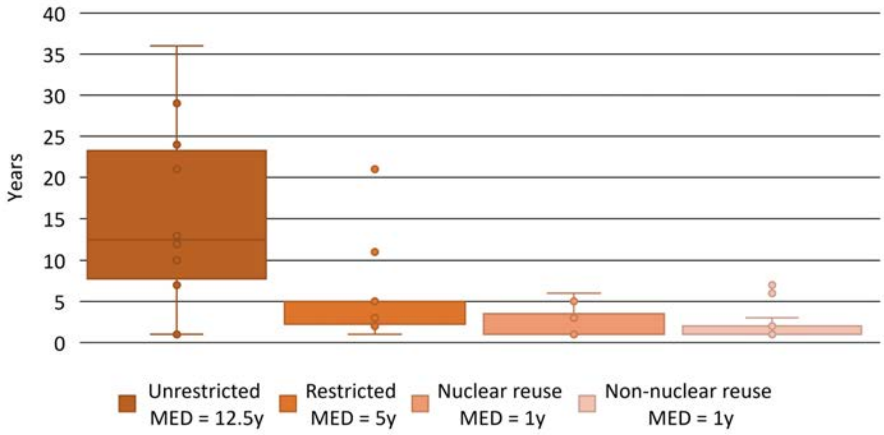

FIG. 27. Duration of dismantling phase for RRs by end state (10 unrestricted, 10 restricted, 8 nuclear reuse, 23 non-nuclear reuse). Horizontal lines represent the median, vertical lines represent spreading, dots represent values and rectangles represent the third and first quartiles. MED, median.

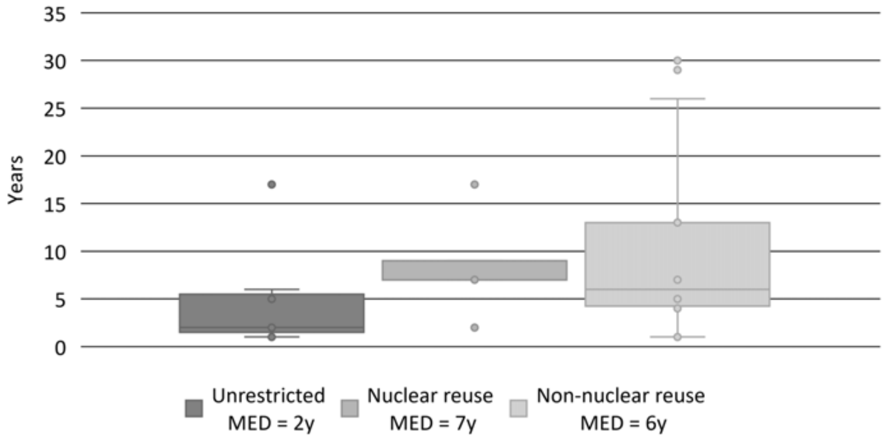

FIG. 28. Duration of dismantling phase for FCFs by end state (2 unrestricted, 0 restricted, 7 nuclear reuse, 6 non-nuclear reuse). Horizontal lines represent the median, vertical lines represent spreading, dots represent values and rectangles represent the third and first quartiles. MED, median.

4.3. DRIVERS FOR STRATEGY SELECTION

The strategy selection process for decommissioning of a nuclear facility requires consideration of the following overarching aspects:

(a) Historical considerations (‘past’);
(b) Capabilities and options (‘present’);
(c) End state objectives (‘future’).

Appropriate consideration of a facility’s history requires definition of its initial situation after permanent shutdown, including the radiological inventory and condition of systems and components, as well as the reasons for shutdown. An analysis of capabilities and options is required to evaluate enabling factors for project implementation, such as waste infrastructure, staff, knowledge and financial reserves. The ultimate aim of the decommissioning process is an important consideration, encompassing the planned end state of the facility and the material and waste treatment options, as well as waste disposal options [27], in order to develop a sustainable decommissioning strategy [28].

Factors that typically influence strategy selection decisions include national regulatory frameworks, safety or environmental requirements, site considerations, financial considerations and solutions for storage or disposal of radioactive waste, as well as the type of facility and its radiological inventory [24]. Each factor influencing the selection of the decommissioning strategy can be associated with one of the above overarching aspects. The main factors influencing the selection of the decommissioning strategy are described in IAEA Safety Standards Series, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities, No. SSG-47 [6]:

“— The national policy and the regulatory framework;
— The type of facility and interdependences with other facilities or infrastructure located at the same site;
— Proposed reuse of the facility or site and the desired end state;
— The physical status (e.g. ageing components and structures) and the radiological status of the facility;
— Safety and nuclear security aspects;

- The availability of expertise (knowledge, skills and experience), technologies and infrastructure (tools, equipment, supporting facilities and services);
- The environmental impact of the facility and of its decommissioning;
- Societal and economic factors and the socioeconomic impact of decommissioning;
- The availability of infrastructure for radioactive waste management, including facilities for pretreatment, treatment, conditioning and storage of waste, as well as existing or anticipated waste disposal options;
- The availability of financial resources for decommissioning."

The combined questionnaire responses for all nuclear facilities suggest that 'national policy/legislation' and 'waste infrastructure availability' are the dominating drivers for selection of a decommissioning strategy (see Fig. 29). The responses (Figs 30-34) further indicate that 'technology/technical readiness' is not a dominant driver for strategy selection, which may be a reflection of the perceived maturity of the decommissioning process. 'Personnel/skills/knowledge' appears not to be a determining driver for strategy selection according to the questionnaire responses, perhaps because competent personnel are required for both decommissioning strategies.

For research reactors and FCFs, 'national policy/legislation' remains a dominating driver, but the importance of 'company strategy' increases significantly in comparison to nuclear power reactors, reaching equal importance for FCFs (see Fig. 32). The responses indicate that 'decay/dose management' plays no decisive role for selection of a decommissioning strategy for FCFs. There were a small number of responses from FCFs following a deferred dismantling strategy for decommissioning (see later Fig. 43).

A number of countries specify in national policy that an immediate dismantling strategy for decommissioning is required. For example, in Germany immediate dismantling of shutdown NPPs has been stipulated by law since 2017 [29]. The competent authority may grant exemptions for plant components on a case by case basis, as long as this is necessary for radiation protection reasons. In Italy, responsibility for decommissioning of nuclear facilities was assumed by the state owned company Sogin in 1999 [30]. Since that time, all permanently shutdown NPPs and FCFs have followed an immediate, rather than deferred, dismantling strategy (see Appendix IV — national and facility specific examples).

A more detailed analysis of drivers for NPP reactors decommissioning strategy selection according to reactor types — see Fig. 33 for light-water reactors (LWRs)[25] and Fig. 34 for graphite reactors (GRs)[26], suggests that the drivers 'waste infrastructure availability' and 'decay/dose' are more important for graphite moderated reactors than for light-water reactors. This is an indication of the greater challenges with waste management and radiation protection for decommissioning of graphite moderated reactors, resulting in a significantly higher fraction of such reactors with deferred dismantling strategies compared to light-water reactors (see Fig. 43). The lack of a generally accepted approach internationally for treatment and disposal of irradiated graphite waste is likely to be a dominating factor (see Appendix IV — Chinon A example).

The type of the facility has an impact on the selection of a decommissioning strategy, together with the characteristics of the site on which the facility is located. When more than one reactor or facility is located on a site the overall decommissioning strategy for the site can lead to deferring dismantling of shutdown reactors or facilities, for instance until the reactors or facilities still in operation are permanently shut down (see Fig. 35 for NPPs and FCFs and Appendix IV — Douglas Point example). Interdependences between nuclear facilities are normally greater on multifacility sites, sometimes only allowing partial dismantling of a particular nuclear facility, for example when systems are used by several facilities and need to remain in operation.

The Sellafield site in the UK provides an example of a multifacility site that follows a site wide strategy involving interim and final end states being defined in increasing detail as progress on risk and hazard reduction is achieved (see Appendix IV — national and facility specific examples). For

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[25] Light-water reactors comprise PWRs and BWRs in this publication.

[26] Graphite reactors comprise GCRs and LWGRs in this publication.

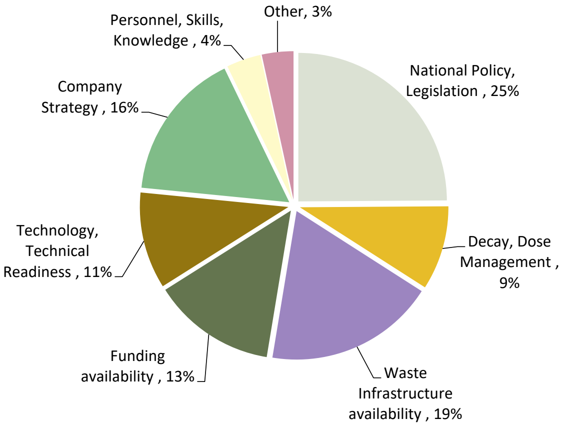

FIG. 29. *Drivers for decommissioning strategy (all facilities).*

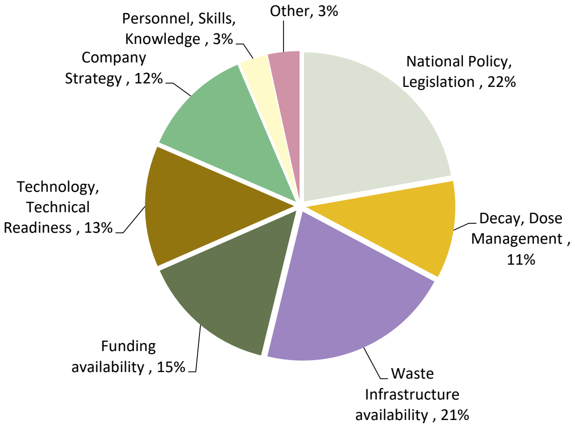

FIG. 30. *Drivers for NPP reactor decommissioning strategy.*

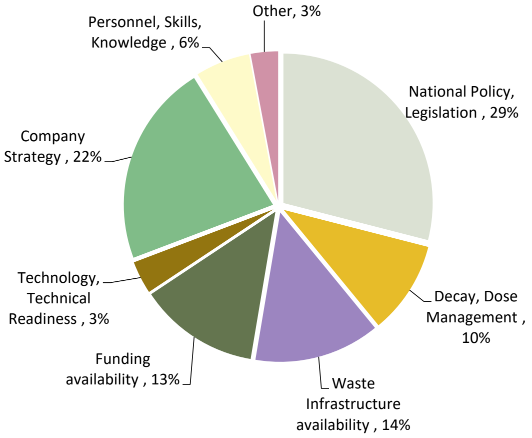

FIG. 31. *Drivers for RR decommissioning strategy.*

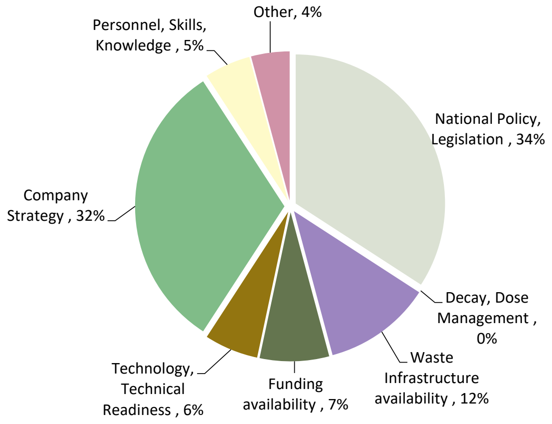

FIG. 32. *Drivers for FCF decommissioning strategy.*

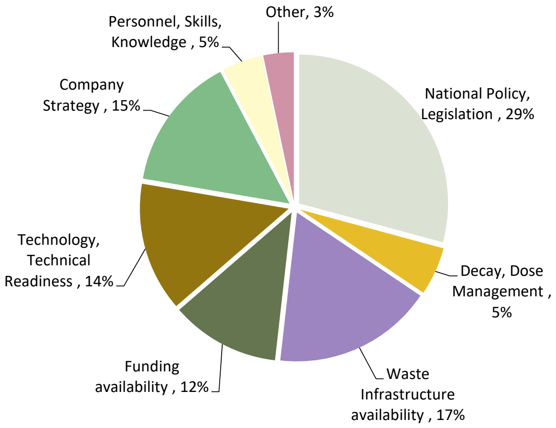

FIG. 33. *Drivers for LWR decommissioning strategy.*

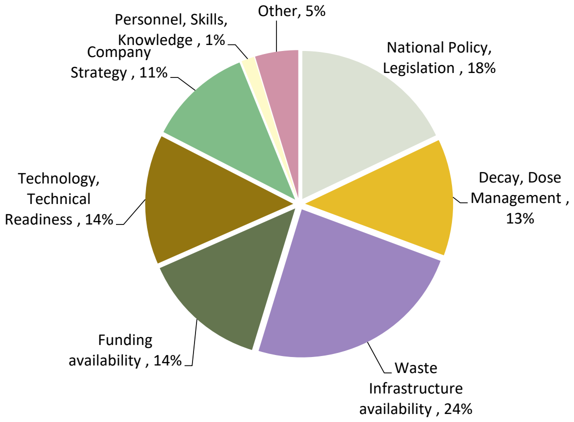

FIG. 34. *Drivers for GR decommissioning strategy.*

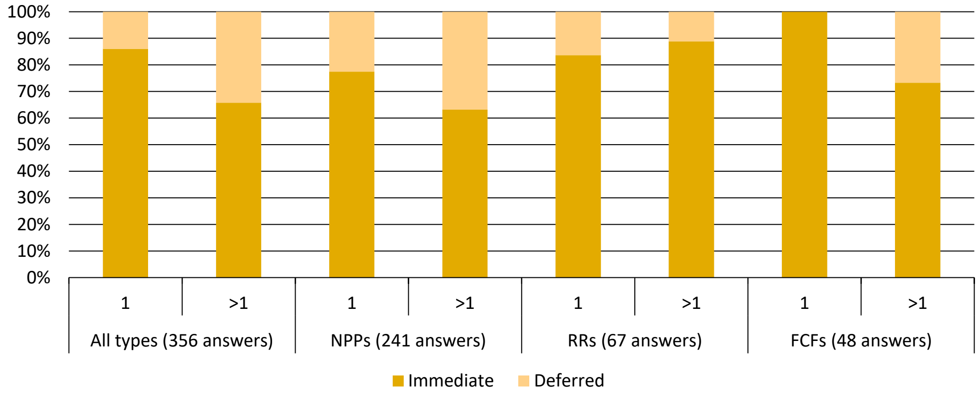

FIG. 35. Decommissioning strategy vs number of reactors (NPPs and RRs) and facilities (FCFs) on site.

this purpose the Sellafield site has been divided into two discrete zones for the purpose of defining the ultimate end state — an inner zone and an outer zone. It is envisaged that any new disposal facilities or long term storage activities will be located in the inner zone, which will be expected to be subject to ongoing institutional controls.

Plans for reuse of a site or facility after decommissioning are an important consideration in the selection of a decommissioning strategy. For German NPP decommissioning projects undergoing immediate dismantling, following the phase out decision in 2011, the end state of decommissioning is unrestricted release[27] with subsequent demolition of buildings or reuse of buildings.

The extent of contamination and the radiological status of a facility depend on operating time, past operating practices and events; this is an important consideration when selecting a decommissioning strategy. Although high radiation levels caused by short lived radionuclides can increase the attractiveness of a deferred dismantling, as this will allow radiation levels to decrease over time, other factors associated with loss of knowledge and the need for long term maintenance to keep the facility in a safe condition are often dominant. The questionnaire responses suggest an increasing preference for immediate dismantling strategies in the case of NPPs, though with significant numbers still following a deferred dismantling approach, especially the graphite moderated reactors (see Fig. 43). Immediate dismantling is generally indicated as being the preferred strategy in questionnaire responses for research reactors and FCFs.

The availability of radioactive waste management systems and infrastructure is also an important consideration when selecting a decommissioning strategy. When radioactive waste storage or disposal facilities are not available, the decommissioning strategy can include a period of safe enclosure until the necessary waste management infrastructure is available. As a consequence, the driver ‘waste infrastructure availability’ has greater relevance for graphite moderated reactors (see Fig. 34) compared with light-water moderated reactors (see Fig. 33).

Changes in the periphery of a facility since the time it was constructed can be a driver for strategy selection; for example, the transformation of a nuclear research centre (Grenoble, France) to a new centre for nanotechnologies necessitated the centre being denuclearized, involving immediate dismantling and cleanup of six nuclear facilities at the centre over a 15 year time frame.

There are also examples with a change of strategy as a result of changing main drivers:

— NPP Lingen (KWL), Germany — which was in safe enclosure from 1988 until 2015. Expecting the likely availability of a disposal facility for decommissioning waste in the future, the operator decided to withdraw the application for further safe enclosure in 2007 and applied for dismantling of the facility (licenced in 2015).

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[27] Release from regulatory control without restrictions on the future use of the site.

- Experimental High-Temperature-Reactor in Jülich, Germany (AVR; see Appendix IV) — for which safe enclosure was planned and under implementation. In 2003 the decommissioning strategy was changed to immediate dismantling to accelerate subsequent cleanup of contaminated soil around the reactor building. The AVR reactor vessel was removed and transported as a large component to an interim storage facility on-site. A concept and technique for later segmentation of the reactor vessel are under development [29].
- Latina Nuclear Power Plant (single Magnox reactor type in Italy; see Appendix IV). The strategy changed from a single phase decommissioning to a new one articulated in two distinct phases due to uncertainties regarding the availability of a national repository and the lack of solutions for long term storage of radioactive graphite from the reactor building decommissioning.
- Douglas Point Demonstration Nuclear Generating Station, Canada (see Appendix IV). A number of factors led to a reconsideration of the business case for a deferred dismantling strategy. The outcome of the review was a decision to accelerate the decommissioning of the facility; the first phase began in 2021 and decommissioning is expected to be completed by 2035.

Changes of preferred decommissioning strategies can be driven by a variety of reasons:

- A paradigm shift from deferred to immediate dismantling in the USA is reported in press publications, ascribed to a complex intersection of diverse economic factors in the US decommissioning market [26];
- In 2000 the French utility Électricité de France (EDF) modified the decommissioning strategy for its first generation of NPPs from deferred to immediate dismantling;
- Over the course of reorganization of responsibilities for nuclear waste management in Germany in 2017 it was stipulated by law that shutdown NPPs had to be dismantled immediately (the only exceptions being in certain cases for parts of the facility with radiological justification);
- In 1999 immediate dismantling was designated as being the envisaged decommissioning strategy for the permanently shutdown Italian NPPs, instead of safe enclosure [30].

4.4. TRENDS AND VARIATIONS

The questionnaire responses were analysed in order to identify potential trends and variations regarding strategy selection and end states, with a particular focus on:

(a) Regional variations (using the PRIS regions);
(b) Temporal trends (subdivided into five year intervals);
(c) Facility type variations (classification of facilities).

The questionnaire results have been analysed in view of potential differences in decommissioning strategy selection, potential end states and main drivers for strategy selection as a function of regions. Potential reasons for regional variations in strategy selection include:

- National policy (e.g. relating to the use of nuclear technologies);
- Level of experience (decommissioning experience available or first time decommissioning);
- Multifacility sites and site strategy;
- Availability of a disposal site.

Due to information gaps in questionnaire responses for some regions, only generic statements can be made regarding the situation in Europe — Western and Europe — Central and Eastern, where most of the responses were received and which dominate the illustrated worldwide situation in this report. Regions such as America — Northern and Asia are underrepresented in this analysis.

Examples of shut down of NPPs following political decisions can be found in Italy (following the Chernobyl accident in 1986) and in Germany (following the Fukushima Daiichi nuclear accident in 2011). Responses show that political reasons have been an important consideration for the timing of reactor shutdowns since the Chernobyl accident (1986), subsequently reaching a peak in 2010—2014 following the Fukushima Daiichi nuclear accident in 2011 (see Fig. 36).[28] Note that the absolute number of responses for shutdown NPPs in periods before 1985 is smaller than for periods afterward.

Analysis of the questionnaire responses indicates immediate dismantling as being the most common decommissioning strategy globally. For Europe — Western as well as Europe — Central and Eastern, immediate dismantling is the most frequently chosen decommissioning strategy (see Fig. 37).

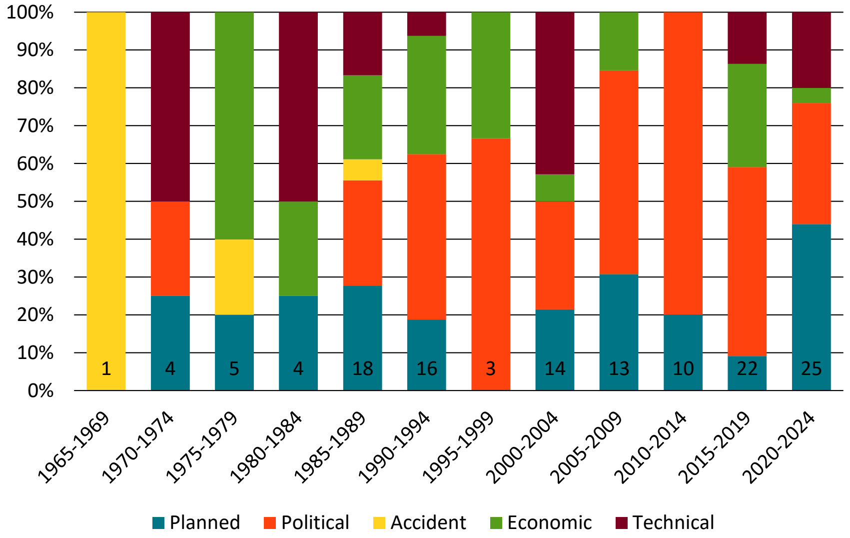

FIG. 36. Distribution of main reasons for shutdown of NPPs in the past (135 reactors), in five year periods. Absolute number of facilities shut down in five-year periods are included.

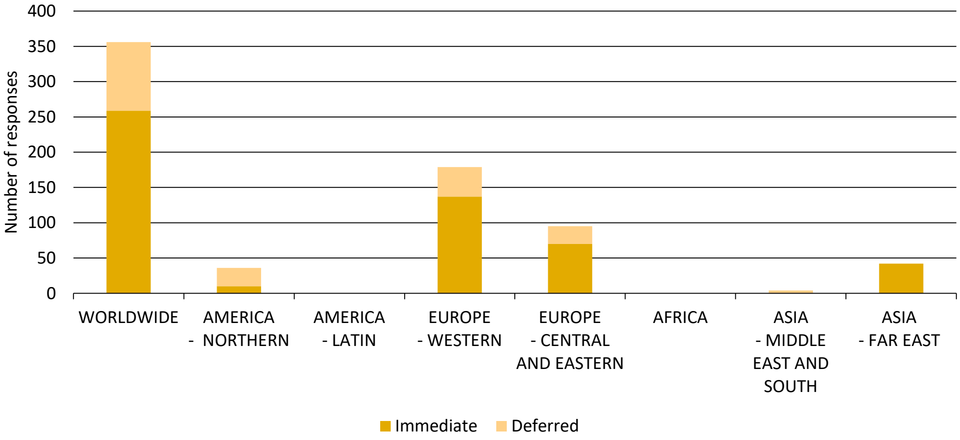

FIG. 37. Decommissioning strategy by region (356 responses).

Note: *For Asia — Middle East and South there were four responses in total, indicating deferred dismantling.*

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[28] No questionnaire answer was received from the Fukushima Daiichi nuclear power plant therefore no accident indication was recorded in the period 2010–2014.

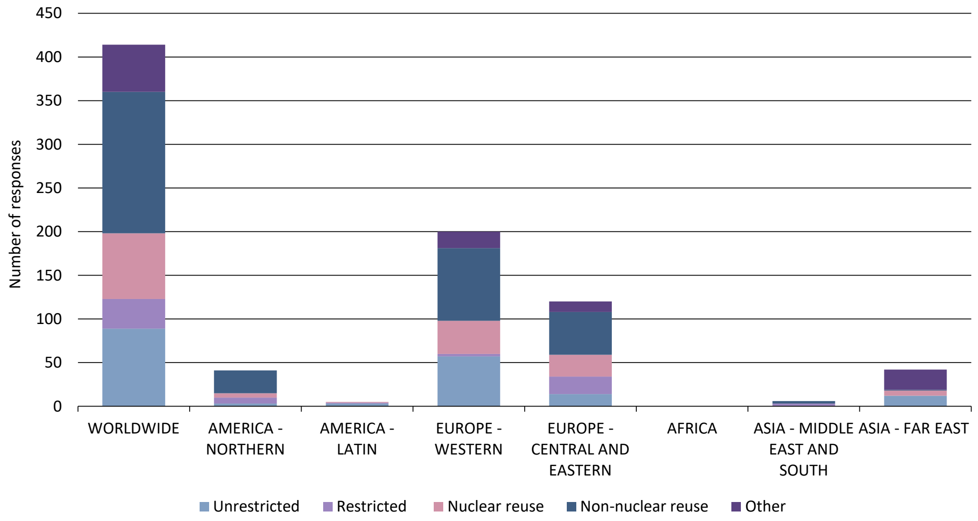

FIG. 38. Predicted end state by region.

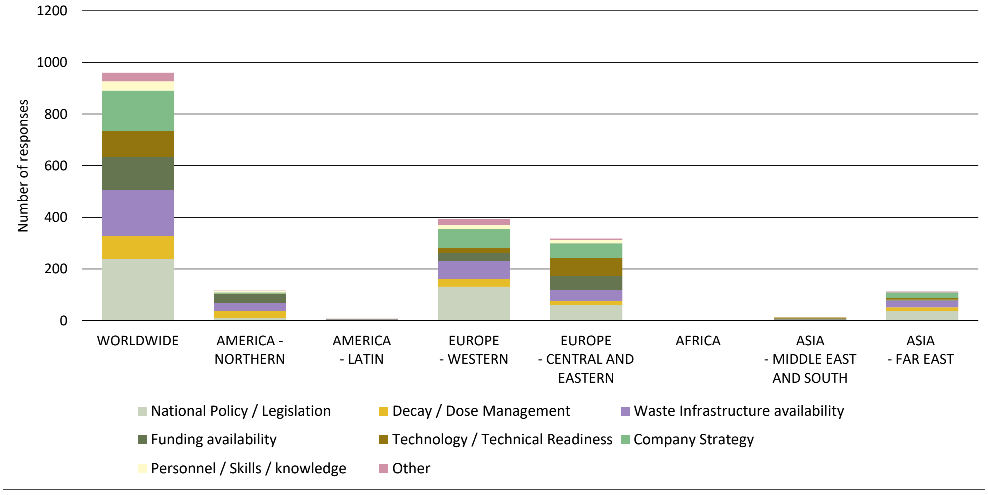

FIG. 39. Drivers for decommissioning strategy selection by region.

The responses show that the most common planned end state is ‘non-nuclear reuse’ (e.g. reuse of the site for industrial purposes). ‘Unrestricted release’ is the next most commonly indicated planned end state (see Fig. 38).

The responses show that ‘national policy/legislation’ followed by ‘waste infrastructure availability’ are identified as the main drivers for selection of decommissioning strategy globally, with some variation on drivers between regions Europe — Central and Eastern and Europe — Western (see Fig. 39).

The proportion of responses indicating immediate dismantling strategy decisions for all types of NPPs (see Fig. 40) increased throughout the period from 2000 to 2004 (over 60%) until approximately 2015–2019 (almost 90%). The increase was interrupted during the 2020–2024 time frame, largely as a result of the UK’s GCRs adopting deferred dismantling strategies [22]. The preference for immediate dismantling is particularly evident when only LWRs are considered (see Fig. 41) compared to GRs (see Fig. 42).

The increase of immediate dismantling decisions in the period 2000–2004 until 2015–2019 is caused by the larger number of LWRs shut down compared with the numbers of GRs shut down during this period.

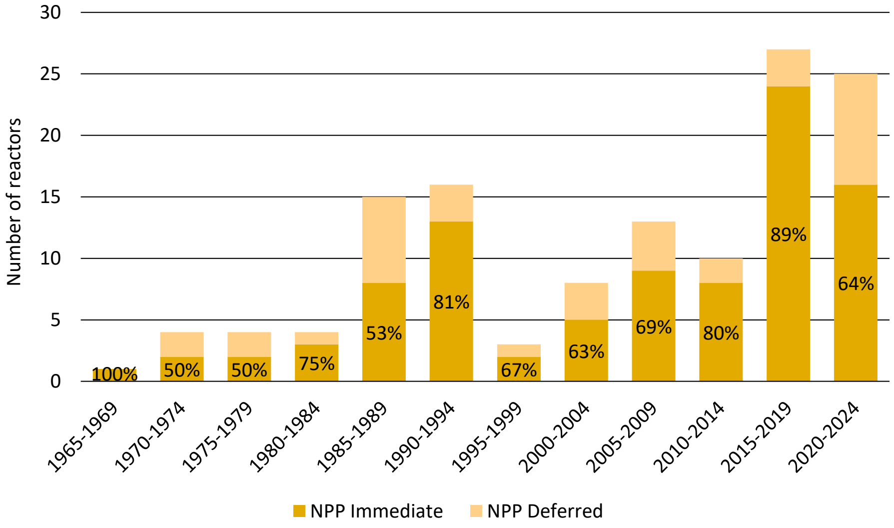

FIG. 40. Strategy decisions for shutdown nuclear power plants (all types) (five year periods). Percentages inside the bars represent the portion of immediate dismantling decisions.

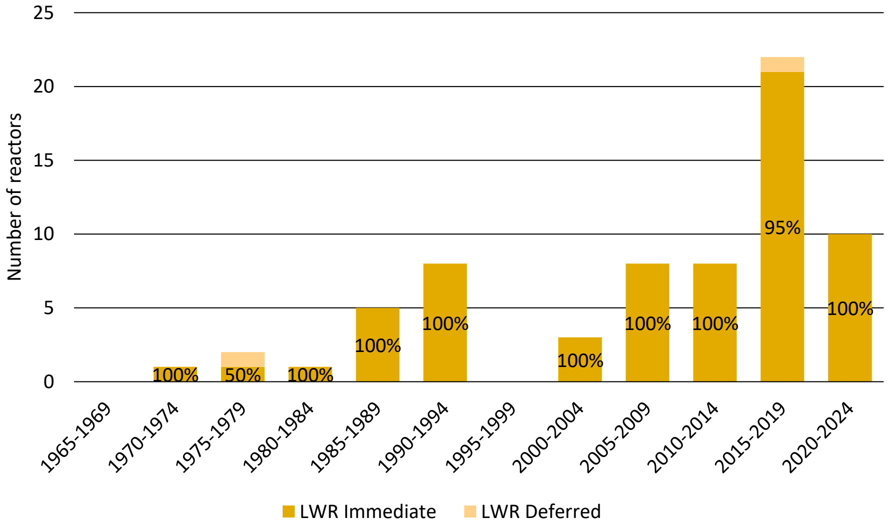

FIG. 41. Strategy decisions for shutdown LWRs (five year periods). Percentages inside the bars represent the portion of immediate dismantling decisions.

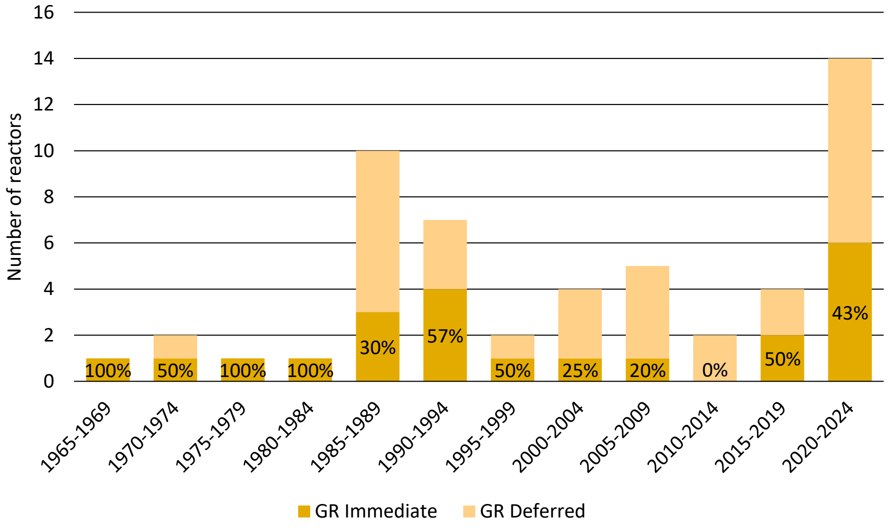

FIG. 42. Strategy decisions for shutdown GRs (five year periods). Percentages inside the bars represent the portion of immediate dismantling decisions.

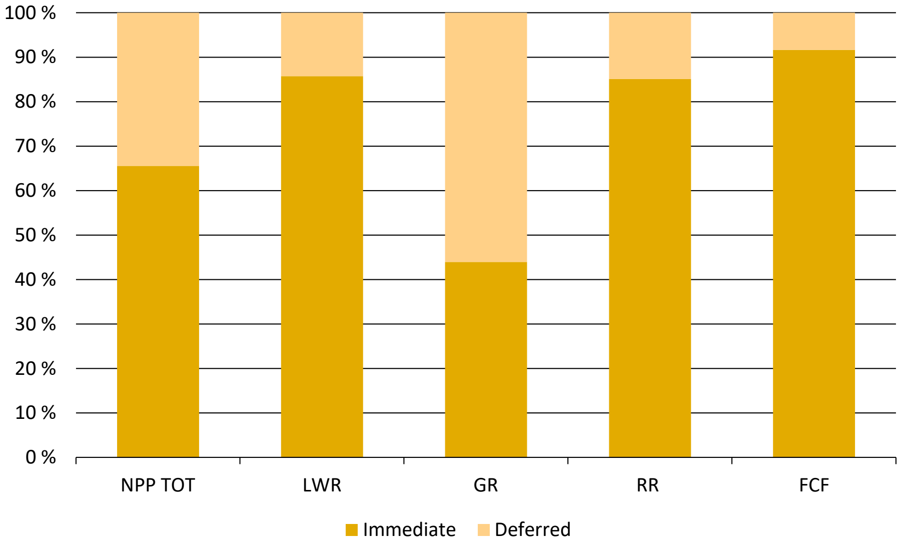

FIG. 43. Cumulative percentage of decommissioning strategy per type of facility.

The questionnaire responses indicate a preference for immediate dismantling when all types of nuclear power plant are considered. This preference becomes much more evident when focusing solely on light-water reactors (>80% immediate dismantling) in comparison to graphite moderated reactors (slightly >40% immediate dismantling).

For research reactors as well as FCFs deferred dismantling is a less favoured option and the preference is clearly for immediate dismantling (see Fig. 43).

4.5. CONCLUSIONS

The selection of a decommissioning strategy for a particular facility depends on a complex set of influencing factors. The variety of influencing factors is such that the preferred strategy can vary for a similar facility depending on the country in which it is located or even within one country for different sites. The weighting of such factors in the strategy selection process depends on the relevant national, political and cultural background. The questionnaire responses suggest an increasing tendency towards immediate dismantling globally.

Regarding the main drivers for the selection of a decommissioning strategy, the questionnaire responses for all nuclear facilities suggest that ‘national policy/legislation’ and ‘waste infrastructure availability’ are the dominating drivers, while ‘technology/technical readiness’ and ‘personnel/skills / knowledge’ appear not to have a major impact on the choice between different overall strategies. The implication, particularly in the case of nuclear power reactors, is that factors that are more typically outside the control of the facility owner or operator are the dominant factors. This conclusion is subject to regional differences.

It is noteworthy that one fifth of the responses obtained for nuclear power reactors envisaged that active dismantling of the facility would proceed while spent fuel remained in the reactor or in the spent fuel pool. In such cases, the safety implications are addressed in the safety analysis supporting the application to proceed with decommissioning.

In the case of research reactors and nuclear FCFs, ‘national policy/legislation’ remains a dominant driver, but factors controlled by the facility owner have greater importance than with nuclear power reactors. Particular considerations apply at multifacility sites, for example in circumstances where supporting infrastructure supports both operational and shutdown facilities. In such cases, site decommissioning strategies may delay the dismantling of some shutdown facilities until other facilities that are still in operation have also been shut down (e.g. an integrated overall site approach).

The responses suggest that immediate dismantling is increasingly becoming the preferred decommissioning strategy. This is more pronounced in the case of light-water moderated reactors than graphite moderated reactors, although the responses suggest that the preference for deferred dismantling of graphite moderated reactors is becoming less pronounced. In the case of research reactors and FCFs, the questionnaire responses indicate that immediate dismantling is the preferred strategy.

5. DECOMMISSIONING IMPLEMENTATION

5.1. RESPONSES TO QUESTIONS ON DECOMMISSIONING IMPLEMENTATION

The ability to implement decommissioning projects is closely related to several enabling factors. These typically include the availability of an adequate legal and regulatory framework, a financing system with an adequate level of funding, infrastructure for management of spent fuel and waste, the availability of competent staff to oversee and implement the project, and access to appropriate technology, either directly or through the supply chain. Questionnaire respondents were asked to rate:

(a) A listing of eight factors that impact on the delivery of decommissioning — see Section 5.2;
(b) Factors relevant to strengths, weaknesses, opportunities and threats relevant to decommissioning — see Section 5.3.

Figure 44 compares the number of facilities for which responses were received on this issue with the total numbers of nuclear facilities and the numbers of facilities for which responses to others were obtained. The figure shows that response levels are generally low, and unlikely to be representative of the

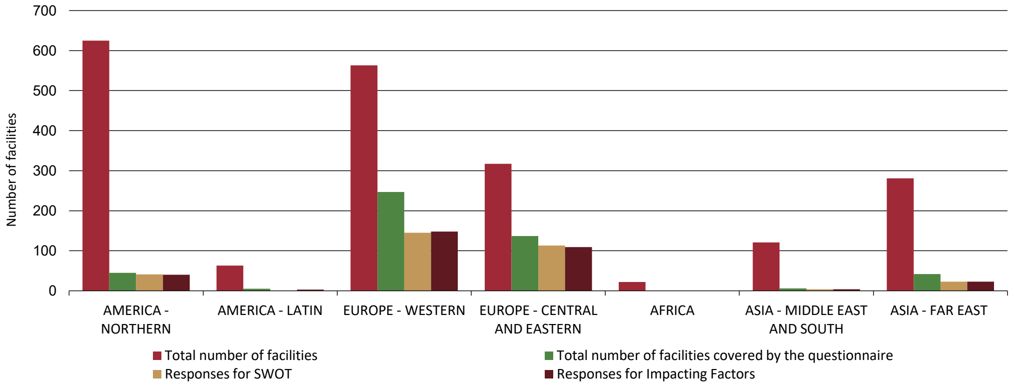

FIG. 44. Comparison of the number of facilities (shown in dark pink) and the number of responses received — to general questions (in green) and for the impacting factors (in violet) and SWOT issues (in beige) in particular.

global situation. The largest number of responses was obtained for the regions Europe — Western and Europe — Central and Eastern.

5.2. FACTORS IMPACTING ON DECOMMISSIONING

In order to explore factors that may impact on decommissioning, questionnaire respondents were requested to rate the importance of the eight factors identified in the project questionnaire. The identified factors are:

(a) Availability of waste management facilities[29] — 'Waste';
(b) Availability of spent fuel management facilities[30] — 'Spent fuel';
(c) Availability of funding — 'Funding';
(d) Availability of technology or knowledge — 'Technology';
(e) Political and stakeholder acceptance — 'Acceptance';
(f) Regulatory framework or interactions — 'Framework';
(g) Availability of personnel or key skills — 'Personnel';
(h) End state and future options — 'Spent fuel'.

Respondents were requested to rate the factors listed above from 1 to 8 based on the relative influence that they had on their ability to deliver their respective decommissioning projects, with 1 having the highest adverse influence and 8 the lowest adverse influence. The questionnaire also highlighted that only the highest and lowest rated factors would be considered in the more detailed analysis. Respondents were further given the opportunity to add comments for specific responses where applicable.[31] The total number of responses received for all types of facilities concerning impacting factors is shown in Fig. 45.

Figure 45 shows that the impacting factor that received the largest number of No. 1 rankings was the availability of waste facilities. The factor that received the second next largest number was the availability of funding. A similar analysis was undertaken for the least influential impacting factors by analysing those with a No. 8 ranking. Here, the factor that had the most No. 8 rankings was the end state and future

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[29] Facilities for processing, storage and disposal of radioactive waste.

[30] Facilities for processing, storage and disposal of spent fuel.

[31] Specifically, if a high rating was given (1–3), respondents were requested to comment on how the delivery may be impacted and any mitigating actions. Where a particular factor was rated as 6, 7 or 8 respondents were also requested to state why these have been considered as having little or no impact on decommissioning delivery.

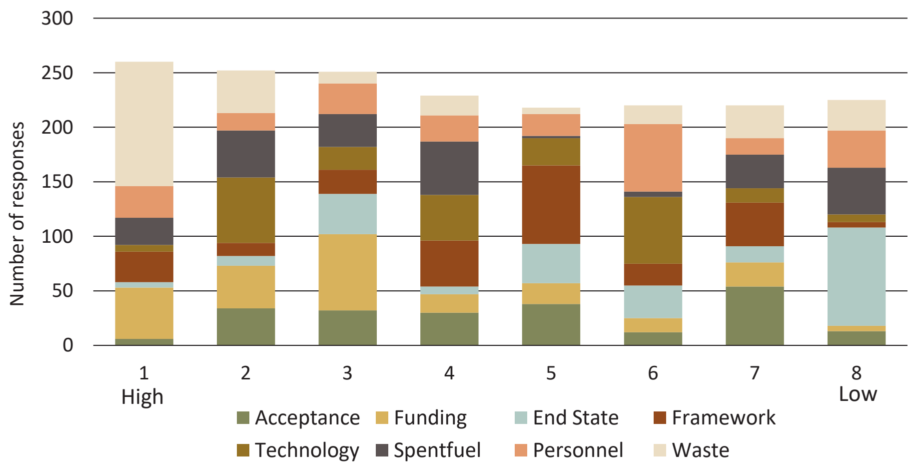

FIG. 45. Impacting factors for delivery of decommissioning — all facility types (327 facilities).

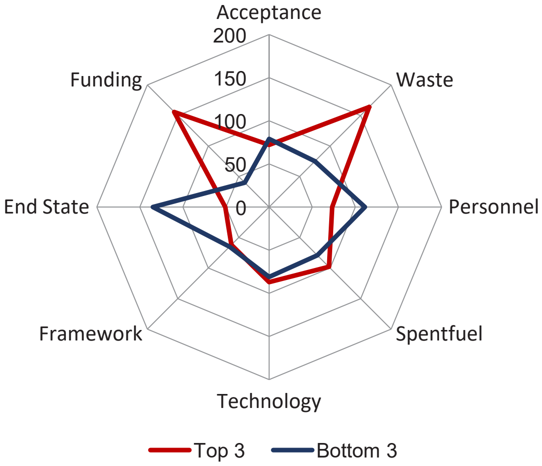

FIG. 46. Top three and bottom three factors for all facility types (327 facilities).

use options factor. The factor that received the second next largest number was the availability of spent fuel facilities, with the availability of key personnel or skills receiving the third largest number.

Following the intention of the original questionnaire, the combined rankings of the three top ranked factors was also determined — see Fig. 46. On this basis the highest ranked factor on an overall basis is the availability of waste facilities[32], followed by the availability of funding. A similar approach was followed for the three lowest ranked factors, to determine which factors had the least overall impact on delivery of decommissioning — see Fig. 46. This shows the factors having the greatest influence on the delivery of decommissioning projects as being the availability of waste facilities and the availability of funding, followed by the availability of spent fuel facilities, closely followed by the remaining factors.

The factors with the least overall impact on delivery of decommissioning, as shown by the blue line in Fig. 46, are the selected end state and future use options, followed by the availability of personnel and key skills. Beyond these low ranked factors were several with a similar level of impact: availability of technology, availability of spent fuel facilities, policy and stakeholder acceptance and availability of waste facilities.

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[32] The availability of waste facilities received 114 No. 1 rankings, 39 No. 2 rankings and 11 No. 3 rankings, which aggregated to a total of 164 top three rankings.

To provide a more detailed understanding of the results obtained, the following sections (5.2.1–5.2.3) repeat the above assessment for each of the three facility types; nuclear power reactors, FCFs and research reactors.

5.2.1. Nuclear power reactors — worldwide/regional

Figure 47 presents an analysis of the factors that impact on decommissioning delivery solely for NPP reactors, based on the total number of responses received (representing 201 reactors). This again shows the availability of waste facilities as being the highest ranking impacting factor, followed by the availability of funding and the availability of personnel and key skills. The factor shown as having the least impact on delivery decommissioning (i.e. with the most No. 8 rankings) is again the selected end state and future use options, followed by the availability of spent fuel facilities and the availability of personnel and key skills.

Figure 48 presents an analysis of the three top ranked factors and the three lowest ranked factors. This again highlights the availability of waste facilities and funding as being the highest impacting factors for decommissioning delivery, while the end state and future use options and the availability of personnel and skills are the least impactful factors. The remaining charts show the results received from the different global regions.

Detailed analysis points to important regional differences; for example, comparison of the results for Europe — Western and Europe — Eastern and Central suggests that, in the former, personnel and end state are the highest ranking impacting factors, whereas in the latter these are the lowest ranked factors. Further, in Europe — Central and Eastern, technology and spent fuel are recognized as being important impacting factors, whereas in Europe — Western these are deemed to have a minimal impact on decommissioning delivery. The availability of waste facilities and the availability of spent fuel facilities and funding scored highly everywhere. Note: only statistically significant values for reactors per region have been displayed in Fig. 48.

5.2.2. Research reactors — worldwide/regional

The availability of funding was identified as the most important factor impacting on the delivery of research reactor decommissioning — see Fig. 49. Availability of waste management facilities was identified as the second most important factor, though having a similar impact on the delivery of decommissioning as the regulatory framework, followed by the availability of spent fuel facilities. The lowest ranked

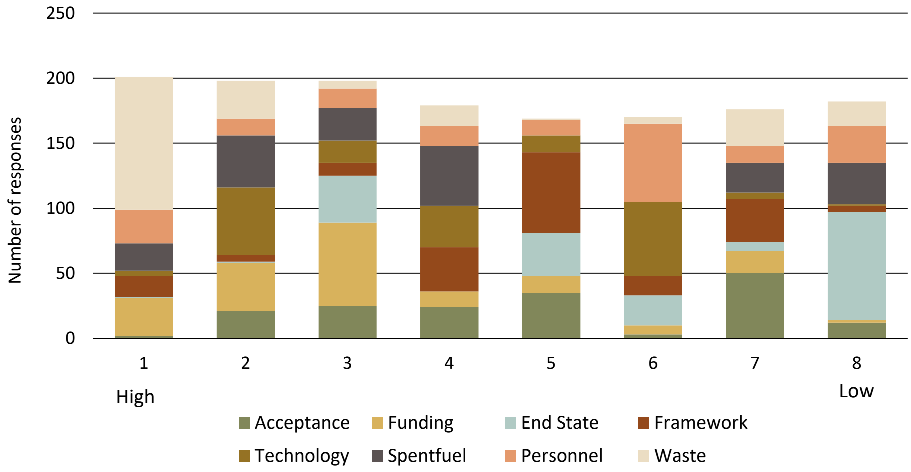
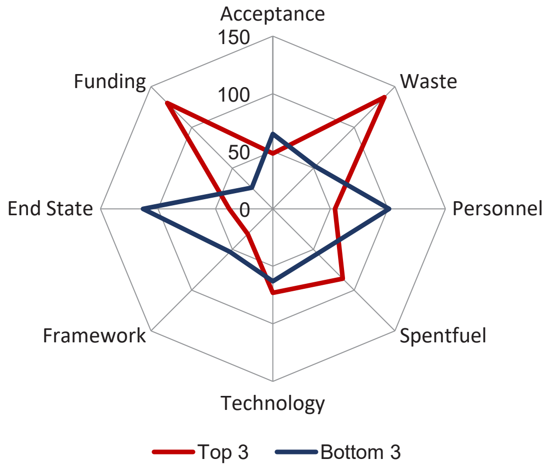
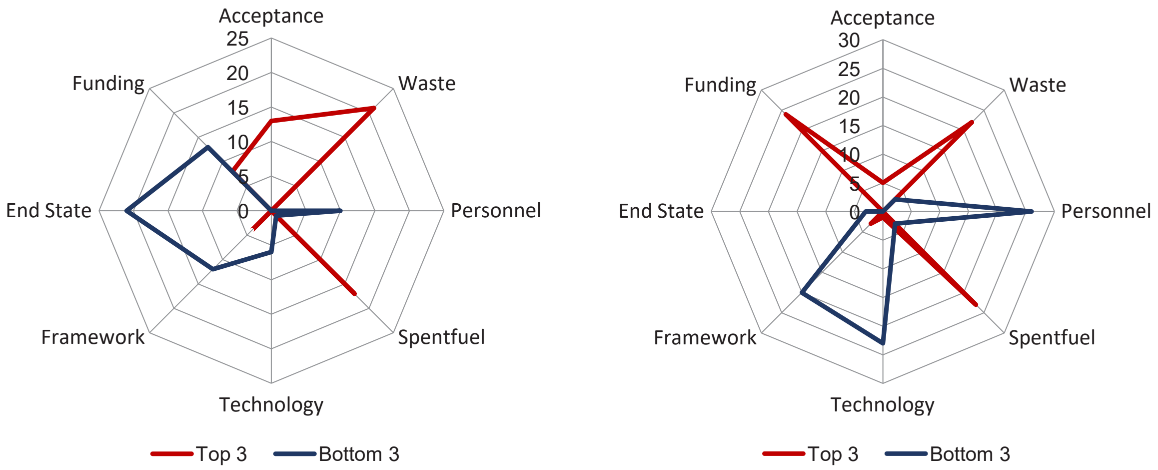


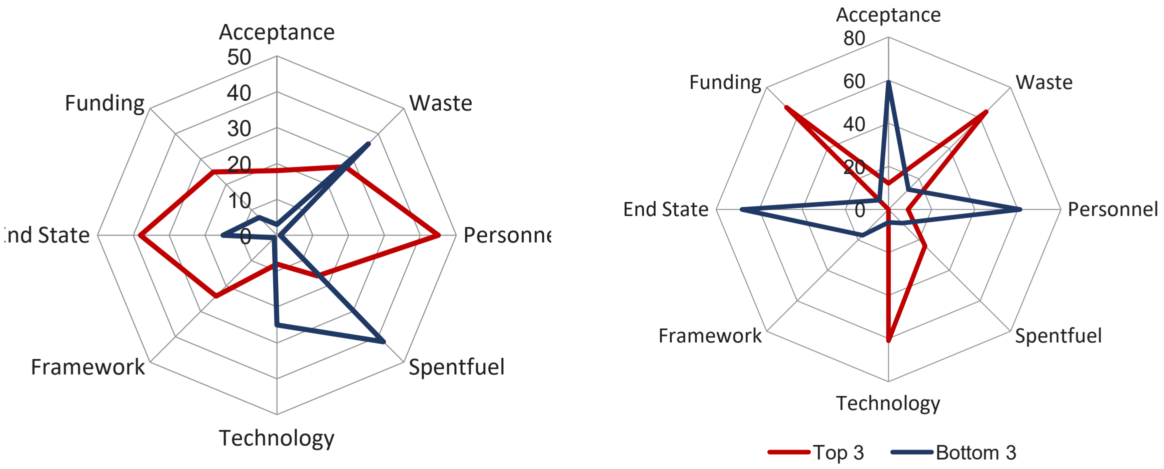
FIG. 47. Impacting factors for the delivery of decommissioning for 201 NPP reactors.



(a) Worldwide (201 reactors).



(b) Asia — Far East (21 reactors). *(c) America — Northern (26 reactors).*



(d) Europe — Western (69 reactors). *(e) Europe — Central and Eastern (79 reactors).*

FIG. 48. Regional review of top three and bottom three ranked impacting factors for NPP reactors.

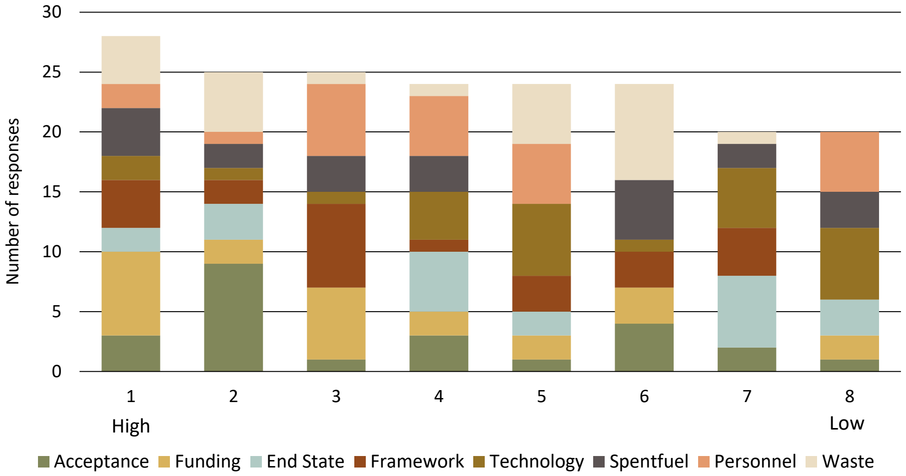


FIG. 49. Impacting factors for the delivery of decommissioning for 57 research reactors.

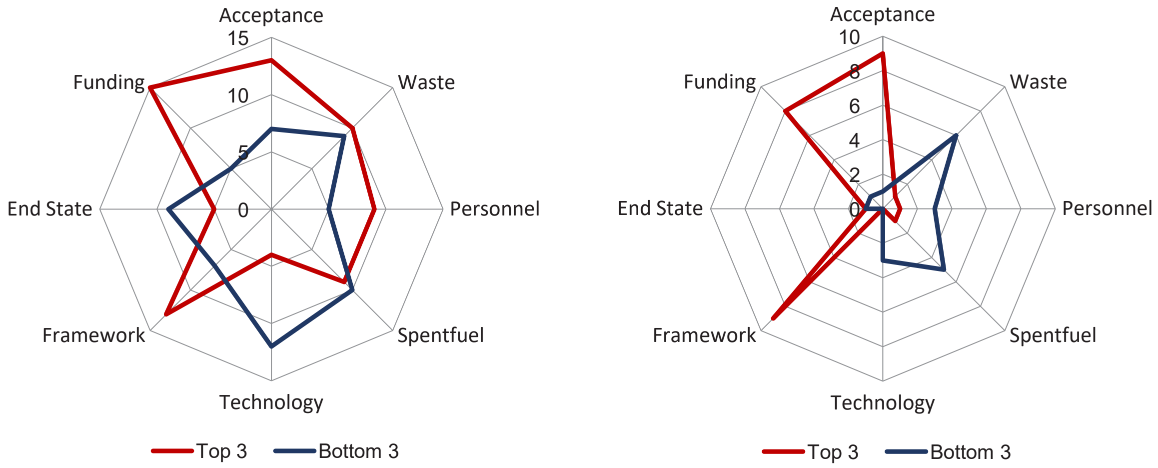
factors— those indicated as having the least impact on the delivery of decommissioning — were the availability of technology or knowledge, closely followed by the availability of personnel.

The questionnaire responses suggest that in Europe — Western the availability of waste facilities, the availability of personnel or key skills and the availability of spent fuel facilities have the greatest impact on the ability to deliver decommissioning — see Fig. 50. In contrast, for Europe — Central and Eastern the factor with the greatest impact is the availability of funding, with the subsequent important factors being the same as for Europe — Western. For America — Northern the availability of funding was also identified as having an important impact on the delivery of decommissioning. In contrast to Europe — Central and Eastern and Europe — Western, regulatory framework, licensing/authorizations and political and stakeholder acceptance were also identified by America — Northern respondents as factors having an important impact on the delivery of decommissioning.

The factors identified as having the least impact on decommissioning in Europe — Western and Europe — Central and Eastern are typically, in approximately equal measure, political and stakeholder acceptance, availability of funding, end state and future use options, regulatory framework, licensing/authorization and the availability of technology or knowledge. In contrast, America — Northern identified that the factors that had the least impact on the delivery of decommissioning were the availability of waste facilities, the availability of spent fuel facilities, the availability of personnel or skills and the availability of technology or knowledge. Other global regions did not provide sufficient responses to allow a meaningful analysis to be completed.

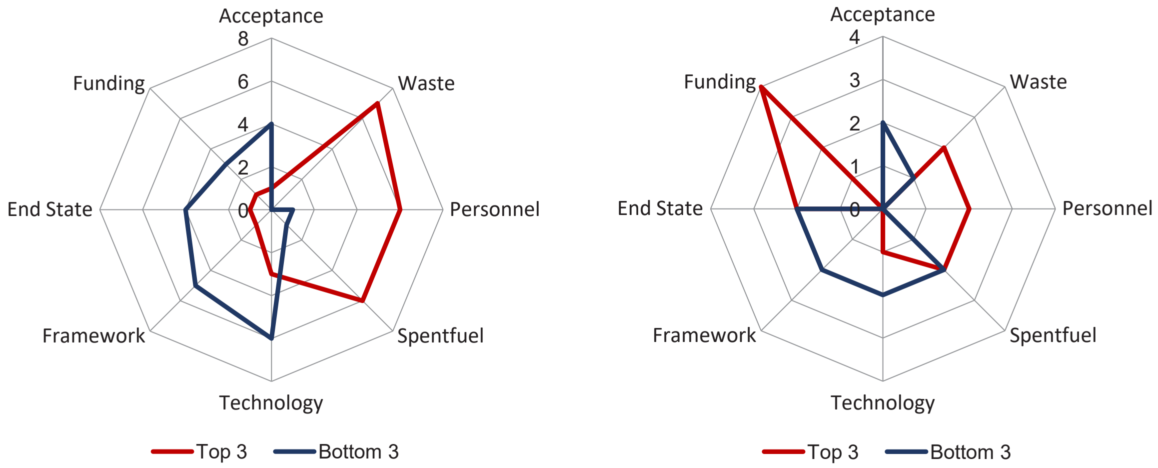
5.2.3. Fuel cycle facilities — worldwide/regional

The availability of funding and the availability of waste facilities were identified as being the factors with the greatest impact on the decommissioning of FCFs — see Fig. 51. The regulatory framework and licensing/authorization were ranked similarly to the availability of waste facilities. Regarding factors with the least impact on FCF decommissioning, a significant number of respondents pointed to the availability of waste facilities, closely followed by the availability of spent fuel facilities, with the third ranked factor being the end state and future use options.



(a) Worldwide (57 reactors).

(b) America — Northern (14 reactors).



(c) Europe — Western (23 reactors).

(d) Europe — Central and Eastern (15 reactors).

FIG. 50 Regional review of top three and bottom three impacting factors for research reactors.

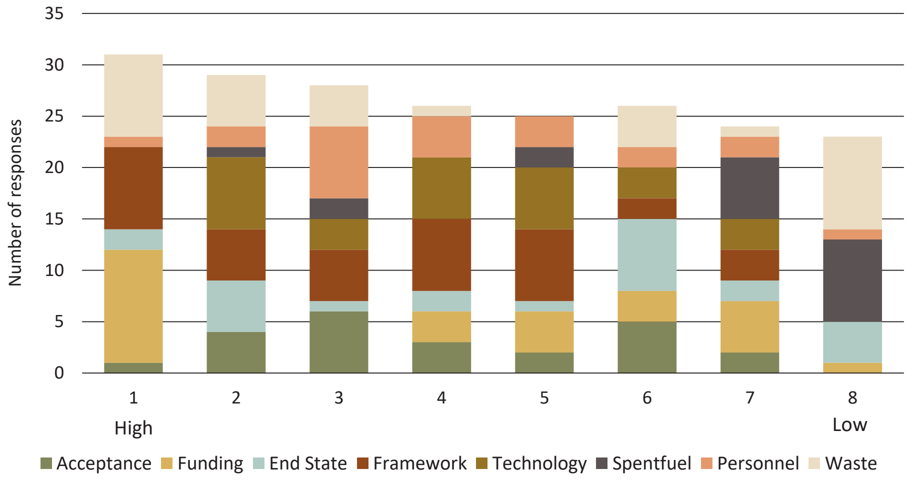
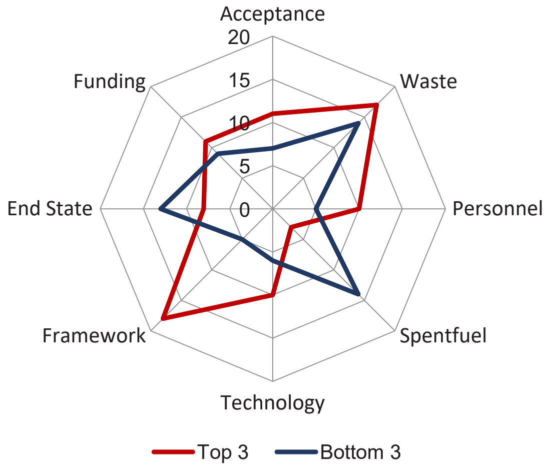
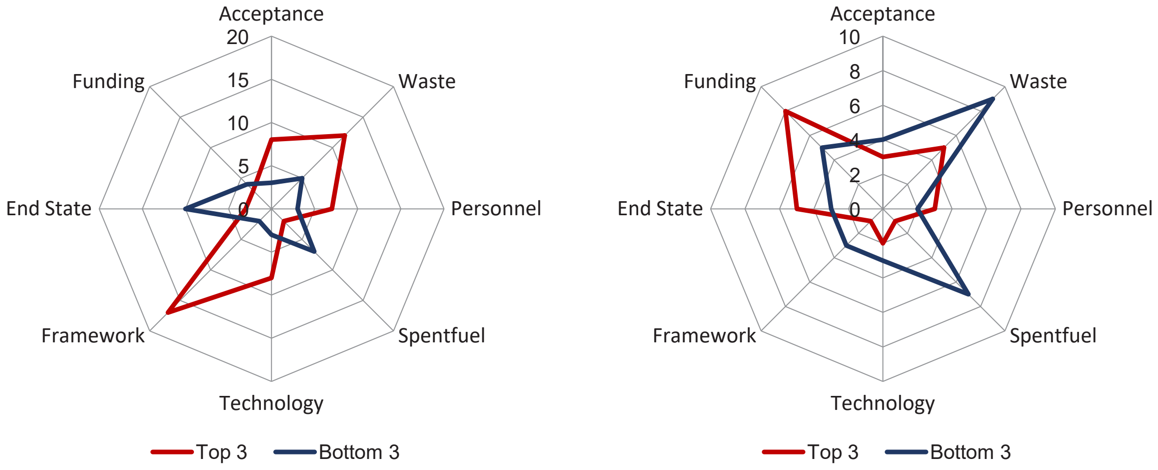


FIG. 51. Impacting factors for the delivery of decommissioning for 69 FCFs.



(a) Worldwide (69 facilities).



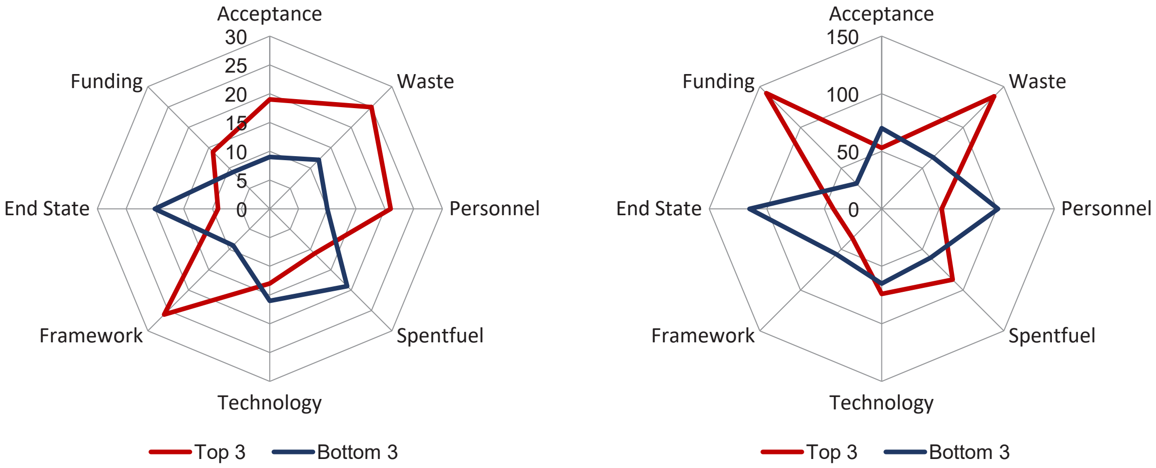
(b) Europe — Western (57 facilities).

(c) Europe — Central and Eastern (14 facilities).

FIG. 52. Regional review of top three and bottom three factors for FCFs.

The regional results for impacting factors for FCF decommissioning were limited to two regions from which responses were received, Europe — Central and Eastern and Europe — Western. The main factors affecting the delivery of decommissioning (top three and bottom three factors) are shown in Fig. 52, highlighting notable differences in the responses from the two regions. For Europe — Western, the factors identified as having the greatest impact on the delivery of decommissioning were the regulatory framework, followed by the availability of waste facilities. The next ranked factors were licensing/authorization and the availability of technology. Respondents from Europe — Central and Eastern identified the availability of funding and the end state and future use options as the highest ranked factors impacting on the ability to deliver decommissioning.

Questionnaire responses for factors having least impact on delivery of decommissioning showed significant regional differences. For Europe — Western end state and future use options and availability of spent fuel facilities were identified as having the least impact, whereas for Europe — Central and Eastern, the availability of waste facilities and the availability of spent FCFs were identified as being the factors with the least impact.



(a) Single unit facilities (52 facilities).

(b) Multifacility sites (responses for sites containing 275 facilities in total).

FIG. 53. Comparison between impacting factors for single and multifacility sites.

5.2.4. Single unit versus multifacility sites

Influencing factors for single unit facilities and those on multifacility sites are compared in Fig. 53, indicating that decommissioning activities at both multifacility sites and single sites were strongly influenced by the availability of waste facilities. Availability of funding was also highlighted by respondents from multifacility sites as having an adverse impact on the implementation of decommissioning. The availability of spent fuel facilities and the availability of technology also ranked highly for the multifacility sites. In contrast, for single unit sites, the regulatory framework and licensing/authorizations had the next highest ranked adverse impact on the ability to deliver decommissioning, with the remaining factors ranked closely together.

The questionnaire responses showed that the least significant impacting factors for multifacility sites were the envisioned end state and future use options, as well as the availability of personnel and key skills. For single unit sites, the availability of technology was the least influential factor by a small margin, but otherwise the factors were broadly ranked equally.

5.3. ANALYSIS OF STRENGTHS, WEAKNESSES, OPPORTUNITIES AND THREATS FOR DELIVERING DECOMMISSIONING

Strengths and weaknesses were designated in the questionnaire as factors that originate from within the organization, whereas opportunities and threats are considered to be factors of external origin — see Fig. 54. Such an analysis distinguishes factors likely to be helpful to project delivery — organizational strengths and opportunities in the external environment — and factors that may be detrimental — organizational weaknesses and threats in the external environment. Questionnaire respondents were invited to select from 16 different factors, as shown on Fig. 55. Respondents also had the option to add additional factors. Some respondents considered certain factors to be both internal and external factors (e.g. contracting/procurement).

FIG. 54. Framework for evaluation of strengths, weakness, opportunities and threats (SWOT).

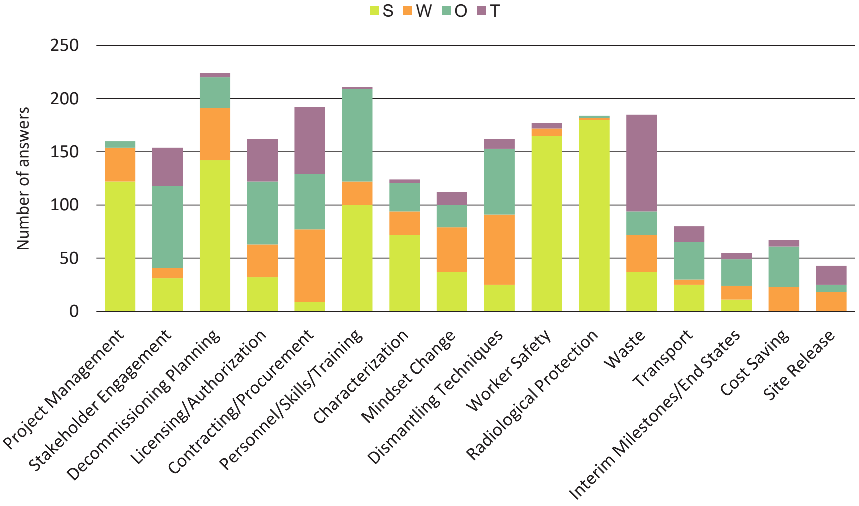


FIG. 55. Responses for all types of facilities.

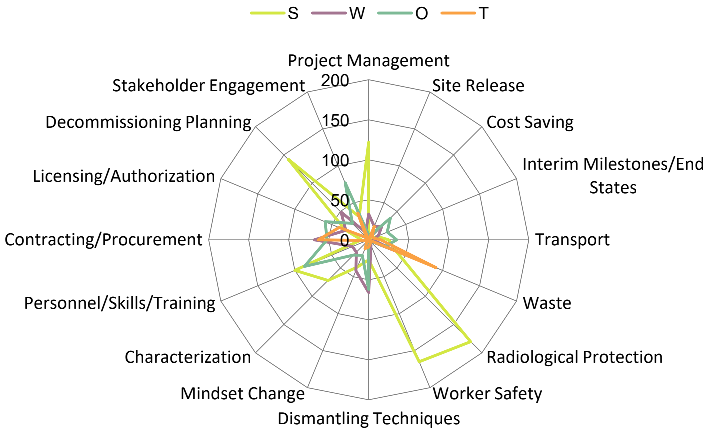
In general, respondents indicated that their organizations had particular strengths in ‘planning’, ‘project management’, ‘personnel/skills/training’, ‘worker safety’ and ‘radiological protection’. Notable weaknesses or threats were identified in the areas of ‘contracting/procurement’ and ‘waste’, with some weakness identified in ‘mindset change’.

Responses concerned with external factors highlighted significant opportunities in the domains of ‘stakeholder engagement, ‘licensing/authorization’ and ‘personnel/skills/training’. The most commonly identified external threat was ‘waste’; other external threats identified included ‘contracting/procurement’, ‘licensing/authorization’ and ‘stakeholder engagement’.

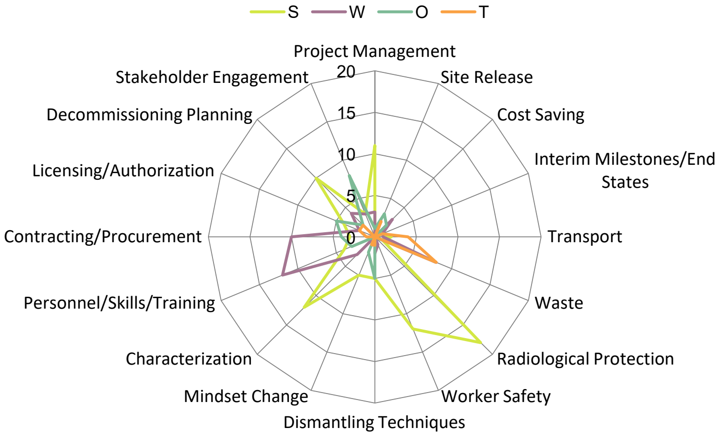
5.3.1. Review of global distribution of strengths, weaknesses, opportunities and threats

To better understand the distribution of these factors across the globe, the results for each type of facility are shown in Fig. 56.

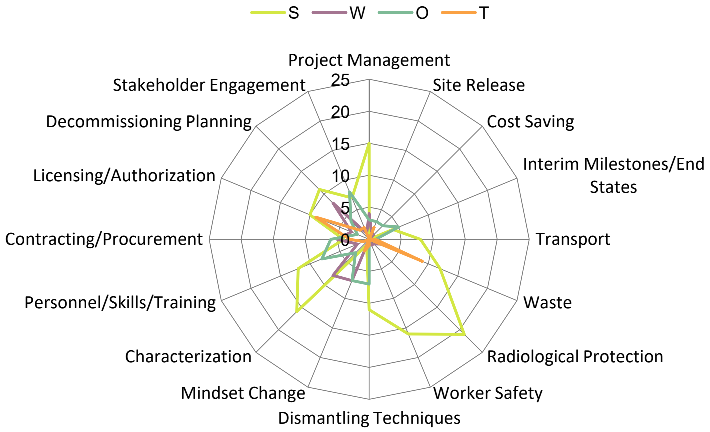
Figure 56 summarizes the results by facility at a global level. In general, the analysis shows that the balance of the factors is broadly similar for the different types of facility. A notable difference is



(a) NPPs (197 reactors).



(b) RRs (55 reactors).



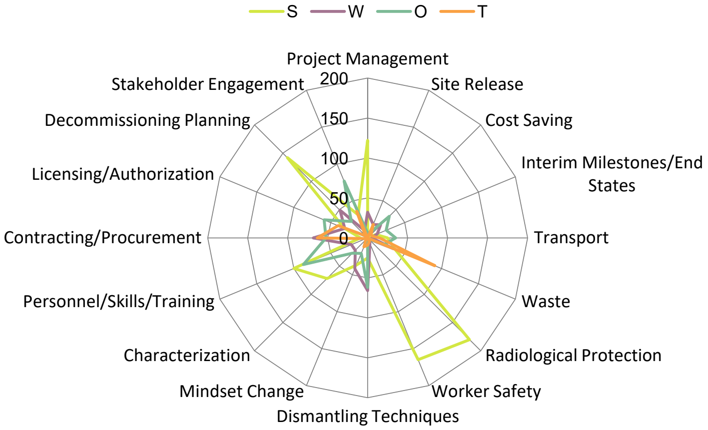
(c) FCFs (74 facilities).

FIG. 56. Global SWOT responses by facility type.

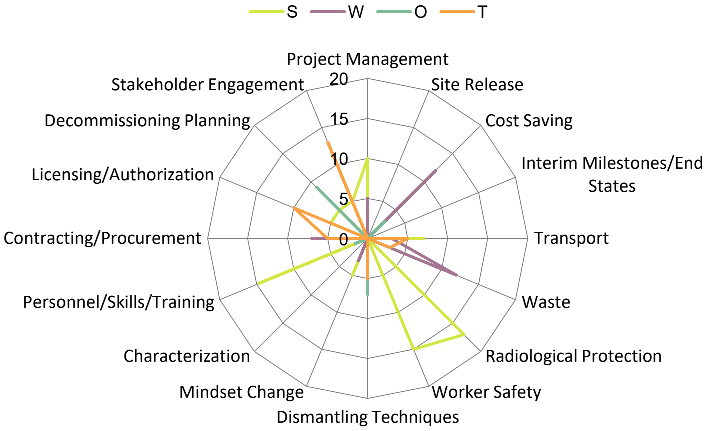
‘dismantling techniques’ for NPPs — identified as a weakness — whereas for other facilities this was identified as a strength. Given the number of responses for NPPs compared to RRs and FCFs, it is evident that this is considered to present a significant challenge for NPP decommissioning.

Figure 57 presents the global response by region.

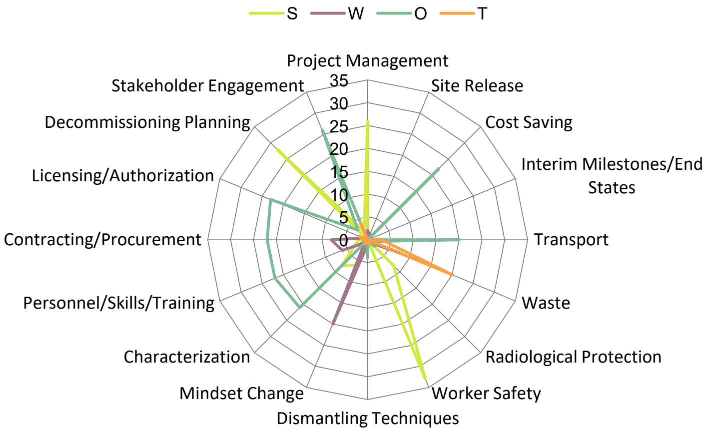
The distribution of factors across the regions from which responses were received is broadly comparable to the global situation as described above — see Fig. 57. Some differences are apparent. ‘Radiological protection’ was not highlighted by respondents from America — Northern, although it did feature in responses for other regions. Another notable difference in responses concerns ‘programme management’, which was noted as being a weakness in Europe — Central and Eastern, whereas it other regions this was designated as being a strength. ‘Decommissioning planning’ was indicated as a strength in Europe — Central and Eastern, in contrast to Europe — Western, where it was indicated as a weakness. Stakeholder engagement was highlighted as a threat in America — North and in Europe — Western, whereas respondents from Asia — Far East recognized this as an opportunity.



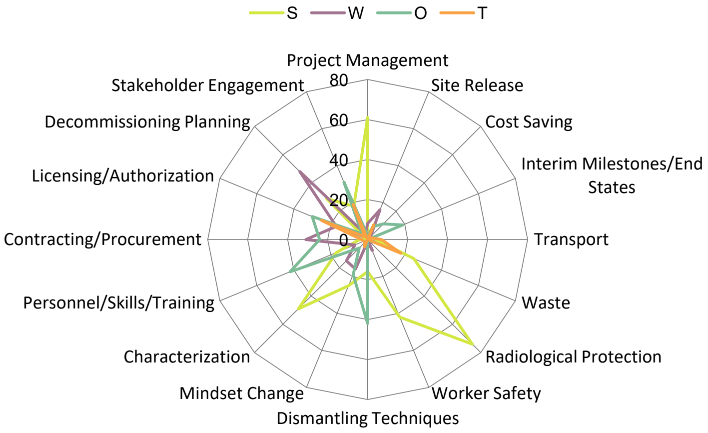
(a) Worldwide (326 facilities).



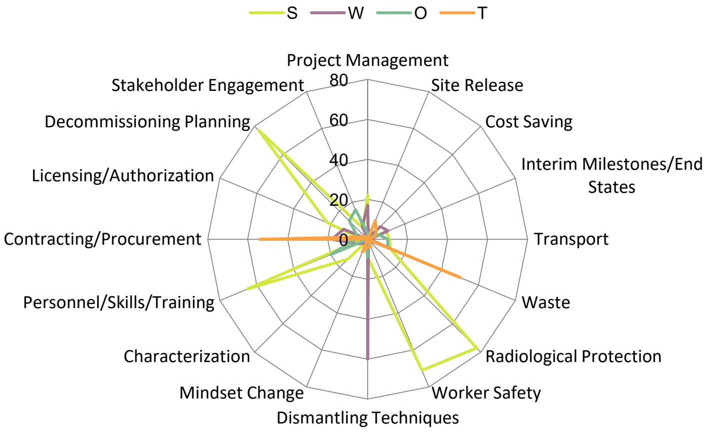
(b) Asia — Far East (23 facilities).



(c) America — Northern (41 facilities).



(d) Europe — Western (145 facilities).



(e) Europe — Central and Eastern (113 facilities).

FIG. 57. Global SWOT responses by region.

5.4. CONCLUSIONS

The majority of responses received for the questionnaire were associated with the regions Europe — Western and Europe — Central and Eastern. The analysis presented is therefore of primary relevance to these regions, rather than necessarily being representative of the global situation. Furthermore, the largest proportion of responses was received from NPPs, which therefore dominate the overall conclusions.

Subject to the above caveats, the availability of waste facilities was the factor identified as having the greatest adverse impact on decommissioning of NPP reactors, followed by the availability of funding. The factor identified as having least impact was end state and future use options — suggesting that this factor, which is determined prior to decommissioning, does not significantly impact on its implementation.

For research reactors, the availability of funding was generally the most highly ranked impacting factor, but the availability of waste facilities was identified as a less important factor than was the case for NPPs, presumably associated with the much lower volumes of waste generated from decommissioning. Furthermore, although the selected end state and future use options was again noted as having a low impact on the delivery of decommissioning of research reactors, the factors identified as having least impact were availability of technology (ranked the least impacting factor) and the availability of spent fuel facilities (ranked the second least impacting factor).

For FCFs, the most important impacting factors again included the availability of waste facilities and the availability of funding, but also included the regulatory framework, with the latter factor being of particular importance in Europe — Western. The least impacting factors differed from the overall global results. The factors identified as having least impact were the availability of fuel facilities and the availability of waste facilities. This finding was most notable for the region of Europe — Central and Eastern, but much less so for the region of Europe — Western

A comparison of factors impacting on decommissioning on single facility versus multifacility sites highlighted the importance of the availability of waste facilities in both cases. The availability of funding was noted as being significantly more important for multifacility sites than single facility sites, with the latter being more impacted by the availability of personnel and the regulatory framework. Concerning the least impacting factor, the selected end state and future use options were highlighted in both cases. For single facilities, the availability of fuel facilities had a similarly low impact.

The SWOT analysis shows that worker safety, radiological protection and personnel/skills/ training are rated highly as strengths, together with programme management and planning. The main weaknesses identified by NPP respondents were dismantling techniques and contracting/procurement. Waste was also considered to be an important weakness and threat in several regions.

The responses to the questionnaire also highlight that both stakeholder engagement and personnel/skills/training were seen as areas of opportunity by several respondents, which suggests that these factors are seen as being of key importance to the successful delivery of decommissioning projects in the future. A similar conclusion may be drawn concerning two additional factors, licensing/authorization and contracting/procurement, which were indicated as representing both opportunities and threats, in approximately equal measure.

Considering the results for the impacting factor and SWOT analyses, it is evident that having access to appropriate systems for management of radioactive waste is a factor of key importance and a lack of such systems is likely to have an important detrimental impact on project delivery. Respondents indicated that waste presents both a threat (external to the organization) and an area of weakness (internal to the organization). Dismantling techniques and technology were also noted as areas of weakness by several respondents.

6. THE WORKFORCE AND LIABILITIES FOR DECOMMISSIONING

6.1. INTRODUCTION

Adequate numbers of competent and motivated personnel need to be available during all of the life cycle phases of a nuclear facility, and there are specific requirements for personnel involved in a decommissioning project [1, 6]. One of the specific responsibilities of an operating organization is to ensure that "properly trained, qualified and competent staff are available for the decommissioning project" [1]. Similarly, there is a requirement to ensure that adequate financial resources to cover the costs associated with safe decommissioning, including management of the resulting waste, are available when necessary [1, 6]. In order to have a current perspective on the liabilities, cost estimates for decommissioning need to be updated on the basis of the periodic update of the initial decommissioning plan or on the basis of the final decommissioning plan [1].

6.1.1. Workforce for decommissioning

The timing of workforce requirements for decommissioning is determined by decisions on permanent shutdown, the strategy to be followed, decisions on organization and contracting approaches, and the duration of actual work and the achievement of the final end state.

As noted in Section 4, in the case of an immediate dismantling strategy decommissioning begins shortly after permanent shutdown of the facility. Here, decommissioning operations begin at sites that already have an operating staff, and the tendency is for a reduction of operations staff to occur following permanent closure and once post-operations activities are completed. Conversely, planning and preparation for decommissioning need to commence before permanent closure so as to ensure a smooth transition from operation to decommissioning. A further buildup of decommissioning personnel may be expected ahead of the start of decommissioning operations, varying throughout the project according to the project plan and schedule.

Further, as noted in Section 4, a deferred dismantling strategy envisages a delay after permanent shutdown during which the facility is maintained in a safe state pending its later dismantling (safe enclosure phase). In this case, following a permanent shutdown and the completion of the transition to the safe enclosure condition, the organization would be expected to reduce to the level needed to maintain the facility in a safe condition during the safe enclosure phase (deferral period). This might consist of only a few or even no project staff. As the safe enclosure period draws to a close, there will be a need to build up the decommissioning organization ahead of decommissioning operations. In a specific example [31], the Dresden 1 BWR decommissioning project was following a deferred dismantling strategy as part of a multireactor site. During the safe enclosure, this project required just 7 permanent staff and was supported by 27 persons from other parts of the site organization providing services such as security and emergency planning.

6.1.2. Cost and liability estimates

There are many factors affecting the decommissioning costs and the estimates of future liabilities. Reactor decommissioning costs at any given power level[33] can vary widely, with a high degree of variability [10, 32–34]. The variability is such that it has been suggested that final decommissioning

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[33] Thermal power for research reactors, electrical output for power reactors.

costs for power reactors are not significantly impacted by the generating capacity [34]. The factors affecting costs of decommissioning of FCFs have not been explored in depth internationally in the same way as for reactors. The degree of variability between the many different types of FCFs complicates comparisons for FCFs.

Analysis for research reactors indicates that estimates vary due to differences in reactor type and design, decommissioning project scope, country specific unit workforce costs and other reactor or project factors [1, 32, 33]. Similarly, for nuclear power reactors, factors that can affect these category costs are the actual degree of contamination, and the specific radioactivity release criteria for materials and cleanup levels applied, as well as the particular technological approaches adopted for the various processes of decommissioning, dismantling and demolition [10, 34]. These factors, which may in turn be affected by other factors, such as the availability of particular waste management routes, can induce considerable variations in the costs. A recent assessment highlights the significance of several country specific and site specific characteristics for overall decommissioning project outcomes [35].

6.1.3. Relationship between workforce and costs

There is a relationship between human resource requirements and the costs of decommissioning. Labour costs dominate the calculated decommissioning costs for reactor decommissioning, for both research and power reactors [32–34]. In the case of nuclear power reactor decommissioning, it has been reported that direct staffing costs account for more than 50% of decommissioning costs [34]. Moreover, it has been calculated that labour costs may represent up to 70% of the total decommissioning costs, if subcontracted work is also taken into account [10]. This highlights the importance of the organizational and contracting model to be applied to decommissioning in the overall costs and in estimating the total future liabilities. Labour costs may be highly variable, due to wide variation in local or national labour costs [1, 32, 33]. In addition, there are major uncertainties related to the estimation of the person-hours for different tasks, as well as the total duration of the decommissioning works [10, 35].

Personnel projections and cost estimates are based on assumptions and decisions about approaches to be used in performing the decommissioning; together these may have a great impact on overall projections of human resource needs and estimates of future liabilities. These assumptions and plans may be adapted over time due to changing circumstances (e.g. organizational or institutional developments, economic or market conditions), as well as experiences from other decommissioning projects. It could be expected that organizations with experience in decommissioning or ongoing projects might have a different perspective than organizations who have yet to undertake decommissioning projects for the first time. Such a relationship was observed in a recent IAEA project on the costs of decommissioning of research reactors, Data Analysis and Collection for Costing of Research Reactor Decommissioning (DACCORD) [32, 33]. When assessing the workforce hours for decommissioning of research reactors, the DACCORD project found that lower workforce hours are reported for completed decommissioning projects than are estimated for planned projects [32].

6.1.4. Timing of workforce and funding requirements

There is limited detailed information available on the future timing of facility shutdown and start of decommissioning, in particular in relation to quantitative data on workforce and funding requirements.

Th timeline data in this project were not collected in such a way as to enable them to be combined with the information provided on workforce and liabilities to produce projections on future requirements workforce and funding requirements over time.

Outside of this project, there are few studies setting out analyses of future decommissioning; see, for example, Refs [25, 36, 37]. These do not offer detailed projections and are limited to nuclear power reactors (i.e. they exclude research reactor and fuel cycle facility decommissioning). Typically, projections do not include estimates of the required decommissioning workforce or funding.

One example offering projections for decommissioning of nuclear power reactors is Ref. [25]. This provides desk based research and a scenario analysis of the present and future situation of 540 nuclear power reactors in 18 countries worldwide until 2047. For that purpose, the information from the PRIS database is extended at a reactor level using information on future usage, political decisions, preferred decommissioning strategies and the duration of the post-operational and dismantling phases. The projections suggest that nuclear power reactor decommissioning will increase considerably between 2020 and 2030 and then stagnate — albeit at a high level — between 2030 and 2045. After 2045, the projection indicates a further market increase. However, Ref. [25] does not include estimates of workforce or funding in its projection, although these issues are discussed.

6.2. WORKFORCE FOR DECOMMISSIONING

This subsection uses information from questionnaire responses to describe the size of the workforce for both past decommissioning activities and those planned in the future. The size of the workforce is shown in full time equivalents (FTEs)[34], as reported in questionnaire responses. The information presented below includes both own staff and contracted personnel, and covers the following decommissioning phases: preparation, safe enclosure, dismantling and demolition.

Figure 58 illustrates the responses concerning the size and regional distribution of the decommissioning workforce for each category of facility. The responses were mainly for the workforce for NPP reactor decommissioning in the regions Europe — Central and Eastern and Europe — Western. The reported workforce requirements for decommissioning research reactors and FCFs are not representative and there were insufficient responses to support a more detailed analysis. Therefore, for the majority of the remainder of this subsection, only the NPP reactor responses for Europe — Central and Eastern and Europe — Western are presented in order to illustrate the types of analysis workforce information could support if there were sufficient data.

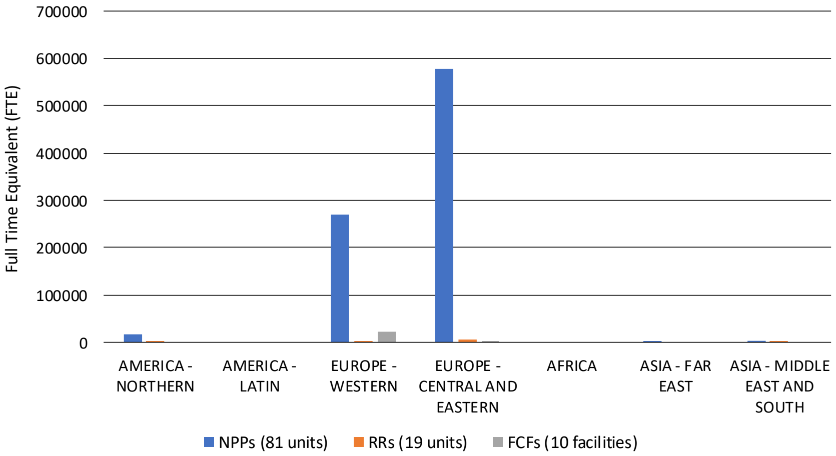

FIG. 58. The size of the reported decommissioning workforce by facility category and region. Data from questionnaire responses. The number of power reactors, research reactors and FCFs reporting data is included in the figure.

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[34] A full time equivalent (FTE) is a unit used in measuring the size of the workforce. An FTE is either a worker employed on a full time standard contract or two or more workers employed on reduced hours or part time contracts totalling up to one full time position. The purpose of full time equivalents, therefore, is to measure the size of the workforce, whilst controlling for the (variable) hours that individual workers are contracted to perform. A measure of workforce size based on full time equivalents can be contrasted with a simple headcount, in which the number of employees is measured, regardless of hours worked.

The data can be further broken down to illustrate the workforce associated with decommissioning activities undertaken up until the end of 2020 ('past' decommissioning) and the workforce associated with decommissioning activities planned to be undertaken after 2020 ('future' decommissioning), as shown in Fig. 59. This figure shows that the majority of the reported workforce requirements in the two regions are for 'future' decommissioning.

6.2.1. Strategy and the workforce

Figure 60 illustrates the total size of the decommissioning workforce reported, by choice of decommissioning strategy, for each category of facility. Both past and planned future decommissioning activities are included. The responses indicate that a majority of the reported overall decommissioning workforce is associated with a deferred dismantling strategy.

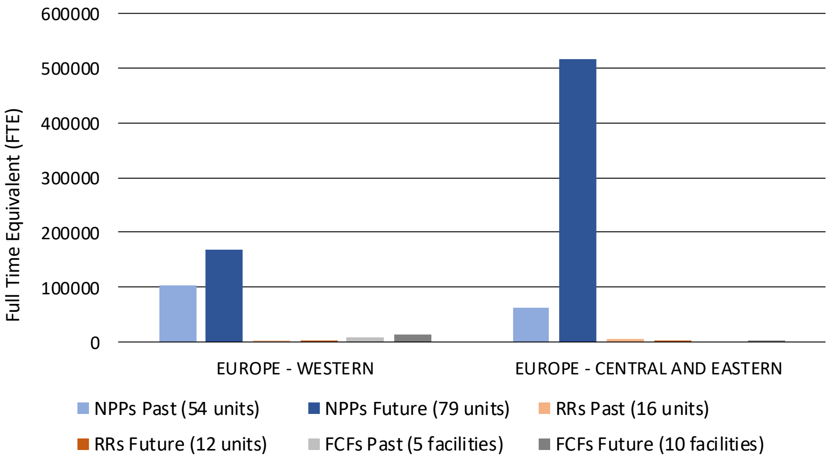


FIG. 59. The size of the reported decommissioning workforce up until the end of 2020 (past) and after 2020 (future) by facility category and region. Data from questionnaire responses. The number of power reactors, research reactors and FCFs reporting data is included in the figure.

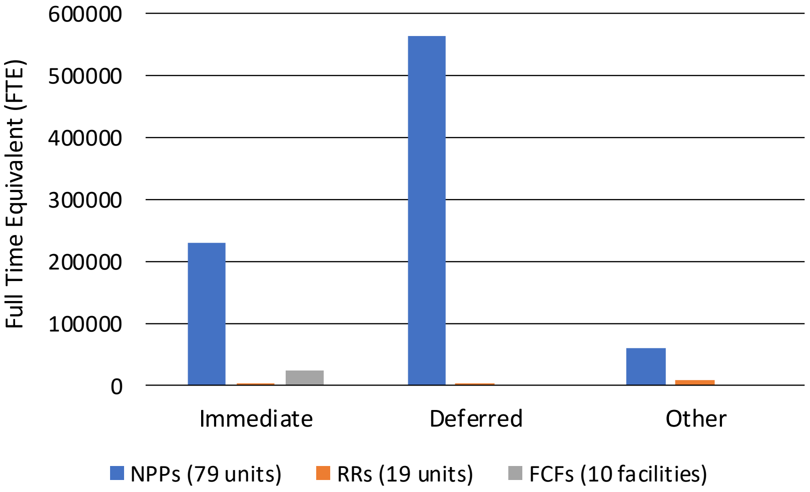


FIG. 60. The size of the reported total workforce for decommissioning, by choice of decommissioning strategy, for each facility category. Data from questionnaire responses. The number of power reactors, research reactors and FCFs reporting data is included in the figure.

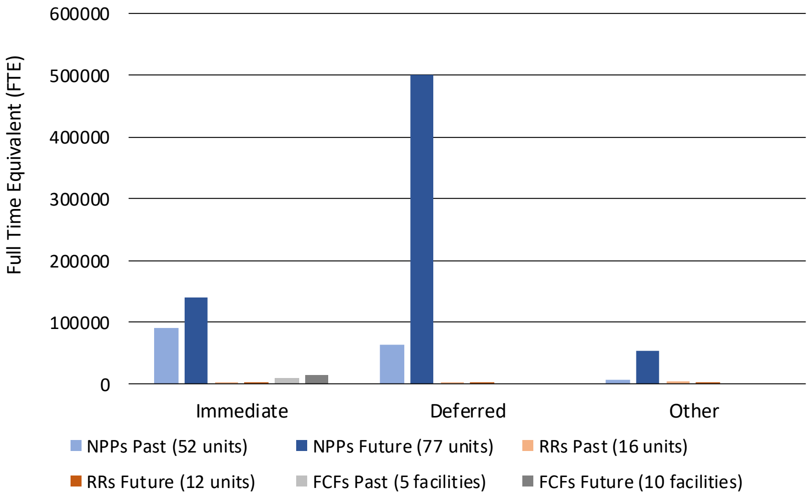


FIG. 61. The size of the reported workforce up until the end of 2020 (past) and after 2020 (future), by choice of strategy, for each facility category. Data from questionnaire responses. The number of facilities reporting workforce data is included in the figure.

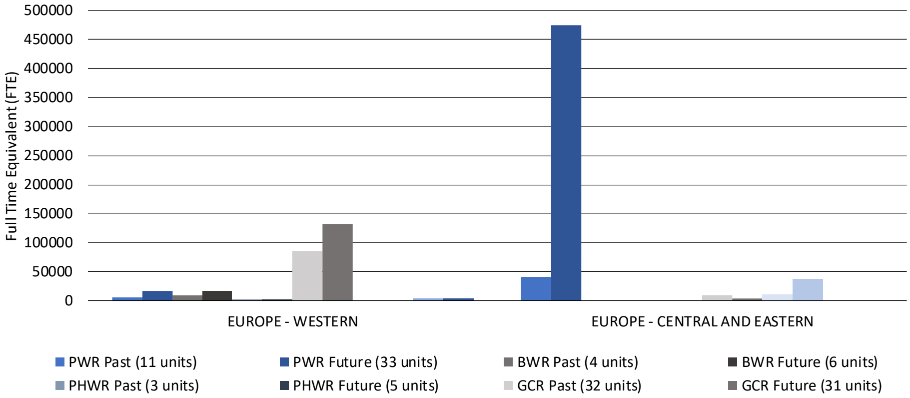


FIG. 62. The size of the reported decommissioning workforce up until the end of 2020 (past) and after 2020 (future) by reactor type and region. Data from questionnaire responses. The number of power reactors reporting data is included in the figure.

The information in the responses can be further broken down to illustrate the workforce associated with each strategy for past and future decommissioning, as shown in Fig. 61.

This breakdown in Fig. 61 suggests that the distribution of reported decommissioning workforce requirements by strategy may differ between past and future decommissioning. For past decommissioning, more of the reported workforce is for immediate dismantling strategies, whereas more of the reported workforce is for deferred dismantling for future decommissioning. However, it should be noted that this outcome should not be considered to be representative because of the relatively small number of facilities covered by the responses.

6.2.2. Workforce for decommissioning nuclear power reactors

Figure 62 shows the reported size and regional distribution of the workforce in Europe — Central and Eastern and Europe — Western for past (i.e. up to the end of 2020) and future (i.e. after the end of 2020) decommissioning by reactor type.

The information presented in Fig. 62 is consistent with earlier sections in that the majority of the reported workforce requirements are associated with future nuclear power reactor decommissioning. In addition, the distribution of the reported nuclear power reactor decommissioning workforce requirements differs between past and future nuclear power reactor decommissioning, as priorities shift between different types of reactor.

The questionnaire responses indicated a large variability in the reported workforce data. There are wide ranges reported for workforce requirements for the decommissioning of the same types of nuclear power reactor reactors, suggesting variation between the regions. There are also significant differences between the reported decommissioning workforces for the various types of reactors.

6.2.3. Observations on workforce

Because of the relatively small number of responses received for the workforce, the information presented in this subsection is necessarily limited. The responses were mainly for the workforce for NPP reactor decommissioning in the regions Europe — Central and Eastern and Europe — Western. The reported workforce requirements for decommissioning research reactors and FCFs are not representative and there were insufficient responses to support a more detailed analysis. Therefore, for the majority of the remainder of this subsection, only the NPP reactor responses for Europe — Central and Eastern and Europe — Western are presented in order to illustrate the types of analysis workforce information could support if there were sufficient data.

Nonetheless, the responses for Europe — Central and Eastern and Europe — Western suggest the following observations:

(a) The majority of the reported workforce requirements in the two regions are for future decommissioning;
(b) The majority of the reported overall decommissioning workforce are associated with a deferred dismantling strategy;
(c) There is an apparent divergence between past decommissioning, where more of the reported workforce are for immediate dismantling strategies, and future decommissioning, where more of the reported workforce are for deferred dismantling;
(d) There are wide ranges reported for workforce requirements for the decommissioning of the same types of nuclear power reactor reactors, suggesting variation between the regions;
(e) There are differences between the reported decommissioning workforces for the various types of reactors.

6.3. DECOMMISSIONING COSTS INCURRED AND ESTIMATES OF FUTURE DECOMMISSIONING LIABILITIES

This section presents information on decommissioning liabilities received from the questionnaire responses, both in terms of decommissioning expenditure incurred up until the end of 2020 (‘actual costs’) and estimates of future decommissioning liabilities (‘future liabilities’).

It is important to note that these data are from a limited number of respondents. In the case of nuclear power reactors, the reported cost and estimated liability data are from reactors corresponding to approximately 18% of power reactors globally, while for research reactors the data are from reactors corresponding to approximately 5% of research reactors globally and for FCFs the corresponding proportion is approximately 13%. Therefore, the information presented here should not be considered representative. Rather, it is provided in order to illustrate the types of analysis workforce information could support if there were sufficient data. For this reason also, only a selection of the available responses are presented here and the responses are not analysed in detail.

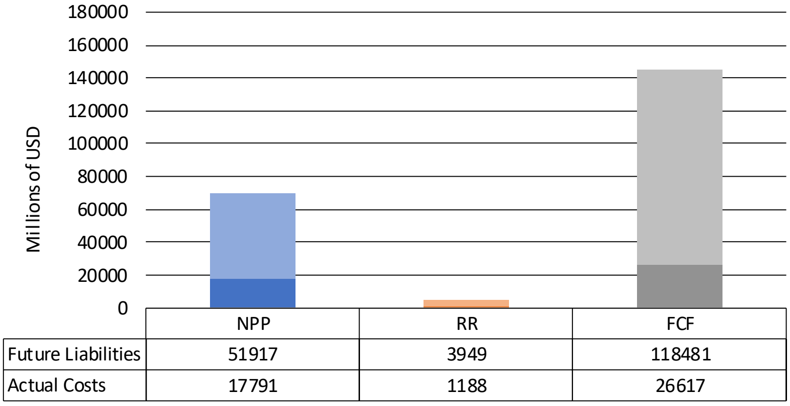
In the figures presented in this section, information is included on the number of facilities represented in the reported data. Information on actual costs and future liabilities are stated in millions of US dollars at 2020 value (millions of USD_{2020}).

Figure 63 shows the actual costs and future liabilities reported for decommissioning of nuclear power reactor reactors, research reactors and FCFs.

The data reported in Fig. 63 indicate that the majority of the reported actual costs and future liabilities for decommissioning are associated with future decommissioning. This is the case for all categories of facilities. Moreover, Fig. 63 also shows that the greatest proportion of reported actual costs and future liabilities is due to fuel cycle facility decommissioning as a whole.

6.3.1. Regional expenditure to date and estimated future liabilities for decommissioning

Figure 64 illustrates the regional distribution of the actual costs and future liabilities for all categories of facilities combined (nuclear power reactors, research reactors and FCFs), as reported in the questionnaire responses.



	NPP	RR	FCF
Future Liabilities	51917	3949	118481
Actual Costs	17791	1188	26617

FIG. 63. Actual costs and future liabilities for decommissioning, by category of facility, in millions of USD$_{2020}$. Darker shaded areas represent the actual costs and the lighter shaded areas represent the future liabilities. Data from questionnaire responses. The number of responses are: power reactors (126 actual, 113 future), research reactors (40 actual, 44 future) and FCFs (62 actual, 66 future). USD$_{2020}$. Darker shaded areas represent the actual costs and the lighter shaded areas represent the future liabilities. Data from questionnaire responses. The number of responses are: power reactors (126 actual, 113 future), research reactors (40 actual, 44 future) and FCFs (62 actual, 66 future).

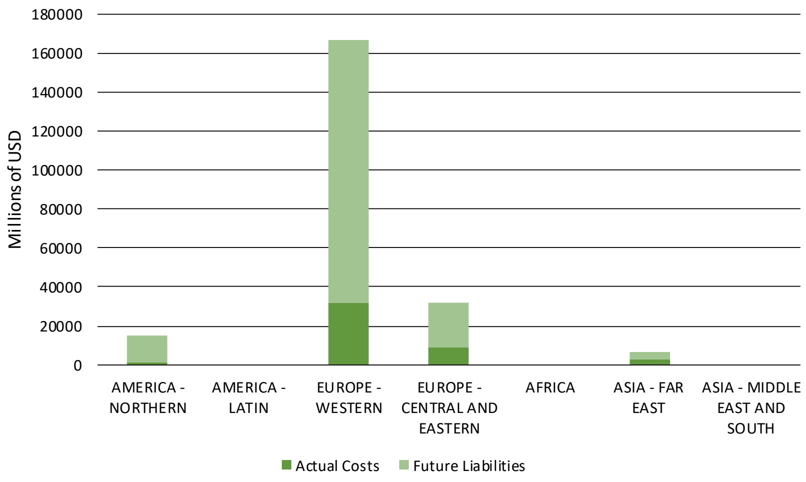


FIG. 64. Actual costs and future liabilities for decommissioning, for all categories of facilities combined, by region, in millions of USD$_{2020}$. Data from questionnaire responses. The number of responses are: power reactors (126 actual, 113 future), research reactors (40 actual, 44 future) and FCFs (62 actual, 66 future).

The data reported in Fig. 64 indicate that a large majority of the reported actual costs and future liabilities are associated with decommissioning in the region Europe — Western, where the greatest portion of this is future liabilities.

6.3.2. Actual costs and estimated future liabilities for decommissioning nuclear power reactors

Figure 65 shows the actual costs and future liabilities for decommissioning nuclear power reactors by region.

The data reported in Fig. 65 indicate that the largest share of reported actual costs and future liabilities for nuclear power reactor decommissioning is associated with the region Europe — Central and Eastern and Europe — Western. The greatest share of the total in all regions is future liabilities.

An additional useful reference for nuclear power reactor decommissioning costs is Ref. [10]. This presents the results of a review of the costs of decommissioning nuclear power reactors across the member countries of the OECD Nuclear Energy Agency, and includes information on actual costs or estimates for a number of nuclear power reactor decommissioning projects.

6.3.3. Observations on costs and liabilities

Because of the relatively small number of responses received for actual costs and future liabilities, the information presented in this subsection is necessarily limited and should not be considered representative. Rather, it is provided in order to illustrate the types of analysis workforce information could support if there were sufficient data. For this reason also, only a selection of the available responses are presented here and the responses are not analysed in detail.

Nonetheless, the responses suggest the following observations:

(a) The majority of the reported actual costs and future liabilities for decommissioning are associated with future decommissioning, and this is the case for all categories of facilities;
(b) Fuel cycle facility decommissioning was the largest category of reported actual costs and future liabilities;
(c) Decommissioning in the region Europe — Western had the highest reported actual costs and future liabilities, where the greatest portion of this comprised future liabilities;
(d) The largest share of reported actual costs and future liabilities for nuclear power reactor decommissioning is associated with the regions Europe — Central and Eastern and Europe — Western,

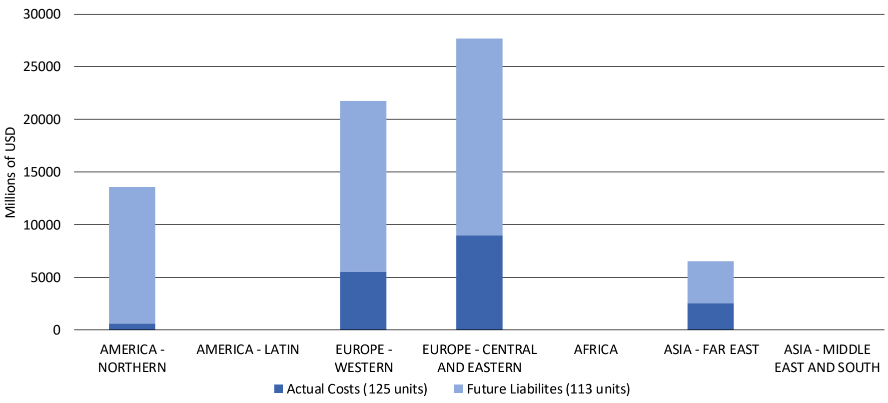


FIG. 65. Actual costs and future liabilities for decommissioning, for nuclear power reactor decommissioning, by region, in millions of USD$_{2020}$. Data from questionnaire responses. The number of power reactors reporting data is included in the figure.

although this should not be considered representative because of the small number of responses involved.

6.4. CONCLUSIONS

There is a need to ensure sufficient provision of both human resources and funding to meet the expected increased demands for these in future decommissioning activities. It is clear from the information presented here that, in comparison to current levels, there will need to be increases in the provision of both human resources and funding over the long term in order to meet the increasing volume of decommissioning projects. A large majority of the reported workforce requirements for decommissioning is associated with future decommissioning, while the reported past decommissioning workforce is relatively small. Similarly, a large majority of the reported actual costs and future liabilities for decommissioning are associated with future decommissioning in general, and future liabilities for fuel cycle facility decommissioning in particular.

On the basis of the information gathered in this project, it is not possible to provide an estimate of the scale of the workforce requirements and funding that will be needed to meet the needs of future decommissioning globally. Similarly, it is not possible on the basis of the current data to make global projections regarding when in time these needs are likely to arise. These limitations arise largely because of the limited number of facilities providing workforce data and data on costs and future liabilities, meaning that the data are not representative of the global picture.[35]

Within these limitations, the following observations can be made based on the responses received:

(a) The majority of the reported workforce requirements in the two regions considered are for future decommissioning, and the majority of the reported overall decommissioning workforce is associated with a deferred dismantling strategy;
(b) Wide ranges are reported for workforce requirements for the decommissioning of the same types of nuclear power reactor reactors, suggesting variation between the regions, as well as for the various types of reactors;
(c) The majority of the reported actual costs and future liabilities for decommissioning are associated with future decommissioning, and this is the case for all categories of facility;
(d) Fuel cycle facility decommissioning is the largest category for reported actual costs and future liabilities;
(e) Decommissioning in the region Europe — Western had the highest reported actual costs and future liabilities, where the greatest portion of this comprises future liabilities;
(f) The largest share of reported actual costs and future liabilities for nuclear power reactor decommissioning is associated with the regions Europe — Central and Eastern and Europe — Western.

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[35] The reported workforce data are limited. In the case of nuclear power reactors, the workforce data are from reactors corresponding to ~10% of nuclear power reactors globally. In the case of both research reactors and fuel cycle facilities, the data are from reactors and facilities corresponding to ~2% of each of these reactors and facilities globally. The reported cost and estimated liability data are similarly limited. In the case of nuclear power reactors, the reported cost and estimated liability data are from reactors corresponding to ~18% of power reactors globally, while for research reactors the data are from reactors corresponding to ~5% of research reactors globally, and for fuel cycle facilities the corresponding figure is ~13%.

7. TECHNICAL CHALLENGES AND TECHNOLOGIES FOR DECOMMISSIONING

7.1. INTRODUCTION

Technologies play an important role in the delivery of decommissioning projects. In preplanning and assessment of options for decommissioning, an assessment needs to be made of the challenges and subsequent technologies that may be needed to meet these challenges. In many cases there may be existing technologies available that can be selected to perform the desired activities. In some cases, however, specific technologies may need to be developed to meet a specific challenge. In larger decommissioning programmes, technology road maps or blueprints are produced that define the main technological developments needed to execute a decommissioning plan.

The decisions made to implement the project depend on the availability and success of these technologies. Regulatory compliance and the successful completion of decommissioning projects depend crucially on deploying appropriate technologies. If a chosen technology fails, its failure might affect the health of the workers, the schedule, the financial capabilities of the respective organization and stakeholder support. To reduce these threats, some facilities often prefer to choose proven technologies available on the market and avoid the application of innovative technologies. Overall, the development, selection and availability of technological methods and tools is a key contributor to successful execution of decommissioning projects and serves to mitigate hazards, improve schedules and reduce costs.

Decommissioning of nuclear facilities presents unique health and safety challenges, because these projects are often complicated by encountering toxic and hazardous materials, compounded by radiological contamination and radiation fields. One of the key drivers for new technology development or implementation in larger projects can be the improvement of worker safety. Typical technologies in this area include the use robots or remote controlled tools to remove operators from hazards and reduce exposure. The use of robotics and automation can also improve scheduling and quality.

The questionnaire aimed to identify areas of good practice in the field of technologies and also areas of improvement where the development of new technologies is needed. Using the structure in Ref. [38] for guidance, the questionnaire was grouped into the following five themes:

(a) Characterization and survey prior to dismantling;
(b) Technologies for segmentation and dismantling;
(c) Technologies for decontamination and remediation (‘cleanup’)[36];
(d) Materials and waste management;
(e) Site characterization and environmental monitoring.

For each of these five main technical areas, the respondents were asked to indicate the status of the respective technology on their site (developed or needed/under development) and had the opportunity to provide details regarding either current good practice or an indicated need for development. There was also the opportunity to provide details of what had been developed to solve what challenge or need under ‘developed’. Further, if there was a need for development or a technology was under development, it was possible to provide details regarding how far development had progressed, the predicted completion date and if any collaboration or support would be beneficial. The responses to the five technical areas are analysed in Section 7.4.

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[36] The term ‘remediation’ is used in Ref. [38], but in the context of this publication ‘cleanup’ is considered to be more appropriate, as it follows the terminology in Ref. [1], and hence it is used here.

In analysing the questionnaire responses, the intention was to identify patterns, both in currently ongoing projects and in planned projects, as well as identifying patterns applying to different types of facilities. Comparisons have been drawn with publicly available data in the literature [38, 39].

There are initiatives to identify decommissioning technology development needs, and in particular the EU project SHARE (StakeHolders based Analysis of REsearch for Decommissioning, 2019–2022)[37]. In contrast to the SHARE project and other similar initiatives, this project did not investigate decommissioning needs in detail, but rather provides a general overview of major trends in the use of technology and current needs for the development of new technologies for different types of nuclear facility.

7.2. TECHNOLOGICAL CHALLENGES FOR DIFFERENT TYPES OF NUCLEAR FACILITIES UNDER DECOMMISSIONING

The different types of nuclear facilities for civilian and commercial use (nuclear power reactors, research reactors, fuel facilities) impose different requirements for decommissioning and hence present different challenges regarding the technologies that are needed to decommission them.

Unique decommissioning challenges requiring bespoke technological solutions may arise where incidents or accidents have resulted in activity entering other areas of a facility or the release of contamination to the environment.

7.2.1. Nuclear power reactors

Future decommissioning was not always considered at the time NPP reactors were constructed, particularly in the case of older reactors. The designs are optimized for safe operation and reliable electricity generation rather than decommissioning. This leads to challenges, including the characterization of the facility, the accessibility of components, and the safe dismantling of large components and concrete structures.

In and around the reactor core, materials are highly activated due to high neutron fluxes. The high radiation levels prevent access by people, which means that characterization has to be done remotely or estimated with computer models. Further, the dismantling activities may need to be carried out remotely underwater or behind other shielding. Additionally, the complexity of systems and structures has to be considered.

The dismantling and removal of large components is a key element for the successful decommissioning of a nuclear power plant reactor. The reactor pressure vessel has to be dismantled and cut, with the resulting waste managed appropriately. The approach selected for this activity requires special equipment to complete the task. Steam generators are often removed as a whole piece. Their size, weight and location pose various engineering challenges and they typically require specialized equipment for technical activities, heavy lifting and transport.

7.2.2. Research reactors

Many research reactors are unique because they were designed and constructed to meet particular needs. This uniqueness leads to a broad range of technical challenges during decommissioning. Experience has shown that the construction methods and materials used are often insufficiently documented, as may also be the case for the operational history. Decommissioning may be further complicated as a consequence.

Additional facilities are often associated with research reactors, such as nuclear laboratories, hot cells, fume hoods, workshops and other experimental equipment that may have become radiologically contaminated and have to be decommissioned, leading to a broad variety of challenges of their own. Depending on the type

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[37] More information is provided on the project website: https://share-h2020.eu/.

and the use of the research reactor, transuranic and exotic radionuclides may be present in the facility. To detect these radionuclides and characterize the facility correctly is significantly more challenging, especially with pure alpha or beta emitters, unless their presence is anticipated.

Research reactors are typically significantly smaller than nuclear power reactors, which results in a smaller total amount of waste. In general, decommissioning of a research reactor is a smaller scale project than for a NPP reactor and is carried out by fewer people, while the radiation levels may be lower.

7.2.3. Fuel cycle facilities

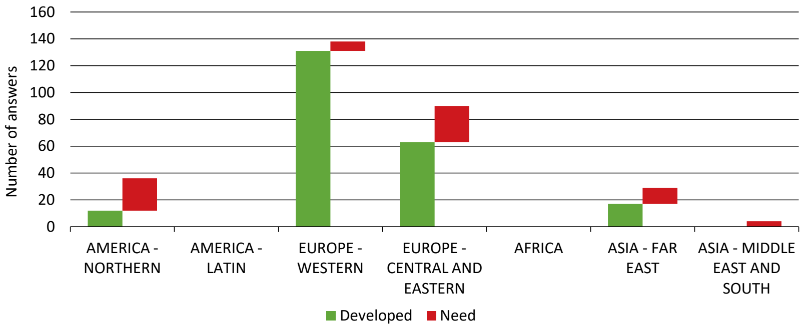
As with research reactors, many FCFs are unique in their construction and operation, resulting in unique challenges in decommissioning and new applications of technologies. Fuel handling facilities typically include heavy equipment for flask handling, decanning or shearing and for dissolution. On-site, tanks or ponds may contain contaminated water and sludges. Fuel reprocessing facilities can have high radiation fields that complicate the decommissioning activities, and may require the use of remote technologies.

Plutonium handling facilities may have to consider criticality during decommissioning activities. Further, special containments such as gloveboxes or ventilated enclosures may be needed for dismantling works to avoid the spreading of alpha contamination, which poses a higher risk to workers from ingestion and inhalation. In such situations it is challenging to characterize the facility accurately prior to dismantling. There are also different challenges for wet product and dry product. Wet product cannot be stored in sealed containers, as it generates hydrogen, pressurising the containers and creating an explosion risk. Dry product is highly mobile and can remain suspended in the air for long periods. Decontamination of dry gloveboxes and equipment is very time consuming.

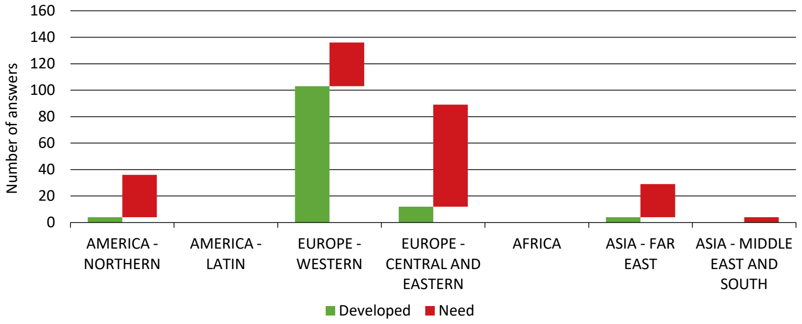
Waste facilities present challenges because of the wide range of wastes that have to be treated. These will include active liquid wastes that usually require solidification. as well as intermediate and low level wastes in solid form. Special wastes such as contaminated graphite, asbestos, mercury, etc. are given particular focus. Interim waste storage facilities generally have a simple design and their operation does normally not result in any contamination, as the stored radioactive waste is already treated and safely packed.

7.3. REGIONAL VARIATIONS

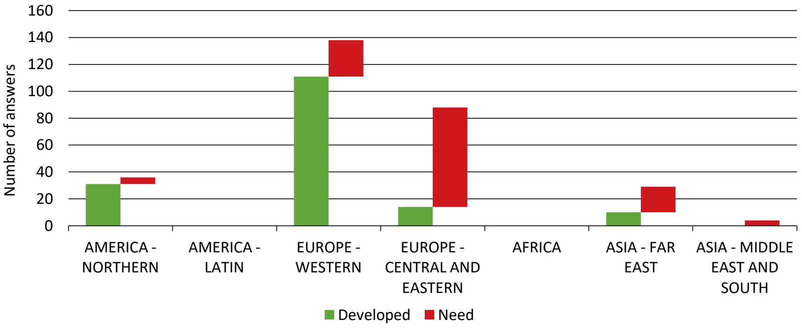
Approximately 300 respondents answered the questions on technology. In analysing the data, which occurs later in this section, it was only possible to process the data of ~240 respondents, since only those indicated an ‘end of operation date’, which was needed to distinguish between current and future needs for development. Consequently, facilities without an end of operation date could not be processed in Section 7.4, but they are nevertheless represented in the geographical distribution (Fig. 66).



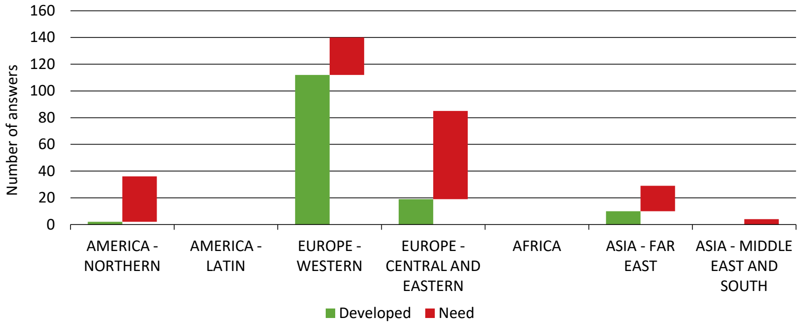
(a) Characterization.



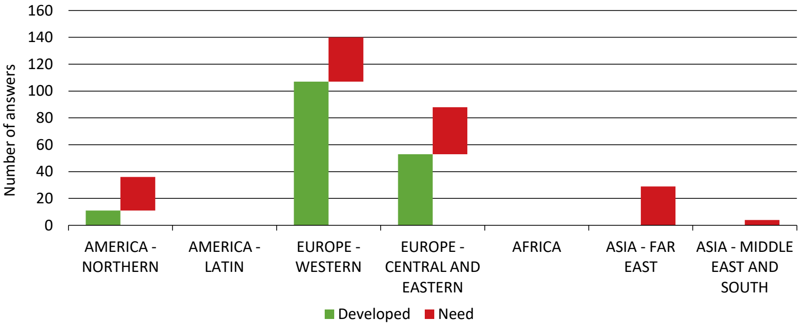
(b) Segmentation.



(c) Decontamination and cleanup.



(d) Materials and waste management.



(e) Site characterization and environmental monitoring.

FIG. 66. Regional distribution of responses received for the five technical areas analysed in this report.

Analysing the responses in the five technical areas shows a regionally variable picture, as shown in Fig. 66 and explained below.

- The majority of respondents in Europe — Western identified no need for development in the area of ‘characterization prior to dismantling’. On the other hand, the majority of respondents from all other regions identified a need for development in the field of characterization.
- A similar pattern was present in responses in the area of ‘segmentation and dismantling’ techniques. A majority of respondents in most regions identified a need for further development, with the exception of Europe — Western. Respondents from Europe — Eastern and Central identified a need for special techniques relating to graphite reactors.
- Responses from Europe — Western and America — Northern suggest that technologies for ‘decontamination and cleanup’ are considered available and are largely sufficiently developed. In contrast, respondents from Europe — Central and Eastern and both Asian regions identified a need for further development of these technologies.
- The responses for the theme ‘materials and waste management’ are comparable to those given for ‘characterization prior to dismantling’ and ‘segmentation and dismantling’. The respondents identified a clear need for development related to the treatment of radioactive waste, although this need was less pronounced for Europe — Western.
- Whereas the responses suggest that technologies for ‘site characterization and environmental monitoring’ (after decommissioning) seem to be sufficiently developed for the majority of respondents in Europe — Western and Europe — Central and Eastern, respondents in the other regions identified a need to further develop techniques in this area.

7.4. TECHNOLOGIES FOR DECOMMISSIONING

There is considerable experience in applying a range of decommissioning technologies, although the precise nature and extent of this experience varies across regions. Reflecting this, a number of responses indicated that there was no need for further development of decommissioning technologies, suggesting that currently available technologies may be considered adequate for implementation of the associated programmes (see also Refs [40–43]). This is also reflected in the experience of the successful utilization of a number of technologies in decommissioning projects for characterization, decontamination, dismantling and segmentation, waste management and environmental monitoring. Where such experience exists, decommissioning organizations may judge that reliance on existing and proven technology might present less project risk than the development of new technologies, which could require additional development, testing and approval prior to deployment.

7.4.1. Characterization and survey prior to dismantling

7.4.1.1. Currently available technologies

A nuclear facility needs to be characterized prior to dismantling. This involves the estimation of the type, amount, extent and distribution of radioactive substances and other hazardous materials in the facility and on the site. Characterization includes historical site assessment as well as measurements on-site. Historical site assessment provides information to ensure that the site characterization is appropriate for the anticipated hazards. The process summarizes an investigation of the past and ongoing operations, including all incident/accident reports and interviews with experienced facility workers.

The objective of the characterization process is to obtain information on and understand the radiological and non-radiological conditions in the facility. Characterization then defines the scope and the extent of the processes needed to decontaminate, remove, package, transport and dispose of materials, systems, structures, soils and tooling. Physical, radiological and non-radiological characterization prior to dismantling is a key element of all decommissioning projects. The characterization can be performed as follows:

- Direct measurements: this method is carried out by placing a detector at or near the surface or in the medium being investigated. This method results in obtaining direct readings of the radiation levels and indicates which radionuclides are present.
- Scanning: this method is carried out by evaluating the dose rate by moving a portable radiation detector at a constant speed at a specified distance from the surface. This technique is applied when a large area has to be covered.
- Sampling: this method is carried out by collecting a representative portion of the material being investigated. The collected material is then analysed in a laboratory under controlled conditions. With this method, the radionuclides can be determined as well as the specific activity.

Gas filled detectors, scintillation detectors and solid state detectors can be used for the measurements. The detectors are well developed, proven and reliable.

The data from the measurements are collected and become part of a statistical evaluation. The analytical information may be used to learn more about the structure of the data and to identify patterns and relationships or potential anomalies.

Additionally, computer calculations can be carried out, especially in and around the reactor block of a nuclear power reactor. Neutron fluxes and energy spectra produced in a reactor are incorporated in a computer code, which then models the neutron interactions with the surrounding materials. There are various models, codes and Monte Carlo methods to estimate the neutron induced activity in materials.

7.4.1.2. Need for development

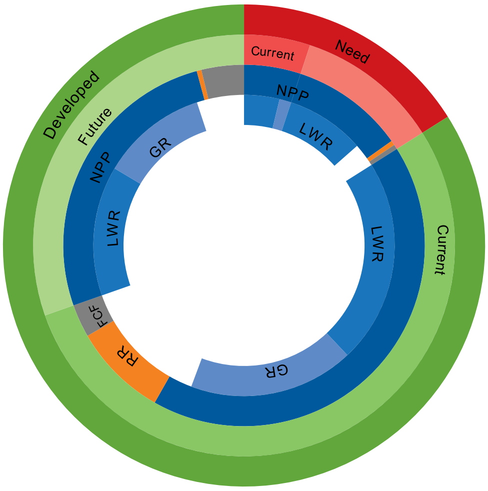
The current well advanced state of characterization techniques is reflected in responses to the questionnaire (see Fig. 67). Most respondents consider these techniques to be well developed and do not see any need for further development. Some of the respondents emphasized the successful characterization of their site and pointed to the advanced technology available.

The responses highlighted a need for further development in two fields in the area of characterization: development of techniques to characterise systems, structures and components (SSCs) with in situ measurements; and the development of codes or models, and processes to improve the accuracy of predictions of potential activation and contamination.

Respondents indicated the need for the development of improved techniques to detect and identify alpha and beta emitters. A similar need was indicated for the development of techniques to characterize complex and/or poorly accessible structures, such as pipes, vessel internals, analytical and sampling cells, and underground tanks with liquid radioactive waste. In this context, the further development and use of robots, remotely operated vehicles (ROVs) and drones has been mentioned and could offer new options, especially in high radiation areas. For site characterization — and later monitoring — the application of remote sensing, telemetry and satellite technologies is increasingly conceivable.

As decommissioning projects also have to handle non-radioactive hazardous substances, such as asbestos, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAH), there is a need to improve and develop techniques to identify these substances on-site. The characterization of soil and groundwater is relatively expensive and therefore seems to have potential for further development.

Furthermore, the responses indicated a need for the development and improvement of computer codes and modelling. The need was not only for characterization purposes but also to support planning and estimation of waste quantities and costs.



1. Ring	*Need for development*		*Developed*		
2. Ring	*Current*	*Future*	*Current*	*Future*	
3. Ring	*NPP*		*RR*		*FCF*
4. Ring	*LWR*	*GR*			

FIG. 67. Visualization of the responses to the questionnaire for the first theme, 'characterization and survey prior to dismantling', grouped by the different types of facilities; 'current' means ongoing decommissioning projects and operating facilities with end of operation before 2020 and 'future' indicates operating facilities with end of operation after 2020.

Note: *The graphics in Figs 67–71 are composed as follows. 'Nested pie charts' or 'nested doughnut charts' have been used to visualize the received responses on technology in Section 7. With these charts data can be presented and analysed on multiple levels. Here, the charts are read from the outside to the inside. The outermost ring indicates if there is a* ***need for development*** *(red) or if the respective technology has been* ***developed*** *(green). The second ring indicates whether the need/developed status is current or in the future, with* ***current*** *meaning ongoing decommissioning in projects and operating facilities with end of operation before 2020 and* ***future*** *indicating operating facilities with end of operation after 2020. The third ring describes the respective types of facility: nuclear power plant reactor (****NPP,*** *blue), research reactor (****RR,*** *orange) or fuel cycle facility (****FCF,*** *grey). Finally, the fourth and innermost ring distinguishes the NPPs into light-water reactors (****LWRs****), including PWRs and BWRs, and graphite reactors (****GRs****), including GCRs and LWGRs. As the categories of LWR and GR do not cover all types of facilities represented in the responses, a small gap might be seen in the chart.*

7.4.2. Segmentation and dismantling

7.4.2.1. Currently available technologies

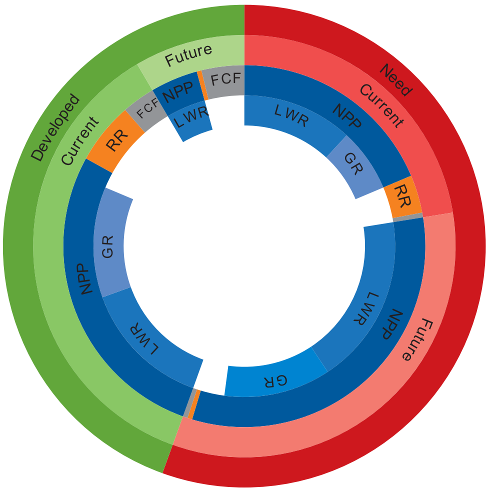
The choice of techniques for segmentation and dismantling depends on the size and complexity of the operation and the materials involved, as well as the objectives to be achieved.

Segmentation is used to reduce large SSCs in size in order to decontaminate them or to better transport, store and dispose of or recycle them. The segmentation of metal items, such as reactor pressure vessels, steam generators, piping and large activated concrete structures is considered dismantling, whereas demolition covers the breakdown of building structures and solid surfaces. Demolition is typically considered to be the final phase of decommissioning. Overall, the available dismantling techniques can be categorized as follows:

(a) Mechanical cutting techniques, including shears, saws, orbital cutters and abrasive cutting;
(b) Thermal cutting techniques, including flame cutting and plasma arc cutting;
(c) Abrasive water jet cutting, including abrasive water injection jet and abrasive water suspension jet cutting;
(d) Electrical cutting techniques, including electro discharge machines and arc saw cutting;
(e) Emerging techniques, including liquified gas cutting and laser cutting;
(f) Mechanical demolition techniques, including busting tools, wire saws, hydraulic shears, wrecking balls, expansive grout and rock splitting.

7.4.2.2. Need for development

Although a great variety of proven dismantling techniques exist, more than half of the respondents of the questionnaire saw a need for further development (see Fig. 68). The responses suggest that mechanical underwater cutting is generally the preferred technique for segmentation, as this reduces the quantity of fumes and dust compared to hot cutting techniques. However, the latest trends in decommissioning projects in the region Europe — Western point in another direction; it seems that for some stakeholders it is more important to achieve a water free state at an earlier stage than to cut the reactor pressure vessel underwater. Therefore, hot cutting techniques have greater significance in this region. In addition, specialist bespoke remote controlled tools have been successfully developed for size reduction.



1. Ring	*Need for development*		*Developed*		
2. Ring	*Current*	*Future*	*Current*	*Future*	
3. Ring	*NPP*		*RR*		*FCF*
4. Ring	*LWR*	*GR*			

FIG. 68. Visualization of the responses to the questionnaire for the second theme, 'segmentation and dismantling', grouped by different types of facilities; 'current' means ongoing decommissioning projects and operating facilities with end of operation before 2020 and 'future' indicates operating facilities with end of operation after 2020.

The responses indicated a need for development in the field of segmentation and dismantling, especially for the dismantling of LWRs that are still in operation. Despite a broad variety of segmentation techniques being available, further development was indicated as being desired. There is a potential for improvement in existing techniques in order to further reduce the production of secondary waste, and improve effectiveness.

The responses indicated a need for further development in the following areas:

(a) Handling and dismantling of large components (e.g. reactor pressure vessels);
(b) Remote controlled (intervention) techniques;
(c) Mobile and/or remote controlled techniques in narrow environments with high dose rates;
(d) Cutting thick concrete structures;
(e) Shot blasting engineering;
(f) Dismantling of graphite structures;
(g) Construction of access arrangements (e.g. scaffolding).

In several instances respondents considered the available segmentation techniques to be sufficient (‘developed’), but commented that the techniques are ‘currently under development’. This can be understood to indicate, for example, that a commercially available technique is being adapted to the specific decommissioning project and its characteristics.

7.4.3. Decontamination and cleanup

7.4.3.1. Currently available technologies

Broadly speaking, decontamination is the removal of radioactive or other hazardous material from areas where it is not wanted. The technology of decontamination is comparable to the cleaning of dirt, oil, or corrosion products, except that radionuclides are associated with the contaminated material.

Radioactive contamination may be loose and fixed. Whereas loose contamination is typically removed by washing or wiping the surface, fixed contamination is held tightly to the surface matrix of the material or has even diffused into it. The removal of fixed contamination often requires harsh decontamination techniques to remove the fixed contamination, but this may also generate significant quantities of secondary waste.

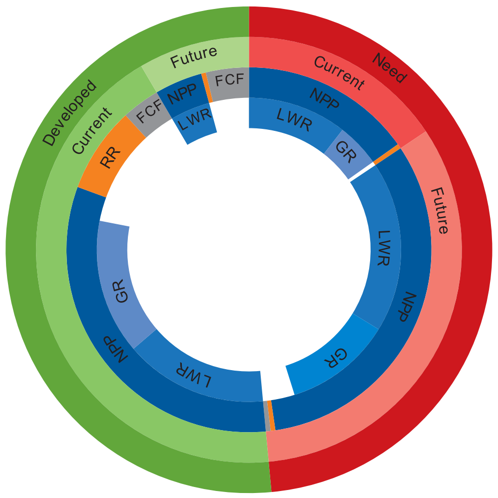
Decontamination techniques are applied not only during decommissioning, but also during operation as a routine process to reduce the amount of radioactive waste. As a consequence, a large variety of decontamination techniques exist, including:

- Chemical decontamination, including chemical solutions, foam, gels, multiphase treatments;
- Mechanical decontamination, including flushing with water, vacuuming, wiping, scrubbing, blasting, steam cleaning, high and ultrahigh pressure water jetting, grinding, milling and sprouting;
- Emerging technologies, including light ablation, microwave scabbling, thermal degradation and electromigration;
- Other techniques, such as electropolishing, ultrasonic cleaning and melting.

The selection of the respective decontamination technique depends on the material and the size of the component, the type of the surface to be decontaminated, the nature of the contamination and the accessibility of the component, as well as the safety and the dose rates of the involved workers.

Despite the large number of available decontamination techniques, approximately half of the respondents to the questionnaire identified a need for development (see Fig. 69). For decontamination tasks in research reactors the commercially available decontamination techniques seem to be sufficient.

Cleanup of underground services, soil and water on the site of a nuclear facility may be needed to remove contamination as a result of radioactive and hazardous substances in the surrounding site environment. Whereas tritium is highly volatile, insoluble radioactive contaminants tend to be trapped



1. Ring	*Need for development*		*Developed*		
2. Ring	*Current*	*Future*	*Current*	*Future*	
3. Ring	*NPP*		*RR*		*FCF*
4. Ring	*LWR*	*GR*			

FIG. 69. Visualization of the responses to the questionnaire for the third theme, 'decontamination and cleanup', grouped by the different types of facilities; 'current' means ongoing decommissioning projects and operating facilities with end of operation before 2020 and 'future' indicates operating facilities with end of operation after 2020.

in the soil in localized areas. As a consequence, the primary strategies are destruction or alteration of contaminants, extraction or separation of contaminants from the environment and immobilization of contaminants. It is possible that cleanup of soil beneath a building might be deferred until a later date when the building structure itself and its foundations will be demolished. Likewise, groundwater contamination might be addressed under a separate project/licence from the facility decommissioning project.

Cleanup techniques include:

(a) Soil cleanup:
  (i) Excavation and disposal;
  (ii) Soil vapour extraction;
  (iii) In situ air stripping;
  (iv) In situ bioremediation;
  (v) In situ soil flushing.
(b) Soil solidification.
(c) Groundwater cleanup:
  (i) Pump and treat;
  (ii) Bioreactors;
  (iii) Natural attenuation processes.

7.4.3.2. Need for development

These techniques are often developed specifically according to the particular situation and need. Most of the respondents who identified decontamination and cleanup as a need for development also specifically mentioned further development in the area of site cleanup techniques. Many respondents indicated that relevant technologies had already been developed, but nonetheless mentioned a need for further development.

A similar pattern to that for the segmentation and dismantling techniques is apparent in the survey for the decontamination and cleanup techniques. A need for further development in this area is identified for the future decommissioning of nuclear power reactors that are still in operation. In contrast, research reactors and FCFs have, according to the respondents, almost no need for development in this area.

The responses indicate a common interest in development regarding primary circuit decontamination in nuclear power reactors. Currently available technologies such as chemical decontamination processes may decrease the radiation level significantly, but further improvements are desired, including the availability of vendors who supply these technologies. Often mentioned is the non-availability of remote controlled technologies for decontamination of highly contaminated materials and the development of remote handling technologies for fuel debris and highly activated materials. In this context, the potential use of robots and automated, modular decontamination processes offers an opportunity for development.

The waste arising from the various dismantling and decontamination processes is another challenge with an identified need for further development, especially for techniques for waste segregation and the respective methodologies.

Some respondents indicated a general need for development of cleanup technologies, noting that they had little previous experience in this area. Others identified a need for further development of decontamination techniques and concepts for cleanup of contaminated soil.

7.4.4. Materials and waste management

7.4.4.1. Currently available technologies

During decommissioning, wastes arise from decontamination, dismantling and site cleanup, which will require safe management, handling, treatment, storage and disposal. According to regulatory requirements and international safety standards, the general principles for the management of radioactive wastes are:

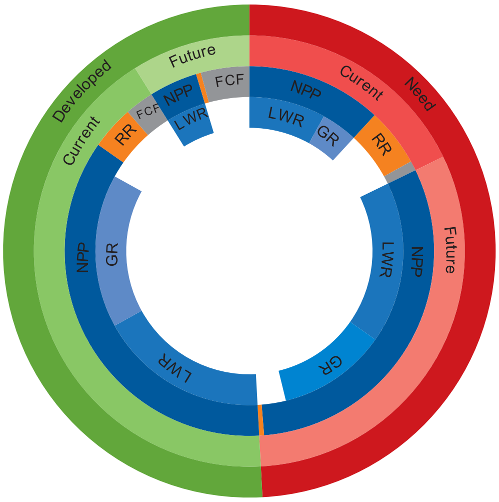
(a) Waste minimization;
(b) Sustainable development;
(c) The polluter pays principle.

The elements of waste management are:

(a) Radioactive waste classification and inventory;
(b) Treatment and conditioning of radioactive waste;
(c) Transportation and storage or interim storage;
(d) Disposal.

Radioactive waste is divided into different classes. Classifications vary and include (very) low level and intermediate level wastes, high level wastes and spent fuel (where this is considered to be a waste).

Waste treatment methods are chosen depending on factors such as the physical state (solid, liquid, gaseous), the quantity, the levels of radioactivity, the half-lives, the final disposal route, the radiotoxicity and the objectives to be achieved. The wastes have to be treated in such a way that they meet the acceptance criteria for long term storage or disposal. The final disposal of radioactive waste is not considered in this publication.



1. Ring	*Need for development*		*Developed*		
2. Ring	*Current*	*Future*	*Current*	*Future*	
3. Ring	*NPP*		*RR*		*FCF*
4. Ring	*LWR*	*GR*			

FIG. 70. Visualization of the responses to the questionnaire for the fourth theme, 'materials and waste management', grouped by the different types of facilities; 'current' means ongoing decommissioning projects and operating facilities with end of operation before 2020 and 'future' indicates operating facilities with end of operation after 2020.

7.4.4.2. Need for development

The responses indicated (Fig. 70) that approximately half of the respondents identified a need for further development, while the other half indicated that no further development is needed. Assessing the data in more detail, it appears that those planning for NPP decommissioning are more likely to identify a need in comparison to those that have already started decommissioning activities. For those facilities that are being decommissioned, the respondents report having adequate techniques to treat the resultant waste.

The respondents indicated a need for further development in the area of materials and waste management regarding the long term interactions between waste, packaging and disposal, for wastes such as irradiated graphite, mixed wastes, organic materials, transuranic and depleted uranium, as well as high and intermediate level wastes.

The responses suggest a need for further development not only in the techniques for waste management but also in processes and strategies that are outside of the scope of this project.

Waste treatment includes the separation of radioactive from non-radioactive waste and the reduction of radioactive waste. Respondents indicated a need for further improvement throughout the whole waste management process, including in areas such as:

- Identification, characterization and treatment of radioactive waste;
- Treatment of contaminated conventional hazardous materials (e.g. asbestos, mercury);
- Development of proven sludge handling techniques;
- Development of immobilization technology for separated plutonium;
- Treatment and storage/disposal of irradiated graphite;

- Techniques to rapidly assay low levels of radiation and contamination in order to sentence materials for low level waste (LLW) disposal and segregate materials for release as clean or exempt materials;
- Techniques for treatment of metal and concrete for release and reuse.

Responses indicated that interim storage facilities may be present on a site of decommissioned nuclear facilities until a long term disposal strategy is implemented. As a consequence, the development of safe vessels and casks for interim storage of radioactive waste, the long term safety of these casks and the safe retrievability of spent fuel assemblies from the casks after several decades is another area in which a need for further development has been identified.

7.4.5. Site characterization and environmental monitoring

7.4.5.1. Currently available technologies

After completion of dismantling activities and before conventional demolition of the remaining buildings and the release of the site from nuclear regulatory control, the site has to be characterized to confirm that the approved end state has been achieved. After completion of decommissioning, an environmental monitoring programme might need to be implemented for a certain period of time.

Technologies for site characterization and monitoring may include three dimensional modelling and non-intrusive sampling for characterization. Also included in this area is the use of complex models to understand potential soil and groundwater contamination and sources of contamination, such as concrete subsurface structures or tanks. Statistical methodologies for site characterization have been developed to complement non-statistical methodologies where all surfaces require direct measurement.

7.4.5.2. Need for development

The majority of the respondents are satisfied with the available technologies. There were no particular needs identified in this area for decommissioning of research and power reactors. However, the responses indicated there is need for development in the field of site characterization and environmental monitoring for the decommissioning of FCFs.

The majority of the respondents (Fig. 71) did not express a need for development in the area of environmental monitoring. If a site is released with conditions, an environmental monitoring programme may have to be implemented that includes periodic measurements and sampling.

The respondents indicated a need for further development in the area of characterization and monitoring techniques, including:

- Development of non-destructive and non-invasive techniques to assess the level of radioactive substances in buildings or structures prior to demolition;
- Methods to be used to demonstrate compliance with free release requirements for soil and groundwater, and for remaining underground structures;
- Development of statistical methods.

With increasing numbers of facilities coming into the phase of final characterization and site cleanup, respondents identified a need for more trained personnel and capacity in the future.

7.5. DRIVERS FOR INNOVATION

The responses showed a need for the development of new or more advanced techniques for each of the five main technical areas analysed in this project. The level of need is diverse, but for each area further development is necessary to a certain extent. Where technologies are already available and have been applied successfully, further development focuses on improvements aiming to make decommissioning safer, faster, more efficient and more cost effective.

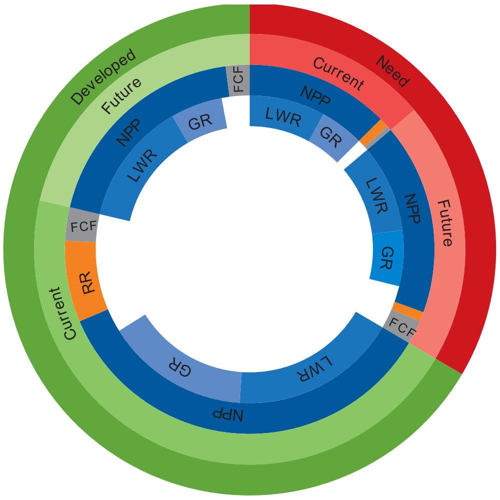
Generally, the development of new decommissioning techniques and technologies can be attributed to three main drivers:

(1) To meet a decommissioning challenge where existing technologies do not exist or are insufficient;
(2) To mitigate a risk that could occur during decommissioning;
(3) To improve safety, shorten the schedule and/or reduce cost.

In routine decommissioning projects there will not usually be a need to develop fundamentally new technologies, as established technologies will typically be used. This may not be the case where a facility has been seriously contaminated and/or physically damaged. In these circumstances, routine decommissioning strategies and techniques may be inapplicable, unusable, or impractical, and new techniques may have to be developed. These are unique situations and may demand the development of unique techniques.

Unique challenges may offer opportunities for basic research to be performed. As a result, unique situations might encourage the development of, for example, 3-D modelling, applications for virtual reality, and remote controlled applications, such as drones and robots.

Approaches to mitigate risks can be based on lessons learned from other decommissioning projects. These might also be required by regulation or could be identified during the decommissioning planning process. To identify potential risks in advance, an efficient knowledge management system is crucial, including technologies that enhance communications, archive data, and monitor and update the status of



1. Ring	*Need for development*		*Developed*		
2. Ring	*Current*	*Future*	*Current*	*Future*	
3. Ring	*NPP*		*RR*		*FCF*
4. Ring	*LWR*	*GR*			

FIG. 71. Visualization of the responses to the questionnaire for the fifth theme, ‘site characterization and environmental monitoring’, grouped by the different types of facilities; ‘current’ means ongoing decommissioning projects and operating facilities with end of operation before 2020 and ‘future indicates operating facilities with end of operation after 2020.

decommissioning. Building information modelling (BIM) and integrated project delivery (IPD) represent two emerging technologies that are now being explored for decommissioning.

New technologies for the planning, management and execution of decommissioning will be deployed where they provide improvements in terms of faster, cheaper and safer projects. In addition, the incorporation of certain technologies might be more effective if initiated at an early stage of a facility's life cycle rather than at the end of it.

An innovative solution developed to address a unique challenge might also be usable in other facilities and situations, offering a potential market for successful technological innovations. Potential interest in the development of technological innovations might be influenced by commercial considerations. For example, an organization might see an opportunity if they are able to offer the newly developed technology to several of their customers, recovering the development cost and potentially building market share through offering an improved product. An organization with multiple facilities might be prepared to invest in innovation and development, where the costs can be spread over several projects and over time. However, this might not be the case where an organization has only one or a small number of facilities, as development and approval are time consuming and expensive.

7.6. EMERGING TECHNOLOGIES AND TOOLS

Historically, technological breakthroughs in decommissioning typically emerge slowly, collaboration is limited and the industry is largely reliant on adopting technologies initially developed and refined in other industries [42]. In order to respond to the drivers for innovation identified in Section 7.5, it is crucial to start gaining knowledge and experience with technologies that are already available in other industries or that have been successfully implemented in other decommissioning projects.

Emerging technologies and tools support the establishment of a knowledge management process that spans the entire life cycle of a nuclear facility, in addition to implementing a continuous improvement process as required by the ISO 9001 standard, an established 'knowledge management' process that spans the whole life cycle of a nuclear facility. The knowledge management process has to be an integral part of the management system because knowledge management directly affects safety and human resources. In line with Ref. [43], the available knowledge has to be collected and/or generated, and it has to be developed, passed on to other stakeholders and preserved.

Newly emerging digital technologies span a range from a fully digitized management system with a digital twin that mimics and monitors facility conditions, to the most common forms of digitization, laser scanning and 3-D modelling.

There are many examples where 3-D scanning and modelling have been used effectively to build an accurate 3-D representation of the decommissioning challenge. This information can then support the design of interfacing to existing plant and equipment or be used for decommissioning planning purposes. In addition, technologies such as virtual reality and augmented reality have also been used to view this information in a safe environment to support familiarization, training and stakeholder management. There are also examples where gamma — or lately even alpha — cameras have been used to identify dose profiles or dose maps in the 3-D environment. Further, dose information can be placed into 3-D spatial models and used to further support decommissioning planning and dose management. Technology has also been used at facilities to provide real time information in the digital environment and displayed in digital models. This is sometimes termed a 'digital twin'.

BIM allows data and information to be organized and tracked relative to 3-D models of a site or a facility. This allows location data to be tagged to coordinates and enables the tracking of a facility's current physical state, equipment, personnel, characterization data and material handling packages throughout the decommissioning project. BIM can be used together with tools for characterization, planning and uncertainty analysis. Coupling BIM with global positioning system (GPS) or location aware Wi-Fi networks enables the deployment of semi or fully autonomous robotics systems and drones.

In the field of dismantling and demolition technologies, there are initiatives to further develop a wide range of hot and cold cutting techniques, including using lasers (open air and underwater).

7.7. CONCLUSIONS

This section identifies needs for further development of technologies for the decommissioning of all three categories of nuclear facilities: nuclear power reactors, research reactors and fuel cycle facilities. The needs relate to characterization, segmentation, decontamination and cleanup, waste management and environmental monitoring. For ongoing decommissioning projects, technologies are currently available. Nonetheless, respondents indicated a need for further development of these technologies with the aim of improving project delivery.

Developing new techniques or improving existing ones can be expensive and time consuming. Deeper cooperation (nationally and internationally), including greater knowledge transfer and sharing of lessons learned, may facilitate technological innovation.

7.7.1. Nuclear power reactors

Responses indicated that the areas where there is the most need for further development are ‘segmentation and dismantling’, ‘decontamination and cleanup’, and ‘materials and waste management’.

The responses show no significant difference between LWRs[38] and GRs[39] in terms of a need for development for future projects. However, for GRs a specific additional need was identified relating to the development of new technologies and methods for the dismantling and treatment of irradiated graphite.

Responses indicated a widespread need for further development in the segmentation and treatment of large components in decommissioning of NPPs. Although large components have been dismantled successfully in ongoing decommissioning projects, there is a desire to either improve available techniques or develop new ones.

7.7.2. Research reactors

There were relatively few responses for research reactors, meaning that these are not representative, and therefore it is not possible to draw general conclusions concerning the technological needs for research reactor decommissioning. Nonetheless, over half of the respondents identified a need for further developments in the field of ‘materials and waste management’. These respondents appear to indicate that technologies for the other technical areas are sufficiently developed for decommissioning of research reactors.

7.7.3. Fuel cycle facilities

There were more responses for FCFs generally, but the responses cover a large and diverse set of facilities and accordingly there are challenges in interpreting the responses. Nonetheless, respondents identified a common need for further development in the areas of ‘site characterization and environmental monitoring’ and ‘materials and waste management’.

In some cases, FCFs are part of large, complex multifacility sites. In such sites, a wide range of wastes arise in various physical forms and in combination with hazardous materials, for example during the production and reprocessing of nuclear fuel. As it is common for FCFs to be unique in design, many FCF decommissioning projects are first of a kind, requiring new approaches for decommissioning.

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[38] PWRs and BWRs.

[39] GCRs and LWGRs.

8. CONCLUSIONS

8.1. INTRODUCTION

This publication presents an analysis of the status as of 2020 and likely future evolution of nuclear decommissioning activities around the world. In general, the online nuclear facilities databases[40] maintained by IAEA and used in this project enable an accurate representation of the numbers and current operational status of nuclear facilities. However, these databases typically do not currently provide comprehensive information on decommissioning status and plans.

In light of the above, IAEA Member States were requested to complete an online questionnaire, providing the data needed to undertake the planned analysis. The level of responses received varied according to the type of facility:

- For nuclear power reactors the responses represent 35% of all nuclear power reactors globally (including those under permanent shutdown or already decommissioned). The response rate for power reactors currently undergoing decommissioning or in a deferral phase was 66%, while it was 28% for those still in operation and 20% for the 20 plants that have already been fully decommissioned. The highest response rate was from the region Europe — Central and Eastern.
- For research reactors the responses represent 9% of all research reactors globally (including those under permanent shutdown or already decommissioned). Higher response rates (25%) were received for research reactors in a state of permanent shutdown or undergoing decommissioning. Although 54% of research reactors (446 reactors) had been fully decommissioned, these are not significantly represented among the survey responses.
- For the types of nuclear FCFs included in this project[41], the responses represent 10% of these FCFs globally (including those under permanent shutdown or already decommissioned). One third of the survey responses obtained were related to facilities currently undergoing decommissioning or in a deferral phase (these facilities represent 17% of FCFs globally). Facilities still in operation were underrepresented in the survey responses (44% of responses compared with 61% of FCFs globally.

The level of responses was not uniform across major regions; for example, in general, there was a significantly higher response rate from European programmes (Europe — Central and Eastern and Europe — Western) than from those in America — Northern, Asia — Far East, or other regions.

Although the findings of the study do provide several important indications of the current status of decommissioning and of major current trends, the level of responses obtained also preclude the development of overarching conclusions of general application. Accordingly, where necessary, appropriate caveats are made to the conclusions below.

8.2. THE CURRENT BASELINE

8.2.1. Nuclear power reactors

At the end of December 2020 there were 442 nuclear power reactors in operation around the world; a further 174 reactors were under permanent shutdown and/or under dismantling, and 20 reactors have been

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[40] PRIS, RRDB and iNFCIS (see Section 2).

[41] For the purposes of this publication, uranium mining and milling facilities have been excluded from the fuel cycle facility category (see Section 2).

fully decommissioned and released from nuclear regulatory control. Many of the nuclear power reactors have been in operation for a considerable period; approximately two thirds are more than 30 years old, over a quarter are more than 40 years old and some reactors have been in operation for more than 50 years.

It is difficult to forecast with any precision when reactors currently in operation will be retired from service, as the reasons for deciding to permanently shut down are not solely related to the original design life of the reactor. Experience indicates that the reasons for deciding to permanently shut down a power reactor are often a combination of political and economic factors, maintenance and/or refurbishment costs and electricity market conditions.

8.2.2. Research reactors

Research reactors serve a wide variety of purposes, including education and training, radioisotope production, irradiation of materials to test their properties and industrial processing of materials. As of the end of December 2020, there were 227 research reactors in operation or in temporary shutdown around the world (in 53 different countries), of which 154 (69%) had achieved first criticality more than 40 years ago. The majority of these are located in America — Northern (32%) and in Europe — Central and Eastern (30%), followed by Europe — Western (14%) and Asia — Far East (9%). Fifty-eight reactors are in permanent shutdown, awaiting decommissioning, and a further 65 are undergoing decommissioning. Four hundred and forty-six research reactors have already been fully decommissioned and, as of the end of December 2020, a further 27 research reactors are planned or under construction.

Research reactors have a broadly similar age profile to commercial reactors, in the sense that a significant number of currently operating reactors are more than 30, and some more than 40, years old. The reasons for research reactor shutdown are nonetheless diverse. As these reactors are typically not income generating to any significant extent, with the exception of reactors whose primary function is radioisotope production, they are less affected by political and economic factors than commercial power plants. Large research reactors are expensive to maintain and refurbish, so that situations involving equipment or structural degradation, or leakages, are often the trigger for a permanent shutdown decision. Further ongoing reductions in the numbers of operating reactors are likely, though without the acceleration in closures that may be expected in the case of power reactors.

8.2.3. Fuel cycle facilities

FCFs, including facilities for uranium conversion and enrichment, fuel fabrication, spent fuel storage and reprocessing and/or conditioning, present a diverse range of decommissioning challenges. The extent of the decommissioning challenge is dependent on both the type of facility and the stage of the process within the facility, with some facilities presenting many diverse challenges, for example due to the presence of high levels of radiation from the front end of fuel reprocessing, or cells with high alpha contamination from plutonium extraction or fuel manufacture. The need to deal with process fluids or sludges from facility operations or fuel storage presents additional challenges. The removal of process fluids and retrieval of contaminated sludges can itself represent a significant precursor activity to dismantling of the plant itself, for example in the case of reprocessing facilities. In general, FCFs have significantly lower levels of uniformity than reactor facilities.

The subset of iNFCIS facilities considered by this project comprises 481 facilities in total, the majority of which are still in operation (290). A significant number of facilities are already in permanent shutdown, including decommissioning (96), or have already been fully decommissioned (66), of which the largest categories are spent fuel reprocessing and recycling facilities (40%) and fuel fabrication facilities (28%). The countries most actively engaged in this field of decommissioning are those with significant long running nuclear research and fuel fabrication and/or reprocessing programmes. These decommissioning programmes may be expected to continue for several decades due to the size and complex nature of the facilities involved, together with the fact that many are located on multifacility sites.

8.3. FRAMEWORKS

This publication provides a brief overview of institutional and legal frameworks for decommissioning, highlighting the principal features and more typical arrangements, whilst noting that there is considerable variation in the specific national arrangements.

8.3.1. National frameworks

As the ultimate responsibility rests with the State in which the facility is located, these have established legislation and regulations including the roles and responsibilities for decommissioning. The specific details of the national arrangements for ensuring that decommissioning of nuclear facilities is safely managed vary from country to country.

National policy typically addresses the following:

- Responsibilities within the country for decommissioning;
- Arrangements for financing decommissioning;
- Decommissioning of nuclear facilities;
- Preferred management options for radioactive wastes arising from decommissioning;
- Public information and public involvement in related decisions.

While the specific details of legal instruments vary from country to country, the national legal frameworks typically assign roles and responsibilities for nuclear activities, including radioactive waste management, to operating organizations, ministries and other governmental organizations. A range of financing arrangements have been put in place for nuclear decommissioning in countries with established nuclear activities.

8.3.2. Responsibility for implementation

The prime responsibility for ensuring the safety of decommissioning and radioactive waste management rests with the licence holder, usually the operator or owner of the facility. In general, following permanent shutdown of a nuclear facility, the licensee implements decommissioning, using a management team drawn from its own staff, or employing a specialist contractor to oversee the project implementation. In some cases, responsibility for decommissioning is transferred from an operator to a dedicated State owned organization for implementation. An emerging trend in the USA has been to transfer nuclear power reactors after permanent shutdown to specialist decommissioning enterprises, together with the funds that were set aside to implement decommissioning.

8.4. STRATEGY

8.4.1. Strategy selection

Once a nuclear facility has been permanently shut down it needs to be brought to a passively safe state. This process typically involves the removal of spent fuel (where present) and highly active liquids, followed by the dismantling of the facility and management of the resulting materials and the site itself, such that these present no ongoing hazard to people or to the environment (i.e. in accordance with a selected end state). Decommissioning may be implemented immediately following permanent shutdown of the facility (immediate dismantling), or there may be an intervening period during which the facility is maintained in a safe interim state during which activity levels diminish through natural decay (deferred dismantling).

Many factors bear on the decision as to which decommissioning strategy to follow, and on the selected end state, including national policy and legal requirements, existing experience in the owner organization and the supply chain, and availability of funding and waste management systems. The socioeconomic impacts of this decisions are generally also an important consideration and, accordingly, the views of local affected communities are taken into account. A deferred dismantling strategy brings certain benefits for subsequent dismantling in terms of the reduced dose levels in the facility; there are also some disadvantages in terms of the cost associated with maintaining it in a safe state during the period of deferral, and the likelihood of a reduced level of historical knowledge of the facility.

The completion of decommissioning is normally marked by the release of the site from nuclear regulatory control, which may occur once the relevant authorities are satisfied that the agreed end state for the site has been achieved. Following site release, it may be used for new purposes, either within or outside the nuclear field. As with other nuclear activities, decommissioning is undertaken in accordance with strict legal requirements, which process is generally overseen by nuclear and environmental regulators.

Immediate dismantling is the selected decommissioning strategy for more than three quarters of all light-water reactors that have been permanently shut down, reflecting the high level of experience already gained in decommissioning this type of reactor, and a lack of significant funding or waste management system constraints in countries involved in nuclear energy production for many years. Although geological disposal facilities do not yet exist for long lived highly active waste and spent fuel from commercial nuclear power programmes, storage facilities have generally been developed in the main relevant countries pending disposal facilities coming into operation.

The selection of immediate dismantling strategies for light-water reactors is influenced strongly by national policy in certain regions, particularly in Europe — Western and Asia — Far East, where this approach is typically associated with sustainability policies that emphasize not passing undue burdens onto future generations. This factor was rated as the most important driver for all facility types (25% on average), generally closely followed by the availability of waste infrastructure (19%). The importance of national policy as a major driver was rated most highly for FCFs (34%), light-water reactors (29%) and research reactors (29%), and somewhat less so for graphite moderated reactors (18%).

In America — Northern region the strategy selected for decommissioning has historically been based on a case by case approach, more influenced by the availability of sufficient funding to proceed with decommissioning than by national policy considerations. The trend in recent years, including in North America, has been an increasing preference for immediate dismantling strategies, also driven by a desire to retire the associated liability from the accounts of the owner organizations.

Multifacility sites represent a special situation due to the possible benefits of adopting a programmatic approach to decommissioning across the site. In such cases, the study found that the likelihood of following a deferral approach was higher for all types of nuclear facility, particularly for nuclear power reactors, for example where the decommissioning of the first unit of a two unit plant might be delayed until the second one has been shut down permanently.

For graphite moderated reactors, both gas and water cooled, deferred dismantling remains the dominant strategy. Such reactors contain large quantities of irradiated graphite, which presents challenges in terms of its removal from the reactor and its subsequent management; there is not yet a settled strategy for disposal of such material. Graphite moderated reactors also present specific problems due to their size, being significantly larger than water moderated reactors. Nonetheless, some significant moves away from deferred dismantling approaches have taken place in recent years.[42]

The basic steps following the permanent shutdown of a research reactor are essentially the same as those for a nuclear power reactor, though typically on a much smaller scale. Subject mainly to the

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[42] For example, the UK's Nuclear Decommissioning Authority has decided to adopt a site specific decommissioning strategy for each of its Magnox reactor sites, with the Dungeness A and Trawsfynydd reactors proceeding with early dismantling on a 'lead and learn' basis. Ignalina Nuclear Power Plant is proceeding with immediate dismantling of its facility, including development of a storage facility for irradiated graphite pending the longer term development of a geological disposal facility in Lithuania.

availability of funding, there are fewer reasons to follow a deferral approach, and more than 80% of the facilities included in the survey have adopted an immediate dismantling strategy. In contrast to nuclear power reactors, it is unusual if funds have been set aside for decommissioning during the period of operation; decommissioning is treated as an operating expense and special funds may need to be diverted from other purposes by the owner organization, or may need to come directly from the government. For this reason, the pace at which decommissioning proceeds in highly sensitive to the availability of adequate funding streams, sometimes provided on an annual basis.

Decommissioning of FCFs also presents a special case, for example because of their diverse nature. As with research reactors, immediate dismantling is generally selected as the preferred decommissioning strategy, but the pace at which this is implemented is closely related to the availability of funding, as well as facilities for storage and/or disposal of radioactive waste. In the case of major fuel fabrication and/or reprocessing facilities, such funding is generally provided, directly or indirectly, from State resources and is therefore dependent on government decisions on competing spending priorities, which may change on an annual basis. FCFs are generally located on multifacility sites, and therefore the detailed decommissioning approach is likely to be optimized across a range of facilities.

8.4.2. Duration of phases and selection of end states

For the purposes of this publication, the following main phases of activity were assumed to occur following permanent shutdown of a nuclear facility:

(a) Post-operation[43] — during which spent fuel (where present) and highly active process fluids and operational waste are removed and safety systems are reconfigured to support the active dismantling phase.
(b) Safe enclosure (where applicable) — during which the installation is maintained in a safe state with minimal interventions over a period of years or decades.
(c) Dismantling — during which the structures, systems and components of a facility are taken down and disassembled, and removed. In this phase, radioactively contaminated plant and equipment are decontaminated and either processed to radioactive waste or released, depending on the levels of residual radioactive contamination.
(d) Demolition — during which the remaining structures are taken down following the dismantling phase and residual contamination is removed so that the approved end state is achieved.

The analysis showed a wide variation in the duration of the above phases. The median duration of the post-operational phase was approximately nine years for nuclear power reactors, six years for research reactors, and only two years for nuclear FCFs. In the case of facilities being prepared for a safe enclosure phase, the median delay before entry into safe enclosure is 13 years in the case of nuclear power reactors and 9.5 years on average in the case of research reactors.

The findings of the study suggest that regulatory approvals to proceed with the dismantling phase are increasingly being obtained while spent fuel removal is still taking place. For the nuclear power reactors for which detailed information was obtained in the study (more than 130 reactors), this occurred in 21% of cases. In the case of research reactors (45 reactors), the proportion was only 2%. The situation in Germany provides an example of this trend where, in recent cases, decommissioning licences were granted at approximately the time of permanent shutdown.

The median duration of the phase of active dismantling without previous safe enclosure is 15 years in the case of nuclear power reactors, 2 years in the case of research reactors and 5 years in the case of FCFs. The latter figure provides an average for a wide range of different facilities, some of which will take significantly longer (e.g. reprocessing facilities). The study suggests that the median duration of the

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[43] This phase is sometimes described as a ‘transition’ or ‘deactivation’ phase for reactor facilities and post-operational clean out (POCO) in the case of fuel cycle facilities, with the latter term being used particularly in the UK.

active dismantling phase, when undertaken after a safe enclosure phase, is slightly reduced to nine years in the case of nuclear power reactors.

The study considered whether the selection of different end states (e.g. unrestricted release, release with restrictions, release with intended nuclear reuse, release for a specific non-nuclear reuse) was correlated with the selected decommissioning strategy. The results suggest that a deferral strategy is more likely to be selected when release of the site with ongoing supervision is anticipated, and more so again if the site will be reused for construction of a new nuclear facility. In the case of nuclear power reactors, the average duration of active dismantling is typically not closely correlated with the selection of an end state based on unrestricted release or restricted release, though the dismantling phase may be accelerated when a site reuse option has been adopted. The latter result also appeared to apply in the case of research reactors.

8.5. IMPLEMENTATION

8.5.1. Impacting factors for delivery of decommissioning

In addition to the factors impacting on the selection of decommissioning strategies, as discussed above, the study also considered the factors impacting on decommissioning implementation. The availability of waste facilities was ranked as the most important impacting factor for nuclear power plants, with funding availability being the second most important factor. The same factors were ranked more highly for research reactor and fuel cycle facility decommissioning, but with the order of importance reversed. The study findings suggest that the selected end state and the intended future use of the facility or its site have little impact on the implementation of decommissioning, apart, presumably, from at the final stage, when the achievement of the agreed end state needs to be demonstrated to the regulatory authorities prior to the release of the facility or site.

Regarding nuclear power reactors, the study found important regional variations in the factors of importance, beyond waste and funding issues, which were universal. In this regard, sufficient survey responses to make a detailed comparison were only obtained from Europe — Western and Europe — Central and Eastern. For Europe — Western, the selected end state, the availability of appropriately skilled personnel, and having access to management facilities for spent fuel were all ranked as important factors. In the case of Europe — Central and Eastern, the availability of appropriate technology received a high ranking, but the other factors received low rankings.

For research reactors, the availability of waste management facilities, skilled personnel and a management route for spent fuel were again ranked as highly important factors, and in this case a similar finding was obtained for both Europe — Western and Europe — Central and Eastern. Here, the availability of funding was not highly ranked by Europe — Western respondents, though it was the most important factor for those from Europe — Central and Eastern. Respondents from America — Northern also ranked stakeholder acceptance and the availability of a well developed regulatory framework as being adversely influential in delivering decommissioning, alongside the availability of funding. The availability of appropriate waste management or spent fuel facilities was not highly rated by North American respondents.

For nuclear fuel facilities, the availability of waste facilities was ranked as the most important impacting factor overall, ahead of the licensing/authorization framework. Availability of adequate funding and of appropriate technological solutions were also generally highly ranked. There were important divergences between different Europe — Western and Europe — Central and Eastern, which again were the only regions from which sufficient responses were obtained to make a detailed analysis. In the case of the former, the major focus was on waste management systems, the regulatory framework and availability of technology, with funding availability not being highly ranked. In the case of the latter, the factors associated with funding, waste management and the selected end state received the highest rankings.

A comparison was also made between important impacting factors for single facility sites (i.e. nuclear power plant sites) and multifacility sites. This suggested that the availability of funding and access to appropriate technologies are more important drivers on multifacility sites, with the licensing and authorizations framework being a less important driver.

8.5.2. Analysis of strengths, weaknesses, opportunities and threats

The study included an analysis of strengths, weaknesses, opportunities and threats (SWOT) for decommissioning to aid understanding of current strategic issues for the industry, as perceived by the questionnaire respondents. In this analysis strengths and weaknesses are issues of internal origin (attributes of the organization) and opportunities and threats are issues of external origin (attributes of the environment). In general, the issues perceived as major strengths were project management and planning capabilities, together with competence in radiological and conventional safety and in the field of characterization. The main weaknesses were identified as being related to contracting and procurement and dismantling techniques. From the perspective of the external environment, major opportunities were identified as being related to stakeholder engagement, licensing and workforce competence development, with opportunities for improvement in available dismantling technologies and associated cost savings also being mentioned. Major identified threats were the availability of waste management facilities and contracting and procurement.

The study findings suggest that there is little distinction in the overall internal attributes (strengths/weaknesses) between different facility types. Competence in dismantling technologies and in licensing issues was scored more highly as a strength by fuel cycle facility respondents than those representing other types of facility. For the particular case of nuclear power plants, dismantling technologies were identified as a key area of weakness. Regional differences were apparent in the analysis of skills and weaknesses, with project management capability being identified as a strength by respondents from America — Northern and Europe — Western but not in Europe — Central and Eastern. The reverse situation applies in the case of availability of appropriately skilled personnel, with this being identified as a strength by Europe — Central and Eastern respondents, but as a weakness by America — Northern and Europe — Western respondents.

Concerning the external environment (opportunities and threats), opportunities relating to improved stakeholder engagement were noted for all facility types, whereas potential improvement in licensing approaches was mainly identified by respondents representing nuclear power plants. Workforce competence development was identified as an important opportunity in the context of nuclear power plants and FCFs, but less so in the case of research reactors. Potential improvements in dismantling technologies and cost saving were noted by respondents for all facility types. Opportunities related to improved stakeholder engagement, licensing approaches and workforce competence development were significantly more highly rated by respondents from America — Northern and from Europe — Western, than those from Europe — Central and Eastern.

The availability of waste management facilities was identified as a major threat for all types of facility, whereas contracting and procurement issues were mainly identified as a threat for nuclear power plant decommissioning. Licensing and authorization were mainly identified as a major threat in the context of FCFs, and to a lesser extent for research reactors. At a regional level, licensing was identified as a major threat in Europe — Western, with contracting/procurement being the main threat identified in Europe — Central and Eastern.

8.6. RESOURCES FOR IMPLEMENTATION

There is a need to ensure sufficient provision of both human resources and funding to meet the demands for these in future decommissioning activities. It is clear from the information presented here that, in comparison to current levels, there will need to be increases in the provision of both human resources and funding over the long term to meet the increasing volume of decommissioning projects. However the limited number of responses prevented a detailed analysis of resource issues in this study.

8.6.1. Workforce

The extent of responses providing workforce data was limited. The majority of responses were obtained from the regions Europe — Central and Eastern and Europe — Western. The limited data provided suggest that workforce requirements for future decommissioning will be larger than those in the past. It is evident that future decommissioning programmes may be expected to last several decades, whereas significant past decommissioning projects have been undertaken during the time frame of the past couple of decades.

8.6.2. Liabilities

As was the case for the decommissioning workforce, the extent of responses providing data on costs and liabilities was limited. The majority of responses were obtained from the regions Europe — Central and Eastern and Europe — Western.

For the limited number of questionnaire responses obtained, a large majority of the reported actual costs and future liabilities were associated with future decommissioning in general, and future liabilities for fuel cycle facility decommissioning in particular. However, the responses are not a sufficient basis on which to make prognoses on financing needs and cannot be considered representative.

8.7. TECHNICAL CHALLENGES AND TECHNOLOGIES

Technologies are crucial to deliver decommissioning projects safely, on time and within budget. According to the respondents, technologies for ongoing decommissioning projects are available and meet the requirements of the implementors. However, the need for development is expressed in all five examined technical areas:

(1) Characterization and survey prior to dismantling;
(2) Segmentation and dismantling;
(3) Decontamination and cleanup;
(4) Materials and waste management;
(5) Site characterization and environmental monitoring.

The needs vary regionally and depending on the type of facility. Generally, it can be stated that in Europe — Western and America — Northern there is less need for development, whereas in Europe — Central and Eastern, as well as in both Asia — Middle East and South and Asia — Far East, more need for development is expressed by the respondents. Additionally, the needs themselves vary; the expressed needs for development range from slight improvements to existing technologies to the completely new development of technologies for special situations or to meet unique challenges. Most progress is observed in the field of digital technologies, where newly emerging technologies range from laser scanning and 3-D modelling through to fully digitized management systems with a digital twin of the facility.

8.7.1. Main technical challenges

For nuclear power reactors the main challenges identified in the publication were associated with activities such as characterization, which need to be carried out in areas where human access is difficult and/or where radiation levels are high. The dismantling of large components and concrete structures, which may have high levels of activation or contamination, was also emphasized as a significant ongoing challenge. In the case of research reactors, the identified challenges are more related to their often complex operational history, linked to their research function, and the associated likelihood of finding unexpected contamination sources, for example related to incidents that were not well recorded. Accordingly, undertaking accurate characterization is an important challenge. Challenges associated with FCFs are related to the different type of facility, but a recurring issue is the potential existence of unexpected levels of contamination, including alpha and beta contamination, which may be difficult to characterize accurately.

Despite the general acceptance of the key importance of characterization in order to be able to undertake effective decommissioning, respondents from Europe — Western, Europe — Central and Eastern and Asia — Far East did not generally identify this as a key development need, suggesting a high level of confidence that existing techniques were fit for purpose. America — Northern respondents, on the other hand, did generally identify characterization as an important development need.

The need for further development of technologies relating to component segmentation was noted almost universally, though not by Europe — Western respondents.

The findings for decontamination and cleanup were similar to those for segmentation, to the extent that most respondents, except those from Europe — Western and America — Northern, noted that these issues require further development.

Finally, concerning the technical domain of site characterization and environmental monitoring, only respondents outside of Europe noted this as an area requiring further development. It may be surmised that the latter group consider that existing proven technologies are fit for purpose.

8.7.2. Main current technology needs

Regarding the technical domain ‘characterization and survey prior to dismantling’, the main identified development needs were concerned with:

- Techniques for improved detection of alpha and beta radiation emitters;
- Techniques for improved characterization of complex and poorly accessible structures;
- Improvements to computer codes used to map and simulate radiation fields.

Concerning the technical domain ‘segmentation and dismantling’, the main identified development needs included:

- Remote controlled intervention techniques;
- Cutting of massive concrete structures;
- Dismantling of graphite cores.

For the technical domain ‘decontamination and cleanup’, the main identified development needs included:

- Improved techniques for chemical decontamination (e.g. of primary reactor circuits);
- Remote controlled technologies for decontamination of highly contaminated materials;
- Remote controlled technologies for removal of fuel debris and highly activated materials.

Regarding the technical domain ‘materials and waste management’, the main identified development needs included:

- Treatment of contaminated conventional hazardous materials (asbestos, etc.);
- Sludge handling techniques;
- Techniques for rapid assay of low levels of radiation and contamination.

For the technical domain ‘site characterization and environmental monitoring’, the main identified development needs included:

- Non-destructive techniques to prove the absence of radioactive substances in building structures prior to demolition.

Appendix I

IAEA ONLINE DATABASES FOR NUCLEAR FACILITY INFORMATION

I.1. POWER REACTOR INFORMATION SYSTEM

PRIS is a unique nuclear power database for nuclear power reactors worldwide. It has been maintained by the IAEA for more than five decades, being a leading international database for nuclear power history, current status and trends.

PRIS contains information on power reactors under construction and in operation, and those being decommissioned. All information and data items are provided directly from officially nominated national liaison officers and data providers at nuclear power reactor sites in IAEA Member States. This makes PRIS the only comprehensive and authoritative nuclear power database in the world.

As the responsible and independent steward of NPP data, the IAEA, through PRIS, provides an overview of the status, specification and performance results of every nuclear power reactor in the world. PRIS data and reports are routinely sourced in a series of technical documents and supplementary references.

PRIS covers the entire history of nuclear power since 1954 and includes the largest collection of worldwide statistical information on operating experience and design information for nuclear power reactors. Statistical reports available through PRIS help users understand nuclear power development and evaluate nuclear power plant performance. PRIS data can also be used for comprehensive trend analyses and benchmarking against best performers and industrial standards.

Furthermore, PRIS status and performance reports help nuclear power plants with safety performance analysis and assist the nuclear industry with analysis of global trends and strategic planning. The PRIS public website includes over 30 types of statistical reports, such as reactor status reports, energy availability, unit capability, unplanned capability loss and trend reports.

Monthly production and power loss data have been recorded in PRIS since 1970 and are complemented by information on nuclear power generated energy provided to non-electric applications, such as district heating, process heat supply or desalination. Information related to the decommissioning process for shutdown reactors is also available from PRIS.

PRIS is available to both the general public and registered users, as follows:

- The PRIS public web site (https://www.iaea.org/pris) is available to the general public and provides information on worldwide nuclear power plant status, operations and statistics. The site also facilitates access to annual publications, high level PRIS statistics and responses to enquiries by organizations.
- PRIS Data Acquisition and Validation Application (DAVA) (https://pris.iaea.org) is used by PRIS data providers for submitting data on their nuclear power reactors to the database. The data provided are verified and approved by PRIS administrators before being published on the PRIS public web site or used in PRIS reports.
- The PRIS Statistics (PRISTA) application, only available to registered users, provides over 80 different statistical reports, based on four levels of access rights: basic, non-nuclear organization, nuclear industry, and governmental organizations and NPP owners and operators. Statistical reports and details within the reports depend on a user’s assigned level.

PRIS registered users have access to statistical reports and tools to generate customized reports to analyse data from all nuclear power reactor units in the world, whether they are under construction, operational or permanently shut down. The most called upon data include reactor status overview, reactor status changes, historical development of nuclear power, NPP analyses using well defined and internationally accepted performance indicators, industrial standards (quartiles, median and average trend analyses) and reactor decommissioning process data.

PRIS data contribute to multiple IAEA publications, including the IAEA Annual Report and the Nuclear Technology Review, resources that inform sessions at the IAEA Board of Governors. Further, two IAEA publications are produced annually using PRIS data:

(a) Nuclear Power Reactors in the World, published since 1981 as Reference Data Series-2 (RDS-2)[44], is one of the IAEA's most popular annual publications. It contains a summary of recent specification and performance data on nuclear reactors in IAEA Member States and technical data on reactors that are either planned, under construction, operational or that were shut down or decommissioned.

(b) Operating Experience with Nuclear Power Stations in Member States (OPEX)[45] has been providing comprehensive information on nuclear power reactor performance in IAEA Member States since 1970. The publication includes statistical information on electricity production and overall performance of individual nuclear power plants that were in operation in the reporting year. In addition to annual information, the report contains a historical summary of performance during the lifetime of individual reactors and showcases worldwide performance data for the nuclear industry.

I.2. RESEARCH REACTOR DATABASE

The RRDB (https://nucleus.iaea.org/rrdb/#/home) is an authoritative database maintained by the IAEA Secretariat. It contains technical, utilization and administrative information on over 800 research reactors, including critical and subcritical assemblies in 70 countries. This information, provided by facility focal points nominated through official channels, is presented in a format that supports historical and statistical analysis.

The database has a dual purpose:

- Sharing technical and administrative information about research reactors to support their utilization, sustainability and reliability;
- Introducing the socioeconomic role of research reactors to the general public.

Each reactor dataset includes the following information:

(a) Header information:
    (i) Location, status, category, last update date and operating cycle.
(b) General information:
    (i) Operator, regulator, contact data and first criticality.
(c) Technical data:
    (i) Power, flux, cooling, ventilation and changes.
(d) Experimental facilities:
    (i) Channels, loops and fluxes.
(e) Utilization:
    (i) Applications, methods and runs or hours per year.
(f) Decommissioning:
    (i) Plan availability and completed/current/planned stages.

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[44] For example, INTERNATIONAL ATOMIC ENERGY AGENCY Nuclear Power Reactors in the World, Reference Data Series No. 2, IAEA, Vienna (2022).

[45] For example, INTERNATIONAL ATOMIC ENERGY AGENCY, Operating Experience with Nuclear Power Stations in Member States, IAEA, Vienna (2022).

The decommissioning related information comprises summary level data on decommissioning planning for the relevant facility, including:

- Decommissioning strategy, for example immediate or deferred dismantling;
- Anticipated dates for each major decommissioning stage;
- Description of the implementation actions through each stage.

An upgraded version of RRDB, released at the end of 2021, enables easier analysis and presentation of the data contained in the database. This new version utilizes a state of the art IT platform, compatible with mobile devices such as smartphones.

I.3. INTEGRATED NUCLEAR FUEL CYCLE INFORMATION SYSTEM (INFCIS)

iNFCIS (https://infcis.iaea.org/NFCIS/Facilities) is a resource for technical and statistical information about nuclear fuel cycle activities worldwide, as reported to the IAEA. The system includes information on FCFs in 54 Member States, being populated by means of an annual questionnaire sent to the participating national programmes. In addition to data collected through this mechanism, information provided at IAEA meetings and in other authentic sources, including publications, is also entered in the system.

In December 2021 the IAEA Secretariat launched a project aimed at upgrading the system to provide the following improvements:

(a) Better synchronization with other facility databases being maintained by the Secretariat (e.g. PRIS, RRDB, SRIS[46], FINAS[47]);
(b) Adding data input portal user interface;
(c) Graphic visualization and other reporting capabilities;
(d) Migration of the system to a new state of the art software platform.

The system includes four databases and one computer simulation system.

I.3.1. Nuclear Fuel Cycle Facilities Database (NFCFDB)

NFCFDB is a database of civil nuclear FCFs around the world, which was first launched in 1985 and upgraded to a web based resource in 2001. It provides catalogue information and statistics on all stages of nuclear fuel cycle activities starting from uranium ore production to spent fuel storage facilities and reprocessing, except for mining and waste disposal. NFCFDB also contains facilities for heavy water production and for zirconium alloy and tube production.

NFCFDB includes information on a range of facility types (laboratory scale, pilot plant and commercial) for:

(a) Uranium mining and milling;
(b) Uranium conversion;
(c) Enrichment;
(d) Fuel fabrication;
(e) Spent fuel storage;
(f) Spent fuel conditioning;
(g) Reprocessing and recycling, including mixed oxide fuel (MOX) fabrication;

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[46] Spent Fuel and Radioactive Waste Information System

[47] Fuel Incident Notification and Analysis System

(h) Other allied industries (e.g. heavy water production, zircalloy tubing).

The database contains information on operational, non-operational and decommissioned, under construction, planned and cancelled facilities. It provides details on the type and scale of the facility, its location, current facility status, date of start of operation and closure, fuel types, design capacity, processes used, feed material used, product material and facility operator/owners, etc.

NFCFDB does not include information on:

- Uranium and thorium ore deposits — such information can be found in the Red Book[48], issued jointly by the OECD Nuclear Energy Agency and the IAEA, and in other IAEA databases — UDEPO and THDEPO;
- Waste management facilities — such information can be found in SRIS, maintained by the IAEA;
- Nuclear power reactors — such information can be found in PRIS, maintained by the IAEA;
- Research reactors — such information can be found in RRDB, maintained by the IAEA;
- Post-irradiation examination (PIE) facilities — such information can be found in PIEDB, maintained by the IAEA and the European Commission;
- Accelerators, gamma irradiation, isotope production and related research and development facilities.

NFCFDB is also linked with the IAEA's Fuel Incident Notification and Analysis System (FINAS).

The IAEA publication IAEA-TECDOC-1613 [44] presents a complete directory of the nuclear FCFs included in the database.

I.3.2. Other iNFCIS databases

I.3.2.1. World Distribution of Uranium Deposits Database (UDEPO)

UDEPO (https://www.iaea.org/resources/databases/world-distribution-of-uranium-deposits) is a database of uranium deposits in the world. It contains information on the classification, geological characteristics, geographical distribution and technical characteristics of the uranium deposits worldwide. The web site provides filtering and search capabilities that include the geological classification of the deposits, current status and country. UDEPO also provides tools to create dynamic summary reports.

(a) Post Irradiation Examination Facilities Database (PIE Facilities Database)

PIE Facilities Database (https://www.iaea.org/resources/databases/post-irradiation-examination-facilities-database) is a catalogue of post-irradiation facilities (hot cells) worldwide. It includes a complete survey of the main characteristics of hot cells and their PIE capabilities. It also includes data on transport casks in use for transport of radioactive material to PIE facilities.

(b) Nuclear Fuel Cycle Simulation System (NFCSS)

NFCSS (https://www.iaea.org/resources/databases/nuclear-fuel-cycle-simulation-system), formerly known as VISTA, is a scenario based computer model for the estimation of nuclear fuel cycle material, service requirements and actinide generation. The NFCSS is a computer simulation system that uses simplified approaches to calculate nuclear fuel cycle requirements. The web site provides a detailed description of the simulation system, an example scenario with results and a simple calculation tool that can be used to calculate annual material flow (in both tabular and flow chart formats) for a selected nuclear fuel cycle option.

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[48] For example, 'Uranium 2020: Resources, Production and Demand', a Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency, NEA Report No. 7551, OECD, Paris, 2020.

Appendix II

FULLY DECOMMISSIONED NUCLEAR POWER REACTORS

TABLE 1. FULLY DECOMMISIONED NUCLEAR POWER REACTORS (2020)

No.	Name	Summary description
	Germany	
1.	Niederaichbach	HWGCR — 100 MWe
2.	HDR Grosswelzheim	BWR — 25 MWe
3.	VAK Kahl	BWR — 15 MWe
	Japan	
4.	JPDR	BWR demonstration — 12 MWe
	Switzerland	
5.	Lucens	HWGCR experimental — 6 MWe
	USA	
6.	Shippingport	PWR demonstration — 60 MWe
7.	Elk River	BWR — 22 MWe
8.	Bonus	BWR prototype — 17 MWe
9.	Hallam	Sodium/graphite demonstration — 75 MWe
10.	Pathfinder	BWR prototype — 59 MWe
11.	Carolinas–Virginia Tube (CVTR/PARR)	PHWR prototype — 17 MWe
12.	Saxton	PWR — 3 MWe
13.	Big Rock Point	BWR — 67 MWe
14.	Haddam Neck (Connecticut Yankee)	PWR — 560 MWe
15.	Fort St Vrain	HTGR — 33 MWe
16.	Yankee (Rowe)	PWR — 167 MWe
17.	Maine Yankee	PWR — 860 MWe
18.	Rancho Seco-1	PWR — 873 MWe

TABLE 1. FULLY DECOMMISIONED NUCLEAR POWER REACTORS (2020) (cont.)

No.	**Name**	**Summary description**
19.	Shoreham	BWR — 820 MWe
20.	Trojan	PWR — 1095 MWe

Appendix III

EXAMPLES OF NATIONAL FINANCING SCHEMES AND FUNDING MECHANISMS FOR SPENT FUEL, RADIOACTIVE WASTE AND DECOMMISSIONING

The information presented in Table 2 is an extract from the annex in the IAEA report, Status and Trends in Spent Fuel and Radioactive Waste Management [18]. The data are based on the national profiles and reports to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the 'Joint Convention'). The table reflects information and data as provided by each Member State participating in the Joint Convention, up until 2018.

TABLE 2. EXAMPLES OF NATIONAL FINANCING SCHEMES AND FUNDING MECHANISMS FOR SPENT FUEL, RADIOACTIVE WASTE AND DECOMMISSIONING

Country	Funding of RWM[a]	Funding of SF[b] and HLW[c] management	Funding of decommissioning
Argentina	Producers pay for RWM	Facility operator, which means State	Owner is responsible for providing the resources required for the safe decommissioning of the nuclear power plant
Armenia	Producers pay for RWM in case of waste from NPP, governmental funding for other institutional waste	Facility funding	Decommissioning fund
Australia	Governmental funding	Governmental funding	Governmental funding
Austria	Segregated trust fund for RWM	Governmental funding	Governmental funding
Belarus	Operator's financial assets or State funding	Operator's financial assets	Operator's financial assets
Belgium	Producer pays, contribution to ONDRAF/NIRAS long term fund. For radium waste: producer pays 'long term' fund by licence holders	NPP operators contribute to the fund managed by SYNATOM	NPP operators contribute to the fund managed by SYNATOM; various funds for historical liabilities fed by the State. Transfer of financial means to ONDRAF/NIRAS (waste funds managed by ONDRAF/NIRAS) when waste is transferred to ONDRAF/NIRAS
Bosnia and Herzegovina	Governmental funding	n.a.[d]	Governmental funding
Brazil	Operator or governmental funding	Operator (governmental) funding	Operator (governmental) funding

TABLE 2. EXAMPLES OF NATIONAL FINANCING SCHEMES AND FUNDING MECHANISMS FOR SPENT FUEL, RADIOACTIVE WASTE AND DECOMMISSIONING (cont.)

Country	Funding of RWM[a]	Funding of SF[b] and HLW[c] management	Funding of decommissioning
Bulgaria	Payments to Radioactive Waste Fund	Operator payments to Radioactive Waste Fund and international contributors	Operator payments to Nuclear Facilities Decommissioning Fund and international contributors
Canada	Each licensee has to create its fund	Each licensee has to create its fund	Each licensee has to create its fund
Chile	Producers pay for RWM	Governmental funding	Governmental funding
China	Provided by the generator and the related government	Collection of the funds into a dedicated account based the electricity production	Provided by the generator and the related government
Croatia	Producers pay disposal fee to Fund for Financing the Decommissioning of the Krsko Nuclear Power Plant and the Disposal of Radioactive Waste and Spent Nuclear Fuel	The Fund for Financing the Decommissioning of the Krsko Nuclear Power Plant and the Disposal of Radioactive Waste and Spent Nuclear Fuel	The Fund for Financing the Decommissioning of the Krsko Nuclear Power Plant and the Disposal of Radioactive Waste and Spent Nuclear Fuel
Cyprus	Producers pay for RWM	n.a.	n.a.
Czech Republic	Producers pay for RWM	Specific fund by licence holders held by Government	Decommissioning fund
Denmark	Producers pay for RWM	The State carries the financial liability	Governmental funding
Estonia	Producers pay for RWM	The State carries the financial liability	Governmental funding
Finland	Producers pay for RWM	Nuclear Waste Management Fund	Nuclear Waste Management Fund
France	Producers pay for RWM, partly government funded	Specific funds set aside by NPP operators. Other facilities partly Government funded	Specific funds set aside by NPP operators. Other facilities partly Government funded
Georgia	Producers pay for RWM. In case of legacy waste founded by State	Provided by waste producer. In case of legacy waste: funded by State	Governmental funding

TABLE 2. EXAMPLES OF NATIONAL FINANCING SCHEMES AND FUNDING MECHANISMS FOR SPENT FUEL, RADIOACTIVE WASTE AND DECOMMISSIONING (cont.)

Country	Funding of RWM[a]	Funding of SF[b] and HLW[c] management	Funding of decommissioning
Germany	Private facilities setting aside provisions. State owned facilities financed by public funds. Small waste producers pay fees to the land collecting facilities	Private facilities setting aside provisions. State owned facilities financed by public funds	Private facilities setting aside provisions. State owned facilities financed by public funds
Greece	Producers pay for RWM	Governmental funding	Licensee, governmental funding
Hungary	Central Nuclear Financial Fund	Central Nuclear Financial Fund	Central Nuclear Financial Fund
Iceland	Producers pay for RWM	n.a.	n.a.
Indonesia	Producers pay for RWM	Producer’s responsibility	Producer’s responsibility
Ireland	Producers pay for RWM	n.a.	n.a.
Italy	Producers pay for RWM	Partly funds set aside by NPP, but due to early shutdown, these are insufficient. Additionally, levy on electricity	Levy on electricity
Japan	Producers pay for RWM	Electrical utilities establish a fund	Electrical utilities establish a fund
Kazakhstan	n.a.	Governmental funding and international donors	Governmental funding and international donors
Korea, Republic of	Producers pay for RWM	Radioactive Waste Management Fund operated by Government (KORAD)	Decommissioning cost of NPPs is accumulated by Korea Hydro & Nuclear Power Co. and for research reactors by the Government
Latvia	Producers pay for RW predisposal management, State pays for disposal	n.a.	Governmental funding and donors
Lithuania	Producers pay for RWM	Funds provided by NPP, State and international contributors	Funds provided by NPP, State and international contributors
Luxembourg	Producers pay for RWM	n.a.	n.a.
Malaysia	Producers pay for RWM	Producer’s responsibility	Producer’s responsibility

TABLE 2. EXAMPLES OF NATIONAL FINANCING SCHEMES AND FUNDING MECHANISMS FOR SPENT FUEL, RADIOACTIVE WASTE AND DECOMMISSIONING (cont.)

Country	Funding of RWM[a]	Funding of SF[b] and HLW[c] management	Funding of decommissioning
Malta	Producers pay for RWM	n.a.	n.a.
Mexico	Producers pay for RWM, governmental funding	Governmental funding	Governmental funding
Moldova	Producers pay for RWM	n.a.	n.a.
Montenegro	n.a.	n.a.	n.a.
Netherlands	Producers pay for RWM	Producers fund the processing and long term management	Financial guarantee to fund future decommissioning and resulting waste management costs
Nigeria	Producers pay for RWM	n.a.	n.a.
Norway	Producers pay for RWM	Producer’s responsibility	Producers pay, partly governmental funding
Oman	Producers pay for RWM	n.a.	n.a.
Poland	Producers pay for RWM	Decommissioning fund or State budget (in case of the research reactor)	Decommissioning fund or State budget (in case of the research reactor)
Portugal	Producers pay for RWM	Producer’s responsibility	Producer’s responsibility
Romania	Producers pay for RWM	Producer has to pay fee to Radioactive Waste Management Funds	Producer has to pay fee to Decommissioning Fund or State Budget (in case of the research reactor)
Russian Federation	Since 11 July 2011 the producer has to pay to special reserve fund, previous waste management is responsibility of the State	The law requires a fund contributed to by operators and Government for storage and research	The law requires a fund contributed to by operators and Government for decommissioning
Serbia	Governmental funding	Governmental funding	Governmental funding
Slovakia	National Nuclear Fund, in case of management of waste of unknown origin, otherwise waste producer is responsible, disposal of RW is financed National Nuclear Fund paid by operators and the State	Storage and disposal of HLW and SF is paid by National Nuclear Fund paid by operators and the State	National Nuclear Fund paid into by operators and the State; in the case of NPP V-1 the EU also contributes

TABLE 2. EXAMPLES OF NATIONAL FINANCING SCHEMES AND FUNDING MECHANISMS FOR SPENT FUEL, RADIOACTIVE WASTE AND DECOMMISSIONING (cont.)

Country	Funding of RWM[a]	Funding of SF[b] and HLW[c] management	Funding of decommissioning
Slovenia	Producers pay for RWM	Fund raised by NPP operators (Slovenia and Croatia)	Fund paid by NPP operators (Slovenia and Croatia). Slovenian funding through Fund for Decommissioning of Krško Nuclear Power Plant and the disposal of radioactive waste from Krško Nuclear Power Plant
South Africa	Currently producers pay for RWM, in the long term owners contribute to National Radioactive Waste Management Fund to be established	Currently producers pay for RWM, in the long term waste producers contribute to National Radioactive Waste Management Fund to be established	Owners/waste producers pay
Spain	Producers pay for RWM	Fund from NPP operators and payments for waste management services	Fund from NPP operators and payments for waste management services
Sweden	Disposal of operational waste paid directly by the operators	Nuclear Waste Fund collected as a fee on nuclear power production	Nuclear Waste Fund included in the fee for SF and decommissioning
Switzerland	Producers pay for RWM	Liability is with the NPP owners, after final Waste Management Fund	Liability is with the NPP owners, after final shutdown Decommissioning Fund
Ukraine	Producers pay for RWM	Governmental funding	Governmental funding
United Arab Emirates	Producers pay for RWM	Annual contributions by nuclear facility operator to Decommissioning Trust Fund (DTF)	Annual contributions by nuclear facility operator to Decommissioning Trust Fund (DTF)
United Kingdom	n.a.	Operational waste management including low level waste disposal is paid for by the operators. Future disposal of spent fuel and other waste will be paid for by the Government with a contribution from a levy on nuclear electricity production	Governmental funding for decommissioning costs for the NDA estate. Decommissioning costs for the currently existing AGR and PWR reactors will be met through the Nuclear Liabilities Fund

TABLE 2. EXAMPLES OF NATIONAL FINANCING SCHEMES AND FUNDING MECHANISMS FOR SPENT FUEL, RADIOACTIVE WASTE AND DECOMMISSIONING (cont.)

Country	Funding of RWM[a]	Funding of SF[b] and HLW[c] management	Funding of decommissioning
United States of America	Producers pay for RWM	Private operators of facilities have to demonstrate capability to fund operational waste management. Public facilities obtain government funding For spent fuel and HLW disposal operators have paid into a Nuclear Waste Fund (currently suspended)	Private operators of facilities have to demonstrate capability to fund decommissioning. Public facilities obtain government funding
Viet Nam	Currently producers pay for RWM, in long term owners contribute to National Radioactive Waste Management Fund to be established	Currently waste producers pay fee for RWM, in long term waste producers contribute to National Radioactive Waste Management Fund to be established	Decommissioning fund from fee on the nuclear energy

[a] RWM: radioactive waste management.

[b] SF: spent fuel.

[c] HLW: high level waste.

[d] n.a.: not applicable.

Appendix IV

DECOMMISSIONING STRATEGY: NATIONAL AND FACILITY SPECIFIC EXAMPLES

IV.1. INTRODUCTION

The selection of a decommissioning strategy for a particular facility depends on a very complex set of influencing factors, as discussed previously. The variety of influencing factors is such that the preferred strategy can vary for a similar facility depending on the country in which the facility is located, or even within one country for different sites. The precise circumstances and the weights attached to individual factors vary from country to country and even from facility to facility, and therefore the strategies selected differ for justifiable reasons and there is obviously not a best option.

With regard to the actual process of balancing the different and often conflicting factors that influence strategy selection, there are various approaches and aids for the decision making.

At present, the emerging international trend is more towards immediate dismantling than was previously the case (e.g. France, Germany, Switzerland, Sweden). The societal concerns about the consequences of deferred dismantling seem to be a significant factor, at least at the government level.

In the case of France, complete decommissioning of already shutdown nuclear power reactors is expected within 25 years. French policy obliges the licensees to adopt a strategy for decommissioning to be completed within the shortest feasible timescale, with the aim of removing all hazardous substances and ensuring the most thorough cleanout possible. The goal of this strategy is to avoid imposing the technical and financial burden of decommissioning on future generations. It also facilitates retaining the knowledge and skills of the teams present during operation of the facility, which is vital during the first decommissioning operations. In June 2016 Électricité de France (EDF) advised the French regulatory authority (Autorité de Sûreté Nucléaire. ASN) that it was adopting a new strategy for decommissioning the six GCR reactors at Bugey, Chinon and Saint-Laurent. EDF plans to undertake the complete dismantling of one of the six reactors before beginning dismantling the other five. In order to bring together knowhow, skills, competences, and technical and economic means and resources in the emerging fields of decommissioning and waste management, in 2015 EDF group created a specialized Directorate: Decommissioning Projects and Waste Management Directorate (DP2D).

In Germany, immediate dismantling is the decommissioning approach being applied generally; of the 26 NPPs undergoing decommissioning at the end of 2020 only 1 is in safe enclosure. In 2011 legislation to accelerate the phasing out the use of nuclear power for the commercial generation of electricity was enacted, setting defined end dates for the operation of NPPs on a step by step basis, with all plants being shut down by the end of 2022 at the latest.

In Italy, the three NPPs Latina, Trino and Caorso continued to be operated until 1987, when they were finally shut down as a consequence of a governmental decision based upon the results of a national referendum that was called after the Chornobyl accident. The Garigliano NPP had been already shut down in 1978 for technical reasons. At the time the nuclear programme was cancelled, the Inter-Ministerial Committee for Economic Planning (CIPE) required that the National Electricity Company (ENEL) start decommissioning the NPPs. For this case a safe storage option was adopted, primarily because the premature closure of the nuclear power plants resulted in a lack of funding. Furthermore, disposal facilities were not available and a national position on clearance of materials from the regulatory system had not yet been determined. However, other factors, such as the risks associated with the potential loss of knowledge and skills, have resulted in establishing complementary funding arrangements, definition of clearance levels and adoption of a coordinated national strategy based upon completing the dismantling of all facilities within 20 years. This example shows both the strategic difficulties associated with insufficient funding and waste management arrangements and the weight of societal and political factors.

In December 1999, the Ministry of Industry, Commerce and Crafts[49] issued a strategic document providing guidelines for the management of liabilities resulting from past national nuclear activities, including the establishment of Società Gestione Impianti Nucleari (SOGIN). The primary mission of SOGIN is the decommissioning of all Italian nuclear installations according to a single step strategy, as well as the safe management of the spent fuel and radioactive waste related to those installations. Another key aspect of this new policy was the adoption of a national strategy of single step decommissioning (until the release of the sites without radiological constraints) for all shutdown nuclear installations, abandoning the previous safe storage option. Due to the current unavailability of a national repository, the national decommissioning strategy is divided into two phases. The first phase aims to attain so called brown field status, in which all of the dismantling and waste treatment activities have been completed and all the radioactive waste (originated by past operation and dismantling) is temporarily stored in dedicated interim storage facilities at the sites. The second phase aims to attain so called green field status, in which all the waste has been transferred to the national repository and the sites have been released without radiological constraints.

The Swedish nuclear programme is in a phase of change regarding new requirements for safety improvements for the continued operation of nuclear reactors and the shutdown and immediate dismantling of other reactors. A similar situation can be found in Switzerland, where the current decommissioning strategy for all Swiss nuclear installations is immediate dismantling. The strategy for decommissioning of the first pressurised water reactor in Finland is also immediate dismantling (within 10 years of shutdown), without a commitment to release the site to a green field end state (i.e. similar to the French situation). The strategy for the first boiling water reactor, however, envisions 30 years of safe enclosure before dismantling.

In Canada, in the case of nuclear facilities, specific requirements for decommissioning planning are set out in the Canadian Nuclear Safety Commission (CNSC) regulations, especially in the regulatory guide REGDOC-2.11.2 [45]. The CNSC also requires licensees to prepare for approval of a preliminary decommissioning plan (PDP). The PDP documents are the preferred decommissioning strategy — whether it is immediate dismantling, deferred dismantling or in situ confinement. The strategy is selected by the licensee, along with objectives at the end of decommissioning.

The United Kingdom has a wide range of experimental and prototype facilities, mostly in state ownership. The strategies for their decommissioning have varied for valid reasons. Some facilities have been dismantled immediately either to gather information and experience and to test new techniques, or because they were in a poor physical or radiological state. Some were dismantled simply because they occupied space that was required for other purposes. Other reactors have been left for approximately 30 years in safe enclosure to take advantage of radioactive decay and reduce worker dose during dismantling activities and to benefit from new or developing technologies (such as remote operations). This illustrates the importance of allowing strategy selection on a case by case study.

For decommissioning of the UK commercial gas cooled power reactors, however, the strategy preferred by operators was deferral of dismantling for approximately 100 years, with safe enclosure after removal of the fuel and certain peripheral equipment and buildings. This choice was influenced by the absence of a disposal facility for graphite and the benefits arising from radioactive decay in terms of allowing manual operations. Another contributing factor is the significant reduction of waste volumes and the substantially reduced costs. The decommissioning strategy for Magnox nuclear power stations was changed to move away from placing all sites in an extended period of quiescence, to adopt site specific decommissioning approaches that may result in some sites being decommissioned earlier than anticipated. Some other UK nuclear facilities, such as the Dounreay, Harwell and Winfrith sites, are undergoing prompt decommissioning to a defined end state.

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[49] Now the Ministry of Economic Development.

As of August 2020, activities at the Sellafield site included nuclear fuel reprocessing, nuclear material and radioactive waste storage, and nuclear decommissioning. Sellafield is a nuclear site complex on the coast of Cumbria that covers an area of 265 hectares and comprises more than 200 nuclear facilities and more than 1000 buildings. The focus of the Sellafield site is now on decommissioning and cleanup of the legacy of the site's early operations, including some of the most hazardous nuclear facilities in Europe. Decommissioning projects include the Windscale Piles, Calder Hall nuclear power station, and a number of historic reprocessing facilities and waste stores. The imperative to reduce the risks posed by these facilities and the challenging nature of the decommissioning activities encourages an approach to regulation that empowers the use of pragmatic and innovative methods to achieve timely and effective decommissioning. The facilities at the Sellafield site are at different stages of their life cycle. Those in the decommissioning phases have individual plans and strategies; some are in a period of deferral, whereas others are set for immediate decommissioning.

The Russian Federation is implementing a long term programme for the development of the nuclear industry and a programme for the development of technologies and scientific research in the field of nuclear energy use. These programs largely determine the strategy for decommissioning NPPs, RRs and FCFs. For nuclear legacy sites, the Russian Federation is implementing the Federal Target Programme with a period of implementation until 2030. It is important to note that for individual legacy sites (due to the new Federal Act in radioactive waste management, RWM) the Government may allow on-site waste disposal if all the requirements for the safety of such disposal are met. Based on these long term programmes, Rosatom is implementing a comprehensive strategy for decommissioning the civilian part of the nuclear industry, with three options for decommissioning (immediate dismantling, deferred dismantling, on-site disposal), and is forming a system for accumulating experience and knowledge in the field of decommissioning. The funding mechanism for this comprehensive strategy is based upon two main sources. For commercial facilities, decommissioning is financed by the owners of these facilities, and for legacy sites, by the State budget.

The examples below are presented as case studies, enabling the reader to visualize the different examples of selected decommissioning strategies.

IV.2. CHINON A (FRANCE)

The three reactors at the French site Chinon (A-1, A-2, A-3), operated by EDF from the early 1960s, were shut down in 1973, 1985 and 1990, respectively. Their partial dismantling was completed in 1984, 1992 and 2007, respectively. To date, the Chinon A1 and A2 reactors do not have the required authorizations to proceed with decommissioning, only the dismantling of the Chinon A3 plant has been authorized (by a decree delivered in 2010). The Chinon A1 and A2 plants are currently in safe storage and incorporate storage facilities for materials originating in the plant. The lack of industrial treatment solutions for irradiated graphite, and the lack of a dedicated disposal facility for irradiated graphite waste, as envisaged in French national policy, are important constraints for implementation of decommissioning.

EDF is meanwhile following a progressive approach to advancing decommissioning operations, particularly through the construction of an industrial demonstrator (Graphite Reactor Decommissioning Demonstrator) near the Chinon nuclear power plant, where dismantling processes will first be developed and tested prior to the decommissioning of the Chinon A2 facility. The test programme is planned to take place over a 10 year period from 2022 to 2032. The Chinon A2 reactor was selected to be the first of the six EDF graphite reactors to be dismantled and the beginning of dismantling is envisaged by 2032.

IV.3. LUCENS REACTOR (SWITZERLAND)

The former Lucens experimental NPP was decommissioned and dismantled after suffering a partial core meltdown in 1969. The decommissioning strategy for entombment of some remaining structures of the Lucens prototype reactor in Switzerland has been selected partly because of the underground construction of the facility. Almost 30 years after the accident that put an end to Lucens operation, the decision was made to fill and seal the caverns housing the reactor facility, and to release and terminate its nuclear licence. The site was released from regulatory control in 1995, except for a small radioactive waste storage area with six containers with approximately 240 t of unconditioned solid radioactive waste. In 2003 the radioactive waste from this storage area was transported to the Central Interim Storage Facility in Würenlingen for storage and conditioning of the waste with a view to later disposal. The complete former site at Lucens was released from regulatory control in 2004. The site is, however, subject to the environmental radiation monitoring programme of the Federal Office of Public Health.

IV.4. BRADWELL SITE (UNITED KINGDOM)

Bradwell's Magnox type reactors were brought into service in 1962 and were two of the UK’s oldest NPPs. Since the station ceased operation in 2002 and all the fuel was removed from the site in 2006, a large scale decommissioning programme has been safely undertaken at the site, with the focus on preparing it for care and maintenance (CandM).

CandM is one of the lifetime phases of a nuclear site. During CandM nuclear sites are managed remotely by a specialized team. The sites are monitored continuously, with planned maintenance and inspection activities undertaken. The sites, and any structures that remain, are kept passively safe and in a secure state for several decades. This allows radiation levels within buildings, such as the reactor safe stores, to decay naturally over time before the reactors are dismantled and the site is cleared.

In 2009, Bradwell was selected as one of two Magnox sites for accelerated decommissioning. Less than a decade later, in October 2018, Magnox Ltd put the Bradwell site into an extended period of CandM, marking a significant achievement for the UK’s decommissioning efforts.

The decommissioning strategy to put all Magnox nuclear power stations into care and maintenance (i.e. safe enclosure) for several decades before final site clearance has recently been reviewed in light of experience with Bradwell and a more general reassessment of the approach. The NDA and Magnox Limited have decided to move away from this blanket approach and to consider decommissioning for some sites earlier than had previously been anticipated, without entering into care and maintenance.

IV.5. ARBEITSGEMEINSCHAFT VERSUCHSREAKTOR GMBH — AVR (GERMANY)

The experimental nuclear reactor of the former Arbeitsgemeinschaft Versuchsreaktor GmbH (AVR) at the Jülich site (a separate area located on the premises of the Forschungszentrum Jülich GmbH (FZJ)), North Rhine-Westphalia, was a high temperature reactor designed as pebble bed reactor with a power of 15 MWe (gross). The AVR was in operation from 1966 to 1988.

The AVR reactor was integrated into the EWN Group through the merger of the nuclear sectors of the FZJ and the AVR in September 2015 to form the Jülicher Entsorgungsgesellschaft für Nuklearanlagen mbH (JEN). An initial decommissioning application from the 1990s provided for the strategy of safe enclosure. In May 2003, the objective of the project was changed to complete removal and return to green field conditions. Until its final disassembly and conditioning into waste packages qualified for disposal, the reactor vessel will be stored in a storage facility at the site of the FZJ. The current work includes the remote controlled dismantling of the concrete structures using a demolition robot. The total mass of concrete and heavy concrete structures to be removed is ~1900 Mg, of which approximately one third is radioactively contaminated and has to be conditioned by JEN for disposal.

IV.6. PHILIPPSBURG NPP (GERMANY)

With entry into force of the Thirteenth Act Amending the Atomic Energy Act on 6 August 2011, as a result of the events at the Japanese nuclear power plant Fukushima Daiichi, the authorization for power operation for Philippsburg 1 expired. Philippsburg 1, an 890 MWe boiling water reactor that began operating in 1979, was among the eight oldest German reactors. For the Philippsburg 2 pressurised water reactor, the authorization for power operation expired on 31 December 2019. For both units, first decommissioning and dismantling licences have been applied for in accordance with § 7(3) of the Atomic Energy Act. Decommissioning licences were granted for Philippsburg 1 on 7 April 2017 and for Philippsburg 2 on 17 December 2019, even before shutdown. Immediate dismantling was chosen as the decommissioning strategy for both units. The operator of both units, EnBW, achieved a first important milestone in the decommissioning process in May 2020, with demolition of both cooling towers. EnBW assumes that the dismantling of KKP 1 and KKP 2 will take approximately 15–20 years until release from nuclear regulatory control.

IV.7. RINGHALS NPP (SWEDEN)

In 2015, the owners of the Ringhals nuclear power plant decided that two of the four reactors (BWR unit 1 and PWR unit 2) would be permanently shut down by 2020, some years earlier than planned. The decisions were based on the overall business and energy market situation due to falling electricity prices. It is planned that the remaining two reactors (PWRs) will continue in operation until the 2040s. Sweden’s oldest pressurised water reactor, Ringhals 2, ceased commercial operation on 30 December 2019. Its neighbouring boiling water reactor, Ringhals 1 was also permanently shut down on 31 December 2020. Preparation for decommissioning is underway and large scale dismantling activities are planned to start in 2022.

IV.8. LATINA NPP (ITALY)

The Latina NPP is located in central Italy and belongs to the first generation of nuclear facilities, The Latina NPP was a UK Gas Cooled Reactor (GCR-Magnox) with an electric capacity of 153 MWe. The Latina NPP was operated by ENEL from 1962 until 1987, when it was finally shut down based on a government decision. In May 2020 the decommissioning licence for the Latina NPP was granted.

Due to the presence of ~2000 t of irradiated graphite and the current unavailability of a national repository, SOGIN’s decommissioning strategy consists of two phases. The first one aims for the safety of all previous radioactive waste or wastes that have been produced from the dismantling of the structures, systems and components of the plant. Another goal is the conservation of the reactor building (with radioactive graphite inside). The second phase is to be implemented only after siting and construction of the national repository. The second phase foresees the dismantling of all plant structures with the purpose of attaining the green field end state (this phase two will be subject to specific authorization).

The main aim for the Latina NPP is to finish dismantling activities in 2031, leaving the graphite in the reactor waiting for the national repository.

IV.9. NOVOVORONEZH NPP (RUSSIAN FEDERATION)

Novovoronezh NPP was one of the first industrial nuclear power plants in the former USSR, located in the south of the European part of the Russian Federation. Seven VVER type reactors (analogous to PWR) were constructed on the Novovoronezh site, all of them are non-serial and having different capacities (from 210 GW to 1200 GW). Currently, reactors 4, 5, 6 and 7 are in operation and it is important to note that reactor 6 has become the most powerful in the nuclear power industry of the Russian Federation and the first nuclear power plant reactor in the world, built according to post-Fukushima safety technologies that meet the most modern requirements for reliability and safety.

Reactors 1 and 2 were shut down in 1984 and 1990, respectively. The initial decommissioning strategy for these units was deferred dismantling, with a 30 year safe storage period. This strategy was partially implemented but was later revised in favour of immediate dismantling, taking into account the new technological possibilities of decommissioning and in order to reduce cost. Currently, work is underway to prepare for the decommissioning of these reactors. The latest systems for decontamination and processing of radioactive waste are being tested at these units, including the widespread use of remote dismantling tools with robots.

IV.10. GENTILLY-1 NUCLEAR GENERATING STATION (CANADA)

The Gentilly-1 Nuclear Generating Station (G-1) was the site of a 250 MW(e) CANDU prototype reactor that was put into service in 1972. The reactor operated intermittently until 1978 and was shut down permanently in 1984, with the intention of bringing the facility to a safe, sustainable shutdown state, equivalent to storage with surveillance (SWS). A three phase approach was established for reactor decommissioning. Phase 1 brought the facility to a safe, sustainable shutdown state. Phase 2 is a period greater than 30 years of SWS and the final decommissioning (approximately 10 years) will occur in phase 3. In 1986, after a two year programme, G-1 was brought to a safe shutdown state and was relicensed by the CNSC as the Gentilly-1 Waste Management Facility. This facility is currently in the long term SWS phase of a deferred decommissioning programme.

IV.11. HEAVY WATER COMPONENTS TEST REACTOR (HWCTR) (USA)

HWCTR was an experimental nuclear reactor, generally referred to as ‘Hector’, at the Savannah River site, USA. Construction work for the reactor started in 1958. It had a cylindrical structure with a hemispherical dome and was located underground, which eventually proved to be conducive to the entombment strategy.

The reactor was built to examine the concept of a heavy water moderated and cooled reactor for civilian power. After a series of tests the HWCTR began power operation in 1962 and was operated for two years, from late 1962 until December 1964. In December 1964, the reactor was placed on six month standby status, but the reactor was never restarted. In 1965, fuel assemblies were removed, systems that contained heavy water as well as fluid piping systems were drained, de-energized and disconnected, and the spent fuel basin was drained and dried. The doors of the reactor were shut, and it was not until more than 10 years later that decommissioning plans were considered and ultimately postponed due to budget constraints. In the early 1990s, the US Department of Energy (DOE) recommenced active planning to decommission the reactor; yet, in the face of new budget constraints, the DOE deferred dismantlement and placed HWCTR in an extended surveillance and maintenance mode. Eventually, decommissioning plans were resumed in the early 2000s. The final decommissioned end state included in situ decommissioning (entombment) with the reactor vessel and two steam generators removed and disposed of in trenches on-site.

Projects were completed ahead of schedule in July 2011 and below cost.

IV.12. SAVANNAH RIVER SITE: THE R- AND P-REACTORS (USA)

During the early 1950s, five production reactor facilities were built at the Savannah River Site (SRS). These facilities were built to support the production of the US stockpile of nuclear weapons in response to the Cold War. The R and P-reactors were the first two facilities completed in 1953 and 1954. The R reactor was removed from service in 1964 due to a combination of several unrelated leaks and an overall state of degeneration. In addition, in 1964 President Johnson called for an immediate reduction in the arms race. The P reactor was taken off-line in 1988 to update the facility. However, work activities to modernize the facility stopped in 1990 with the end of the Cold War. Since that time, both reactors have been in a cold and dark state (US terminology for passive safe enclosure) and have been identified as the first two reactors at SRS for final closure.

Final closure for the reactor buildings involved in situ decommissioning (ISD). It was estimated that this strategy would facilitate significant savings. Decommissioning work involved filling all below grade levels of the buildings with a low density cement.

This approach immobilized any residual contamination contained within the buildings and stabilized the structural integrity. The reactor vessels were filled with a low density cement to the maximum practical extent and capped with a reinforced concrete cap. Above grade sections of the buildings were demolished. On 28 June 2011, senior officials from DOE, Savannah River Site and other organizations sealed the access to the historic P and R Reactors as part of a footprint reduction and legacy cleanup at the Savannah River Site.

IV.13. DOUGLAS POINT NUCLEAR GENERATING STATION (CANADA)

Construction of the 200 MWe Douglas Point demonstration nuclear generating station began in 1960. First criticality occurred on 15 November 1966, with the facility being brought into full operation in 1968. The facility operated successfully until it was shut down in 1984, by which time it had generated 17 billion kWh. Over the next two years to 1986, the facility was defuelled and dewatered. From 1986 to 1991 the facility was in phase 1 decommissioning. This involved transferring fuel from the fuel bay to dry canister storage, draining and decontaminating the fuel bay and removing the turbines and diesels, as well as performing some decontamination and hazard removal activities. In parallel with the phase 1 decommissioning, the administration building was leased for office accommodation to support a refurbishment programme at the adjacent Bruce facility. From 1991 the facility was transferred into long term care and maintenance.

The decision to place the facility into long term care and maintenance was based on the following assumptions:

(a) No intermediate level waste (ILW) disposal facilities available in Canada;
(b) Interim above ground ILW storage would be required, adding to the liability;
(c) Delaying the dismantling of the reactor would allow decay of the activated components;
(d) Dismantling would be coordinated with decommissioning and dismantling the adjacent facilities on the Bruce site in the 2050s;
(e) A deep geological disposal facility will be available for spent fuel and ILW by this time;
(f) On-site fuel storage can continue until the deep geological repository is available to receive the fuel;
(g) Long term institutional control costs will not be significant;
(h) Some income could be attained from Ontario Power Group for utilization of storage space in the turbine hall and use of the administration building to support the refurbishment programme.

The business model for delaying the decommissioning of the Douglas Point Facility, based on the above assumptions, was put into place in 1991. As the facility continued through long term care and maintenance there were a number of incremental changes to the assumptions. Individually, these were not significant and did not justify a reassessment of the deferral strategy.

In 2015 the Canadian government established the Government Owned Contractor Operated model, with management of the relevant State liabilities being overseen by Atomic Energy of Canada Limited[50] (AECL) on behalf of the government. The international experience that this contract brought was tasked with challenging previous assumptions on a variety of programmes across AECL's liability portfolio. At this time, as outlined below, a number of assumptions on the long term institutional control costs had already incrementally changed. In addition, there were also some upcoming changes that had the potential to impact on the ongoing care and maintenance costs:

- Security costs were steadily increasing above inflation due to global security challenges.
- Facility degradation (roofs, building fabric, concrete wall claddings, etc.) was greater than anticipated and was requiring widespread ongoing repairs.
- Degradation of asbestos cladding resulted in exclusion of access to the reactor building without respiratory protection, which was introducing additional cost, time and labour to perform routine maintenance or inspections.
- Licensing requirements to maintain essential services required upgrades to the facility.
- Replacement of obsolete essential components required the redesign, revalidation and upgrade of various systems, including ventilation, emergency alarms, power distribution and lighting.
- Minimal income was received from Ontario Power Generation (OPG) for interim storage of components or utilization of administration facility for staffing peaks during refurbishments.
- Utility costs were about to experience a step increase. The Douglas Point Facility was one of the remaining facilities using the Bruce site steam utility system and was justifiably being required to absorb the burden of maintaining and operating this system.
- Shielded modular above ground storage facilities had now been built at Chalk River and the costs of these were quantifiable with minimal ongoing maintenance costs.
- Over the next 10 years, fuel storage is being consolidated at the Chalk River site from two other decommissioning sites. This provides the availability of staff and licensed transportation flasks to transfer the Douglas Point fuel to a location where at some point in the future it can be conditioned prior to final disposal.

The subsequent outcome of the adjustments above has been an incremental increase in the annual care and maintenance costs that was not anticipated back in 1990. The coordination of fuel transfers from other CNL sites over the next 10 years is fortuitous, as it provides the capability that was previously not anticipated to be available for many decades and which significantly reduces the security costs for the site. Reconsideration of the business case for long term care and maintenance no longer showed a benefit from deferring the dismantling of the facility to coordinate with the dismantling of the adjacent Bruce facility. The decision was taken to accelerate the decommissioning of the facility. A virtual public hearing was held in November 2020 and the proposal for phased acceleration of the decommissioning of the facility was approved and decommissioning began in March 2021. The initial phase is removal of the non-nuclear facilities and the characterization of the reactor. Future phases to remove the remaining nuclear facilities and the reactor will require consultation with stakeholders and indigenous communities, a public hearing and regulatory approval prior to further advancement of the decommissioning. The full decommissioning and dismantling of the site is now expected to be complete before 2035.

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[50] Atomic Energy of Canada Limited is a Canadian federal Crown corporation.

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ABBREVIATIONS

BWR	boiling light water cooled and moderated reactor
DACCORD	Data Analysis and Collection for Costing of Research Reactor Decommissioning
EDF	Electricité de France
FBR	fast breeder reactor
FCF	fuel cycle facility
GCR	gas cooled reactor
GR	graphite reactor
iNFCIS	Integrated Nuclear Fuel Cycle Information System
KM	knowledge management
LWGR	light water cooled, graphite moderated reactor
NEA	Nuclear Energy Agency
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission (USA)
OECD	Organisation for Economic Co-operation and Development
PHWR	pressurized heavy water moderated and cooled reactor
PRIS	Power Reactor Information System
PWR	pressurized light water moderated and cooled reactor
RR	research reactor
RRDB	Research Reactor Database
SAT	systematic approach to training
SWOT	strength, weakness, opportunity, threat
WENRA	Western European Nuclear Regulators Association

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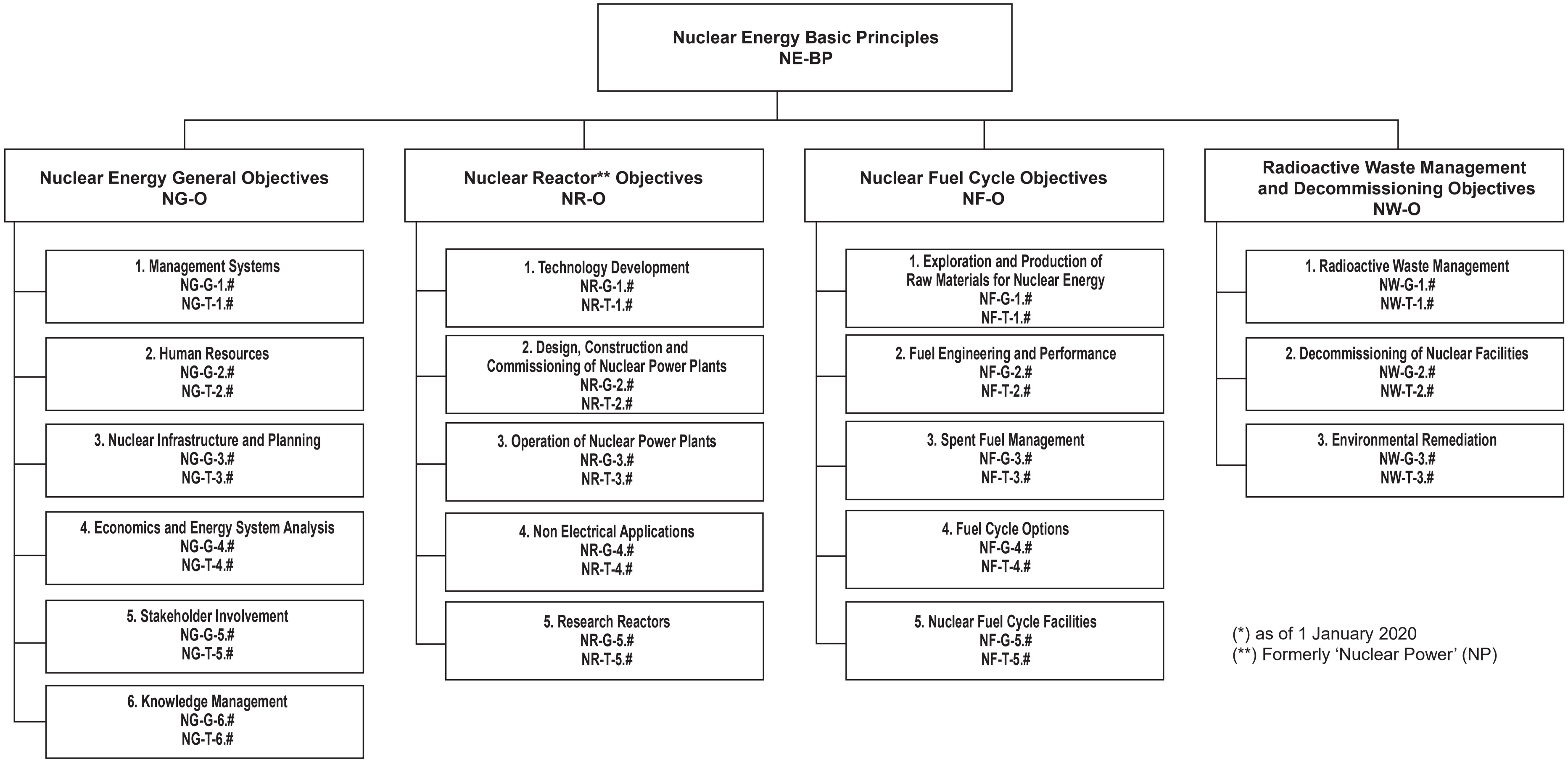

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