IAEA Nuclear Energy Series

No. NF-T-3.9

Research Reactor Spent Fuel Management: Options and Support to Decision Making

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RESEARCH REACTOR SPENT FUEL MANAGEMENT: OPTIONS AND SUPPORT TO DECISION MAKING

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2021

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1400 Vienna, Austria
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email: sales.publications@iaea.org
www.iaea.org/publications

Printed by the IAEA in Austria
December 2021
STI/PUB/1954

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Research reactor spent fuel management : options and support to decision making / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2021. | Series: IAEA nuclear energy series, ISSN 1995–7807 ; no. NF-T-3.9 | Includes bibliographical references.
Identifiers: IAEAL 21-01448 | ISBN 978–92–0–120021–1 (paperback : alk. paper) | ISBN 978–92–0–120121–8 (pdf) | ISBN 978–92–0–120221–5 (epub)
Subjects: LCSH: Spent reactor fuels — Management. | Radioactive wastes — Management. | Reactor fuel reprocessing. | Nuclear reactors — Safety measures.
Classification: UDC 621.039.59 | STI/PUB/1954

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 Agency 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.

Research reactors are operated in more than 50 countries around the world and play an important role in science, industry and medicine. Each country is responsible for the radioactive waste derived from its research reactor operations, including research reactor spent nuclear fuel (RRSNF). An effective RRSNF management plan comprises the management of the RRSNF from its removal from the research reactor core until its final disposal, and may include interim stages such as storage, conditioning and reprocessing, either domestically or abroad.

To help Member States address their RRSNF responsibilities, the IAEA organized a three year coordinated research project entitled Options and Technologies for Managing the Back End of the Research Reactor Nuclear Fuel Cycle. The goal of the project and of this resulting publication was to provide a comprehensive set of RRSNF management strategies and to assist in the decision making process for selecting the preferred option for each Member State's situation. A set of decision support tools was developed to consider not only the costs of the possible RRSNF management strategies but also the non-economic factors that might influence their selection. These tools and the tutorials on their use are available for download as supplementary files on the publication's individual web page at www.iaea.org/publications.

The IAEA wishes to thank all of those who participated in the CRP and helped in the drafting and preparation of this publication. The IAEA officers responsible for this publication were F. Marshall and S. Geupel of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORAL NOTE

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CONTENTS

1. INTRODUCTION

This IAEA publication summarizes the results of the Coordinated Research Project (CRP) T33001 on Options and Technologies for Managing the Back End of the Research Reactor Nuclear Fuel Cycle, which took place from 2015 to 2018 with the participation of 16 institutions from 15 Member States.

1.1. BACKGROUND

Research reactors (RRs) are used worldwide for activities such as the education of nuclear scientists and engineers, for general and refresher training of the nuclear power workforce, to produce medical and industrial radioisotopes, for silicon doping, to perform advanced fuel and material testing to support life extension of operating nuclear power plants (NPPs), to validate safety analysis design methods for new power plants, to qualify new fuels, and to validate modelling and calculation tools. RRs are also key tools in building and maintaining national nuclear capacity and achieving public acceptance of nuclear technologies [1]. As of March 2019, there are 227 RRs operating around the world, with another 23 planned or in construction [2]. An additional 136 RRs are in extended or permanent shutdown, or under decommissioning.

There is a clear and unequivocal understanding that each country is ethically and legally responsible for its own spent fuel and nuclear waste, as stated by both the IAEA, via the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [3], and by the international nuclear waste disposal concepts [4] summarized by the World Nuclear Association (WNA). Member States operating or having previously operated a RR (research reactor) are responsible for the safe, secure and sustainable management of associated radioactive waste, including RR spent nuclear fuel (RRSNF). This includes the storage and ultimate disposal of conditioned RRSNF, or the corresponding equivalent waste generated and returned following reprocessing of the spent fuel.

The main objective in managing and disposing of radioactive waste is to protect people, including future generations, and the environment. Regional or national laws and directives provide a regulatory framework for the management of spent fuel. The IAEA provides Member States with safety standards, guidelines and good practice examples to enable them to establish and maintain a responsible waste management programme.

Selection and implementation of the most appropriate nuclear waste management programme can be very challenging considering the numerous elements and factors that must be addressed, such as technological feasibility, economics, social acceptance and environmental impact. The aim of this publication is to support RR operating organizations and Member States in developing a spent fuel management programme, including final disposal, that is sustainable, is secure [5], and complies with international and national regulations.

One key challenge when developing general recommendations for RRSNF management options lies in the diversity of spent fuel types, locations and national or regional circumstances, rather than mass or volume alone, particularly since typical RRSNF inventories are relatively small. Presently, many countries lack an effective long term policy for managing RRSNF. A methodical review and compilation of technology options for RRSNF management is therefore needed.

1.1.1. IAEA initiatives related to RRSNF issues

The importance of the RRSNF management challenge has been highlighted in past IAEA publications and workshops. One of the first reports, IAEA-TECDOC-1508, Spent Fuel Management Options for Research Reactors in Latin America [6], originated from a regional Technical Cooperation project. Reference [6] summarizes the results of this project in identifying and assessing a number of viable alternatives for RRSNF management from five participating countries (Argentina, Brazil, Chile, Mexico and Peru). The basic conditions for a regional strategy for managing spent fuel, the options for operational and interim storage, spent fuel conditioning and final disposal were considered.

Based on requests from Member States, the IAEA has continued to address elements of RRSNF management. Other IAEA publications about RRSNF storage are Management and Storage of Research Reactor Spent Nuclear Fuel: Proceedings of a Technical Meeting held in Thurso, United Kingdom, 19–22 October 2009 [7], IAEA-TECDOC-1637, Corrosion of Research Reactor Aluminium Clad Spent Fuel in Water [8], IAEA Nuclear Energy Series No. NP-T-5.2, Good Practices for Water Quality Management in Research Reactors and Spent Fuel Storage Facilities [9], and IAEA Nuclear Energy Series No. NW-T-1.11, Available Reprocessing and Recycling Services for Research Reactor Spent Nuclear Fuel [10].

Starting in the 1990s, along with the efforts of RR operating organizations to eliminate the use of highly enriched uranium (HEU), several countries have taken advantage of the so-called ‘take back’ programmes supported by the IAEA, the Russian Federation and the United States of America. These initiatives include the United States of America’s Foreign Research Reactor Spent Nuclear Fuel (FRRSNF) acceptance programme and the Russian Research Reactor Fuel Return (RRRFR) programme.

In 2006, the IAEA organized a Technical Meeting on National Experiences on Return of Research Reactor Spent Fuel to the Country of Origin, which mainly dealt with the requirements for technical and administrative preparations for the shipment of RRSNF to the United States of America under the FRRSNF acceptance programme. It included national experiences of shipping back fuel to the United States of America as the country of origin, and resulted in IAEA-TECDOC-1593, Return of Research Reactor Spent Fuel to the Country of Origin: Requirements for Technical and Administrative Preparations and National Experiences, published in 2008 [11]. The IAEA has assisted both fuel return programmes, providing logistical support to Member States for the fuel shipments. More detail on these return programmes is provided in Section 2 of this publication.

To help address Member States’ responsibilities mentioned above, the IAEA organized a CRP on Options and Technologies for Managing the Back End of the Research Reactor Nuclear Fuel Cycle (2015–2018), to address the issues faced by owners of RRs with regard to the management and disposal of RRSNF. This CRP, the results of which are reported in this publication, emphasized concerns specific to countries that do not possess the infrastructure for a large commercial nuclear power programme.

The goal of the CRP was to develop a comprehensive set of technology options for RRSNF management. This includes storage, transport, processing and ultimate disposal. In addition, the CRP developed a set of tools to assist Member States in developing an RRSNF management strategy. First, a decision-support tool, Back end Research Reactor Integrated Decision making Evaluation (BRIDE), was designed to analyse scenarios comprising these options with a focus on their economic and non-economic aspects, taking into consideration technology development, and human and economic resource requirements. The options analysis helps to inform decision makers about the advantages and disadvantages of each option, assisting new and existing RR operating organizations in taking decisions on future disposal strategies. Additionally, a bottom-up detailed cost estimating tool, Fuel Cycle Cost Estimation for Research Reactors in Excel (FERREX), was developed. The tools, their methodologies and the applicable data and parameters are described in the present publication. The focus is on matching feasible options to the capabilities of countries with RRs, particularly for those without a civilian nuclear power industry.

1.1.2. Meetings held to complete CRP objectives

Several meetings have been held to develop, organize and compile the work presented in this publication. The first meeting was a consultancy meeting held in Vienna, Austria, in July 2014, to ascertain the Member States’ interest and confirm the need for an IAEA CRP to address the issue of RRSNF management. This meeting was attended by eight consultants from six Member States, and the conclusion from this meeting was that a CRP would be valuable. The IAEA initiated the CRP in late 2014 and 15 Member States were accepted for participation. The CRP participants represented organizations that operate RRs, provide spent fuel management services and support data analysis efforts.

The first research coordination meeting (RCM), attended by 21 participants from the 15 participating Member States, was held in Vienna, Austria, in June 2015. The main objectives of this RCM were (a) to share information and expertise between participants on RRSNF management options; (b) to identify the feasible RRSNF management options, from removal of RRSNF from the reactor core to final disposal; (c) to help prepare a standard costing model to identify initial technical and economic issues; and (d) to identify qualitative factors to be included in the decision process and how they could be included in the cost model. The CRP team developed a CRP work plan, with individual Member States' work assignments, and proposed a draft outline of this publication.

A consultancy meeting was held in Vienna, Austria, in December 2015 to discuss the path forward on the decision tool options, with the participation of 13 representatives from eight Member States. The primary objective of this meeting was to identify the method to use for the evaluation of qualitative information and how to integrate it into the overall decision-support models alongside the cost estimates. An analytic hierarchy process (AHP) and two costing models, G4ECONS and FERREX, an evolution of the Cost Estimation for Research Reactors in Excel (CERREX) model, were introduced.

An additional consultancy meeting was held in Vienna, Austria, in February 2016, to review the cost estimation models G4ECONS and FERREX, with the participation of 16 representatives from 12 Member States. The purpose of these meetings was to identify how the two models available, G4ECONS and FERREX, could be used to compare RRSNF management options and to determine how they could be integrated into an overall decision framework for RRSNF management. It was decided to use G4ECONS as a basis for the Back end Analytical Scenario Cost Estimation Tool (BASCET). To incorporate non-economic criteria, a multiattribute tool, BRIDE, was developed. It was decided that FERREX would be used as the complementing detailed cost estimation tool.

The second RCM, attended by 17 participants from 13 Member States, was held in Kjeller, Norway, in August 2016. The meeting objectives were (a) to finalize and merge all feasible qualitative RRSNF management options in terms of flow charts and text descriptions, from removal of RRSNF from the reactor core to final disposal; (b) to test the decision tools (BRIDE and FERREX) with Member State data; (c) to critique models for further adjustments to finalize tools for use by other Member States; and (d) to review the draft table of contents and CRP participant contributions to the final CRP report.

A consultancy meeting was held in Vienna, Austria, in December 2016 to initiate this publication. The outline and table of contents as developed in the two RCMs were evaluated and the sections contributed by the CRP participants up to that time were reviewed. A preliminary draft version of the publication was prepared.

A consultancy meeting was held in Vienna, Austria, in October 2017 to discuss the BRIDE and FERREX testing that Member States had completed during the previous year. The objective was to provide implementation guidance to the tool developers to enable them to finalize the tools before the third RCM. Nine Member States were represented by 13 participants.

The third RCM was held in Vienna, Austria, in December 2017. Thirteen participants represented 11 Member States. The objectives of the meeting were (a) the presentation by each participant of a summary of their work performed during the CRP; (b) discussion of the modifications to the BRIDE and FERREX decision framework tools; and (c) review of the latest revision of the CRP publication.

A consultancy meeting was held in Vienna, Austria, in April 2018 to finalize the content of this publication. Nine participants represented seven Member States. A draft document was prepared for review and comments by all CRP participants.

In Vienna, Austria, in November 2018, an IAEA Workshop on Research Reactor Spent Fuel Management brought together owners, operators, designers and regulators of RRs from 24 countries, represented by 43 participants, who had the opportunity to test an early version of the BRIDE tool. Participants considered it useful and influential to decision makers in the consideration of RRSNF management strategies and budgeting and expressed interest in further training or workshops on the topic.

In March 2019, a consultancy meeting was held in Vienna, Austria, to review and finalize this publication.

1.2. SCOPE

The scope of this publication is to report on existing technology options that can be used for RRSNF management. The intention is to present only those options that are feasible now, or expected to be available soon, with little technology development required. The level of detail of the technology options presented in this publication is intended to introduce the options without providing all details, which can be obtained in various references. Examples of the technologies that are currently used by some States are provided.

Additionally, this publication provides information about the Excel based decision-support tools developed as part of this CRP, along with case studies and tutorials to assist users.

1.3. OBJECTIVES

The objective of this publication is to report the results of the CRP, focusing on the two objectives of identifying the options available for managing RRSNF and the use of the decision-support tools developed to assist States in developing their RRSNF management strategies. The focus is placed on how States can use technological information to select the appropriate option for their situation.

The intended users of this publication are owners and operators of RR facilities, waste management organizations, regulators, decision makers and stakeholders who have responsibility for RRSNF management. The use of the decision-support tools is intended to assist RR operating organizations with development of their spent fuel management strategies. The results of this CRP could be particularly useful for States that are building, are planning to build, or have recently completed the construction of their first RR.

1.4. STRUCTURE

This publication reports the results of this CRP and provides information to assist States in utilizing the information for their specific situations. Section 2 of this report discusses the currently available technologies for RRSNF management. In Section 3, the most common solutions used today by RR owners are discussed in more detail. Section 4 discusses the non-economic factors that States need to consider in deciding which RRSNF management strategy would be best for their situation. Section 5 discusses the decision framework tools and how to use them, while Section 6 provides concluding remarks and recommendations.

Annex I provides information on the RRSNF management strategy in fourteen Member States. Annex II provides case studies from four Member States on their decision process. A Glossary is also included to ensure consistency of use of terminology. The on-line supplementary files for this publication (BRIDE and FERREX tools, tutorials and handouts) can be found on the publication’s individual web page at www.iaea.org/publications. Member States may request IAEA assistance with their implementation.

2. TECHNOLOGIES FOR RRSNF MANAGEMENT

The intent of this CRP was to collect information about currently available technologies for RRSNF management and provide these details to Member States, to help support their decision making in relation to the development of a spent fuel management strategy. The information in this section provides both a description and examples (where available) for the existing technologies.

2.1. STORAGE

Storage of RRSNF is a challenge for operators, as storage could be needed for more than 50 years until a decision has been made about final disposal. Spent fuel storage is an interim step in the back end of the nuclear fuel cycle. The general trend, however, has been for ever increasing storage periods, and durations of more than 100 years are now being envisaged. The basic safety aspects of spent fuel storage are applicable to spent fuel from RRs as well as from NPPs; guidance and recommendations on the design, operation and safety assessment of spent fuel storage facilities can be found in IAEA Safety Standards Series No. SSG-15 (Rev. 1), Storage of Spent Nuclear Fuel [12].

2.1.1. Wet storage of RRSNF

Wet storage is the most common form of storage for RRSNF. Wet storage of RRSNF is almost always used as the first cooling stage after irradiation of the fuel in the reactor core, allowing the decay heat to dissipate before further handling of the fuel. Depending on the reactor and facility design, the storage pools or ponds are located either within the reactor building with fuel being transferred from the core to the pool using specific tools, or in another on-site building. In the latter case, the fuel could be transferred using shielded transfer casks, or via water channels.

A large variety of RRSNF with different fuel compositions, different geometries and different enrichments in ^{235}U is presently stored in pools. Research reactor fuel is not designed for an unlimited duration in wet storage. After lengthy periods (sometimes decades) of wet storage, corrosion is being observed on many RRSNF elements. In some cases, corrosion-induced degradation of the cladding has been observed, compromising the integrity of the fuel.

Localized corrosion of aluminium (Al) depends on the quality of the fuel storage pool’s water, which could range from highly deionized water to untreated and uncirculated water. The latter is an extremely aggressive environment for Al and could result in pitting corrosion. This kind of environment was not uncommon in the early 1990s, and pitting corrosion of Al-clad fuel was an issue at several wet storage facilities [13]. A reliable water purification and quality monitoring system can reduce corrosion concerns.

2.1.1.1. Corrosion concerns in wet RRSNF storage

Most RRSNF is stored in water for decades, and despite storage pool water quality management programmes, pitting corrosion has been reported to be the main form of degradation. This could lead to cladding failure, the release of fissile material and radioactive contamination of the storage facilities. Most of the fuels affected by pitting corrosion are clad in Al or Al based alloys. The Al alloys used are usually AA 6061 or AA 1100, and range in thickness from 0.375 to 0.75 mm. These alloys are susceptible to general or localized corrosion in water of less than optimum quality. General corrosion of Al and its alloys is reasonably well understood and is not a concern for RRSNF. However, localized corrosion of Al-clad spent fuels is a complex phenomenon, is very difficult to predict and has caused concerns at some RRSNF storage sites. The three main forms of localized corrosion are pitting corrosion, crevice corrosion and galvanic corrosion. Pitting corrosion of the Al fuel cladding has been attributed to synergism in the effect of some basin water parameters on the corrosion of Al and its alloys [13]. Hence, some form of corrosion protection of the Al cladding would extend the possible duration of long term wet storage.

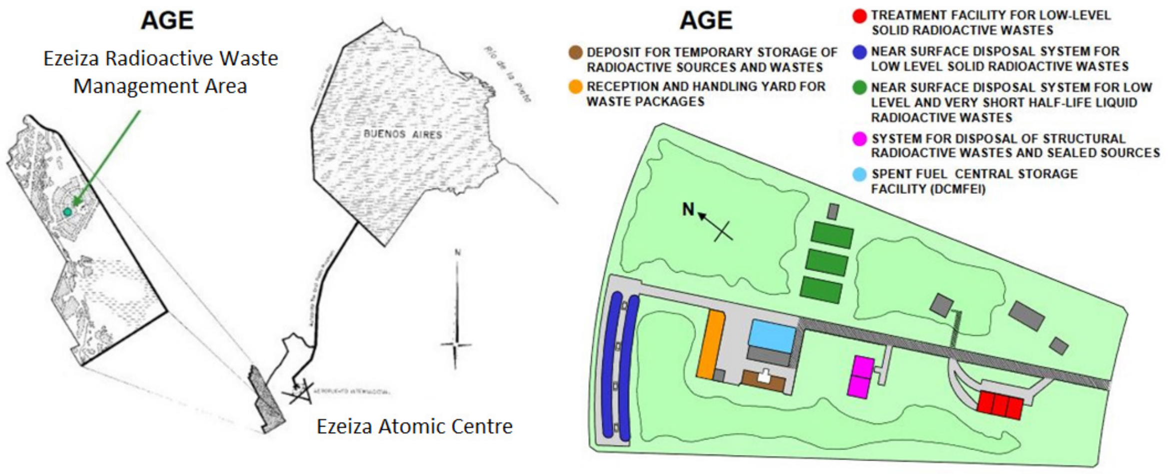
Coating the cladding surface is an option. Conversion coating is a type of coating formed when metallic surfaces are given a chemical or electrochemical treatment during which the surface metal is converted into a protective compound. These coatings have been widely used to control the corrosion of a range of metallic materials in many industries, and rare-earth compounds have been used to inhibit aqueous corrosion of Al alloys [14]. Further, there are chemical treatments to form rare-earth based conversion coatings on Al alloys [15, 16, 17]. The physical structure of Al-clad RR fuel and the radioactivity of spent fuels preclude electrochemical surface treatments. Thus, chemical surface treatment to form a coating is the only option, and the use of conversion coatings to protect spent Al-clad RR fuel was proposed in 2007. Studies carried out in Brazil, in which a variety of coatings were developed and tested, indicated that hydrotalcite (HTC) coatings further augmented with cerium significantly increased the corrosion resistance of the Al alloy substrate. Further details can be found in Section I–3.2 of Annex I.

2.1.1.2. Example: wet storage in Argentina

Since 1972, Argentina's National Atomic Energy Commission (CNEA) has managed the Central Storage of Special Irradiated Fissionable Material (DCMFEI) facility, which is located in the Ezeiza Radioactive Waste Management Area (AGE) of the Ezeiza Atomic Centre, Buenos Aires province (see Fig. 1) [18].

The facility (Fig. 2) comprises a group of stainless steel tubes installed underground (each tube is 2.10 m long and 0.141 m in diameter). The tubes can hold two materials testing reactor (MTR)-type spent fuel assemblies (SFAs) or one control element. For safeguards reasons, the tubes are closed with lead-filled steel plugs and a sealing device. The installation is complemented with a water circulation system between the tubes made of pipes arranged in a communicating vessel system and connected to an ion exchange resin water purification system. The total storage capacity of all sectors of the installation is 396 fuel units. The first sector, built in 1972, comprises six batteries for 16 tubes each and the other sector, built in 1980, also comprises six batteries but for 17 tubes in each line.

This facility was designed to store fuel assemblies with HEU (90%). Due to availability of the FRRSNF acceptance programme, the HEU MTR spent fuel assemblies were sent to the United States of America in the year 2000. At present, the DCMFEI stores spent fuel from the RA-3 RR.



(a) (b)

FIG. 1. (a) Site location and (b) site plan of AGE (courtesy of CNEA).

FIG. 2. View of the DCMFEI facility (courtesy of CNEA [18]).

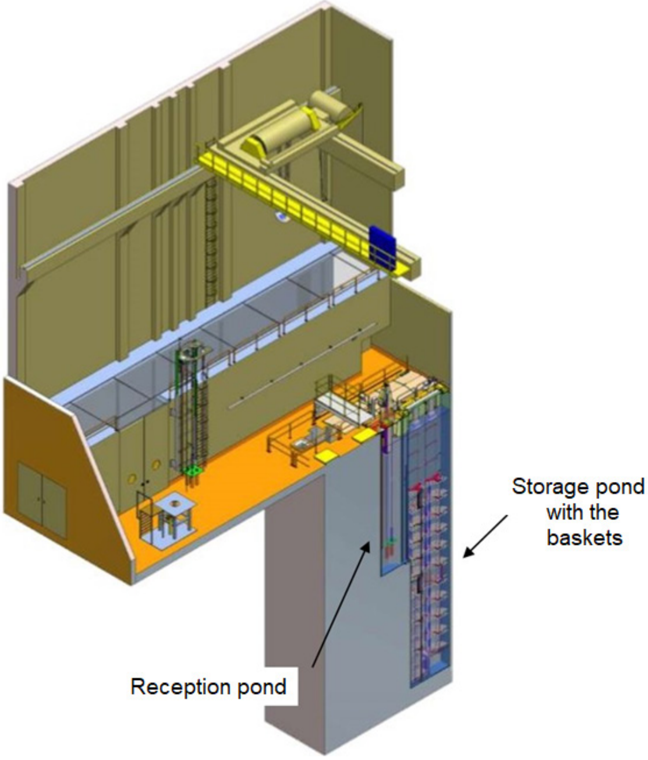


FIG. 3. Artist's impression of the FACIRI (courtesy of CNEA [18]).

Examination of the HEU spent fuel prior to shipment to the United States of America revealed corrosion problems attributed to water quality. A study confirmed that the long term wet storage system had proved to be incompatible with the fuel and facility design. This was due to the lack of access to inspect the spent fuel inventory on a more regular basis. Therefore, the CNEA decided to build a new wet storage facility, the Facility for Irradiated Fuel from Research Reactors (FACIRI) [18], which replaces the DCMFEI and which is shown in Fig. 3. The FACIRI has been conceived for the centralized wet storage of

SFAs unloaded from the RA-3 RR and to provide a more effective monitoring of the storage water quality and spent fuel cladding integrity.

Spent fuel showing signs of failure or corrosion will be encapsulated before being stored. The FACIRI storage capacity is based on grids arranged on top of one another (Fig. 4), forming two columns of grids located in a 16 m deep pool [19].

In total, 608 SFAs can be stored, distributed in two columns (Fig. 5) of 19 grids storing 32 SFAs each. There are 416 positions for standard fuel assemblies, 96 positions for control rods and 96 positions for encapsulated SFAs [20].

The storage pools have a double stainless steel lining and include a treatment system that allows for water quality control to preserve the integrity of spent fuel during storage. An underwater camera is placed in one of the pools to allow visual inspection of the stored SFAs (see Fig. 6).

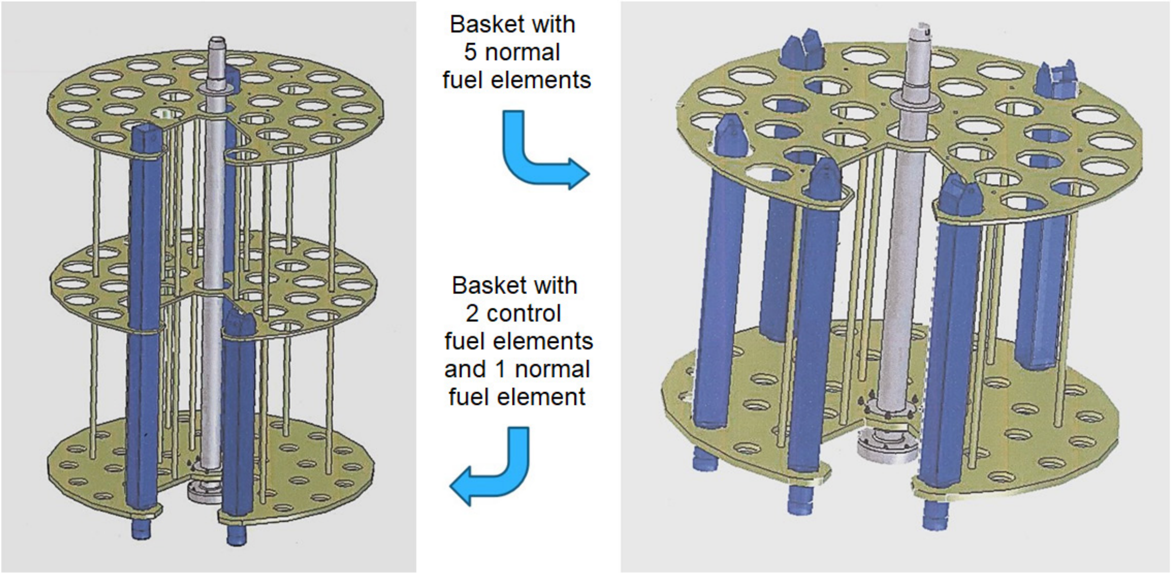
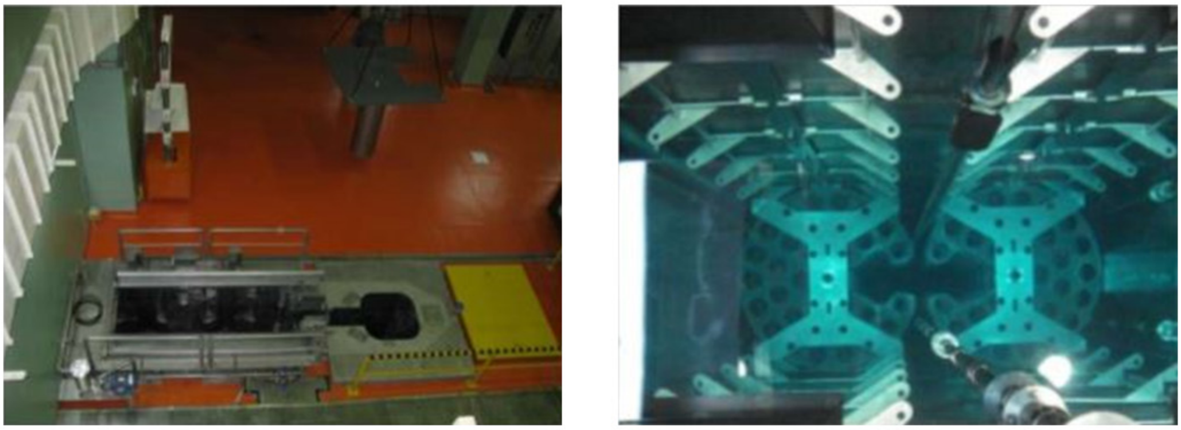
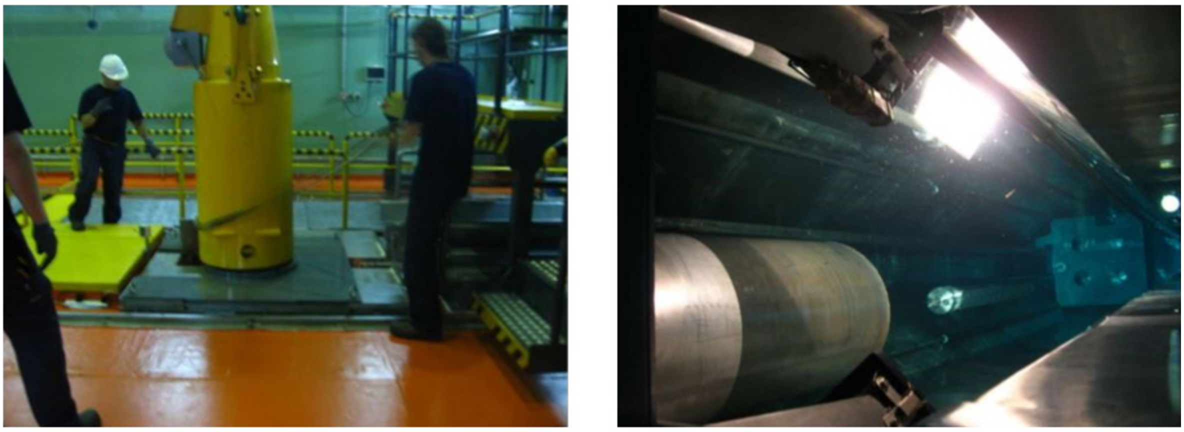


FIG. 4. Artist’s impression of the baskets and RRSNF elements (courtesy of CNEA).



(a) (b)

FIG. 5. (a) View of the upper part of the FACIRI pools (storage and reception); (b) view of the basket columns from above (courtesy of CNEA).



(a) (b)

FIG. 6. (a) Cold test of the positioning of the transfer shielded container; (b) cold test of the positioning of the canister with dummy spent fuel in the transfer pond (courtesy of CNEA).

On 5 September 2014, the Argentinian Nuclear Regulatory Authority granted FACIRI a startup license and the first spent fuel was transferred from the RA-3 reactor on 9 September 2014. The full operation licence was granted on 29 November 2016 [20].

2.1.1.3. Example: wet storage in Australia

The Australian Nuclear Science and Technology Organization (ANSTO) operated the High Flux Australian Reactor (HIFAR) reactor from 1958 to 2007. Following removal from the reactor core, the fuel was temporarily stored in a shielded storage tank (containing deionized water) located within the reactor containment building. A minimum wet storage period of one month was required to allow decay of the short lived radionuclides and to remove some of the residual decay heat.

To reduce the volume of the overall fuel assembly the shield plug (non-fuel component) was sheared off from each irradiated fuel assembly. The sheared assemblies (containing the fuel) were then transferred from the storage tank to an externally located cooling pond (deionized water) referred to as the ‘cropping/irradiation pond’. The transfer of the spent fuel was completed using a shielded dual purpose shear/transport flask.

The Open Pool Australian Light Water (OPAL) reactor is an open pool design, comprising dual pools — a reactor pool and a storage/service pool — as shown in Fig. 7.

The spent fuel pool is connected to the reactor pool and provides a storage capacity for 330 SFAs (ten year capacity). The OPAL reactor uses about 30 fuel assemblies per year. Once spent, the fuel assemblies are transferred from the reactor pool to the spent fuel pool via a transfer channel. The spent fuel can be stored in the pool until it reaches capacity. The OPAL reactor is designed for the spent fuel to be removed from the spent fuel pool via wet loading into a shielded transport cask for dry storage or shipment for reprocessing. The Transnuclear MTR (TN MTR) cask (Fig. 8) has been used to transport the OPAL spent fuel.

2.1.2. Dry storage of RRSNF

Dry storage facilities can store fuels directly taken from the RRSNF pool or waste from reprocessing of SNF for periods of more than 50 years with an appropriate level of monitoring, surveillance and ageing management planning. Over the past 20–30 years the role played by dry storage in filling the gap between available wet storage and other back end services has increased. The main attractions of dry storage are its

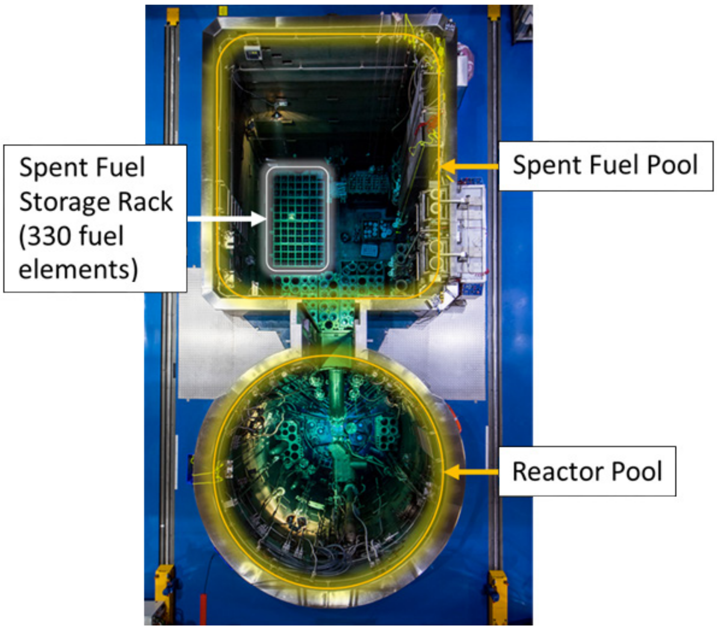


FIG. 7. OPAL reactor and spent fuel pools (courtesy of ANSTO).

FIG. 8. TN MTR spent fuel transport cask (courtesy of ANSTO).

passive cooling capability, reduced possibility of fuel cladding corrosion (over wet storage), reduced life cycle costs through the ability to add incremental capacity, and lower maintenance costs compared to a spent fuel pool.

There are two primary dry storage options for RRSNF: engineered facilities and casks built for this purpose [7]. After prolonged dry storage, it may be necessary to inspect the fuel; therefore, dry storage systems should enable fuel inspections.

Engineered structures are an established option already used by several RRs. These structures could be vaults (above or underground, vertically or horizontally arrayed), near surface boreholes, pits or pipes containing arrays of storage cavities suitable for the containment of one or more fuel assemblies. A cask is a sealed, bolted metal cylinder used to store the SNF. Cask storage is also a solution used by several RRs, with an integrated transportation option, depending on the flexibility required for the implementation of further RRSNF management steps. In the future, dry storage could be used to store conditioned RRSNF (see Section 2.2).

2.1.2.1. *Example: dry storage at ANSTO's Moata reactor*

The Moata reactor was a 100 kW thermal reactor operated by ANSTO from 1961 to 1995 (Fig. 9). Once removed from the reactor core, Moata spent fuel was placed in a dedicated in-ground dry storage facility located adjacent to the reactor. Between 1961 and 1995, 177 fuel plates were irradiated to a combined burnup of 26.1 MWd.

The SFAs were stored in a four-by-four array of steel-lined vertical holes set in a concrete-filled cavity located near the reactor's biological shield (Fig. 10). The spent fuel was kept in a dry nitrogen atmosphere to minimize corrosion.

2.1.2.2. *Example: dry storage of RRSNF in Norway*

The Institute for Energy Technology (IFE) has operated RRs on the Kjeller and Halden sites in Norway. At Kjeller, two RRs have been decommissioned — Joint European Experimental Pile (JEEP) I and Norwegian Zero-Power Reactor Assembly (NORA) — while JEEP II was operated from 1967 to 2019. In Halden, the Halden Boiling Water Reactor (HBWR) was operated from 1959 to 2018.

Both wet and dry storage are currently used in Norway. In Halden, while the majority of fuel assemblies are currently stored wet, some HBWR fuel assemblies are in dry storage. At Kjeller, JEEP I, JEEP II and experimental HBWR fuels (following post-irradiation examination (PIE)) are stored in a dry storage facility. The fuel types are summarized in Table 1 below.

The dry storage facility in Halden (Fig. 11) is adjacent to the reactor building. It is above ground and consists of a concrete shell with 2 m thick walls, with a 1 m thick front shield of reinforced concrete. Seven-metre long steel tubes are fitted horizontally through holes in the front shield. The spent fuel rods

FIG. 9. The Moata fuel storage holes are visible on lower right hand side (courtesy of ANSTO).

FIG. 10. *Moata spent fuel holes inspection (courtesy of ANSTO).*

TABLE 1. SUMMARY OF NORWEGIAN FUEL IN STORAGE

Reactor	Fuel	Cladding
JEEP I	Metallic uranium	Aluminium
JEEP II	UO_2	Aluminium
HBWR legacy	Metallic uranium	Aluminium
HBWR	UO_2, mixed oxide, ThO_2, etc.	Zircaloy, stainless steel, etc.

FIG. 11. *Above ground, horizontal dry storage facility in Halden, Norway (courtesy of IFE).*

are placed in Al storage capsules, which are in turn placed in the steel tubes. A metal frame to support the tubes is fitted inside the concrete shell. The steel tubes are cooled by the natural circulation of air.

HBWR fuel rods that are known to have failed, together with experimental fuels which have been subject to PIE, are stored in a dry storage facility (Brønnhuset) on the Kjeller site.

The fuel elements are packed into stainless steel cans before being placed in the dry storage facility. This consists of a concrete block with its top at ground level, located beneath a building specifically designed for the loading and unloading of transports of radioactive material. The concrete block drains through a pipe to a delay tank. The block houses 84 vertical steel tubes, of depths of 3–3.5 m. After insertion of the stainless steel cans, the tubes are sealed with lead plugs.

The experimental fuels stored at Kjeller are not in the form of entire, intact rods since they have been cut for PIE. The pieces thus comprise rod sections and PIE samples, many of which are mounted in epoxy. Figure 12 shows the Brønnhuset storage facility at Kjeller.

The oldest spent fuels in Norway, from the JEEP I reactor, in operation from 1951 to 1967, are stored in a dedicated dry storage facility: Stavbrønn. This facility consists of top and bottom concrete slabs, with the top one at ground level and the bottom one approximately 3 m underground. There are 97 vertical holes in each block and in each hole a 2.7 m long stainless steel pipe is positioned (to hold the Al baskets), which is fixed into the 20 cm thick slab. The top of each tube is covered with a metal cap and an expansion gasket. The space around the tubes between the two slabs is filled mainly by a mixture of sand and gravel. The storage block is covered by a free-standing building. Figure 13 shows the Stavbrønn storage facility at Kjeller.

2.1.2.3. Dry storage of waste from RRSNF reprocessing

Reprocessing RRSNF, which is discussed in more detail in Section 2.3, enables the separation of the spent fuel constituents into potentially valuable material (uranium and plutonium) and radioactive waste (comprising the fission products). The radioactive wastes from reprocessing contain the fission products and non-soluble metallic components. The fission products are vitrified and then poured into sealed stainless steel canisters, and the metallic components are compacted and then loaded into other

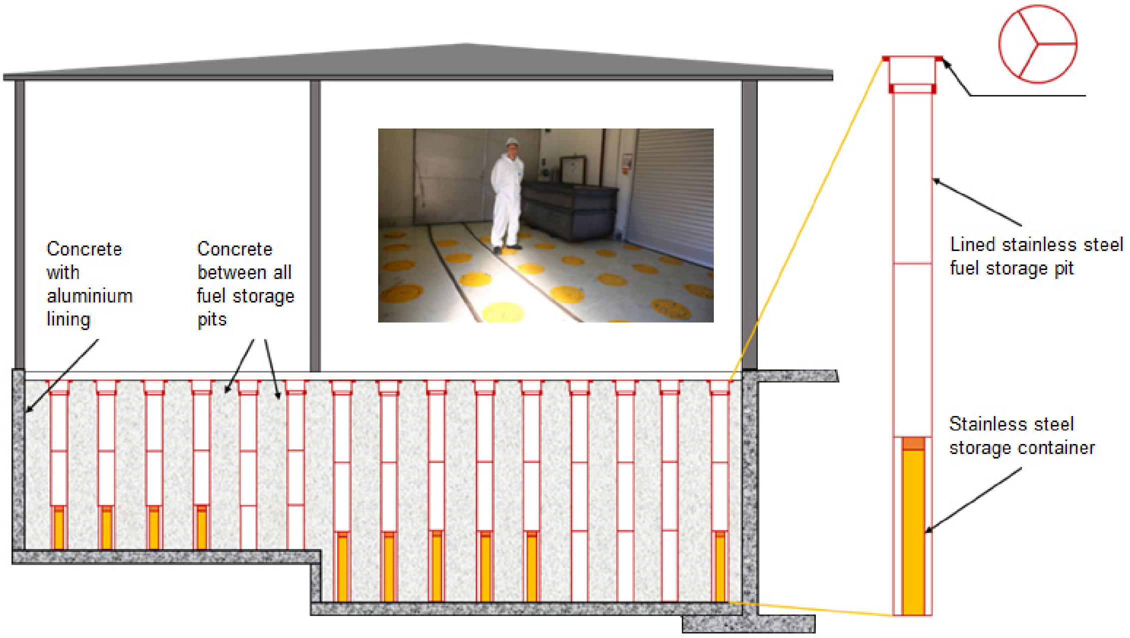


FIG. 12. Dry storage facility 'Brønnhuset' at Kjeller (courtesy of IFE).

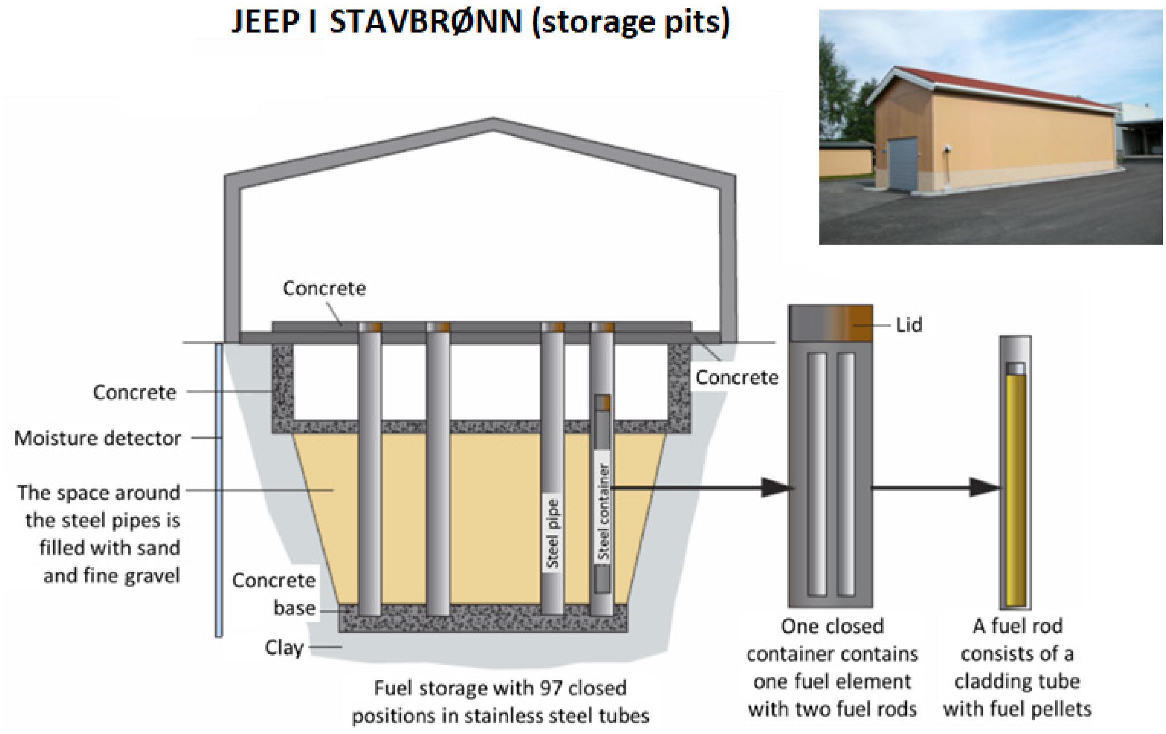


FIG. 13. The Stavbrønn dry storage facility at Kjeller (courtesy of IFE).

canisters. The radioactive wastes arising from reprocessing present a significant reduction of volume and radiotoxicity compared with unprocessed spent fuel.

These waste canisters are generally stored either in engineered structures or in casks, similar to unprocessed spent fuel. Dry storage of waste canisters may be implemented as an interim solution while waiting for suitable disposal options. Vitrified waste from reprocessing is designed to be a safe long term storage option and is stable for thousands of years. This can lead to significant simplification of storage design features.

2.1.2.4. Example: dry storage of waste from reprocessing RRSNF

A total of 1288 SFAs originating from HIFAR operation were reprocessed in France; the process flow for the return of the reprocessed vitrified waste to Australia is illustrated in Fig. 14.

The spent fuel was shipped to France over four separate shipments between 1999 to 2004. The resulting vitrified waste was returned to Australia in accordance with a governmental agreement between Australia and France (return of the radioactive waste to the country of origin).

ANSTO received an equivalent amount of intermediate level waste (ILW) which met the Australian ILW category/classification of <2 kW/m^3 of heat output. Twenty vitrified waste canisters were shipped to Australia at the end of 2015. All the canisters were placed in a single duel transport/storage cask (TN 81). The contact radiation dose on the TN 81 cask was less than 5 μSv/h at ambient temperature.

The TN 81 cask will remain in storage at ANSTO until such time that a national disposal or storage facility becomes available. The TN 81 is licenced to store the ILW canisters for a period of up to 40 years. Work is currently in progress to extend the storage period to 60 years. Figure 15 shows the TN 81 cask in its vertical storage position at the ANSTO site.

For more information, see Section I–2.1.2 of Annex I.

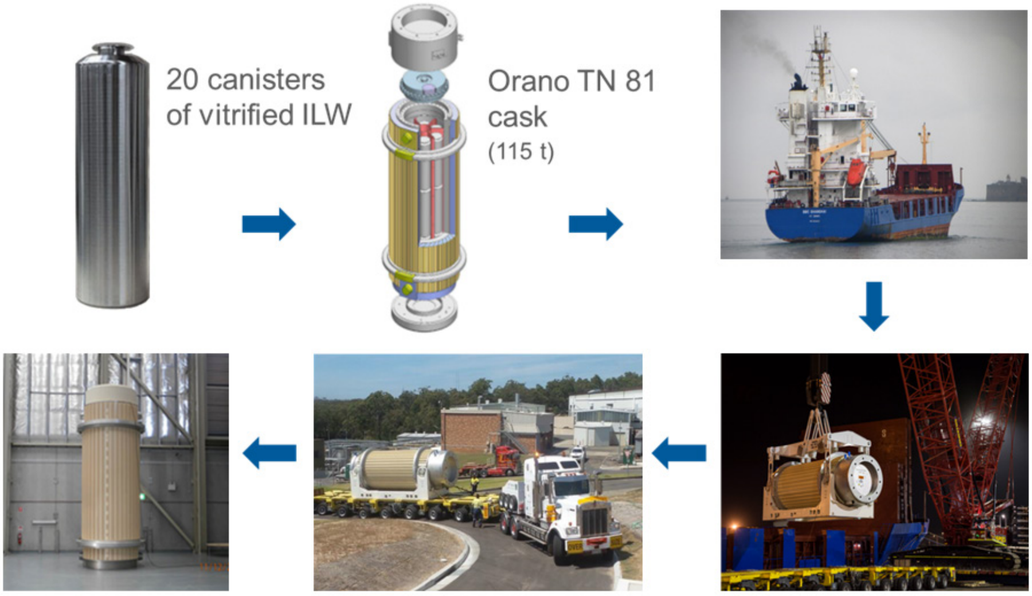


FIG. 14. Return of vitrified ILW from reprocessing HIFAR RRSNF in 2015 (courtesy of ANSTO).

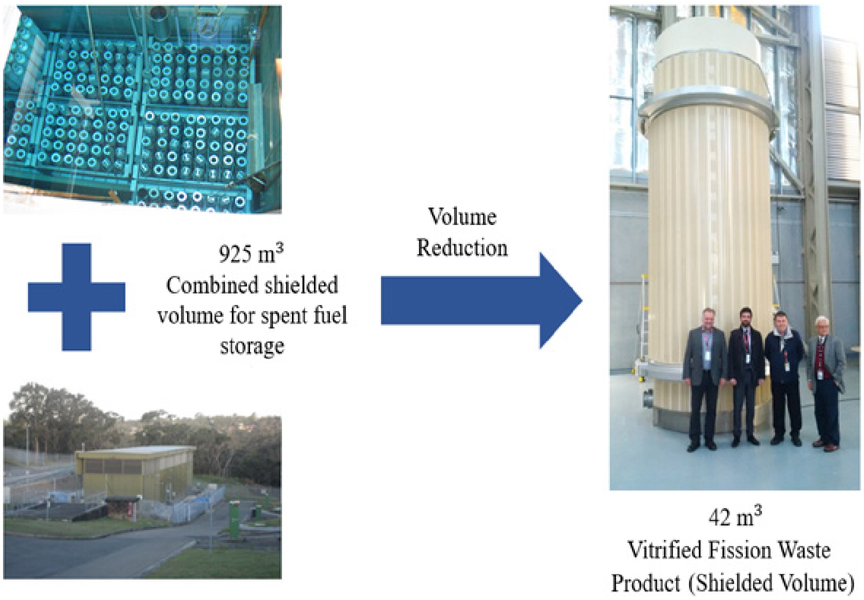


FIG. 15. Illustration of volume reduction and a TN 81 dual transport and storage cask at ANSTO, containing 20 vitrified waste canisters (courtesy of ANSTO).

2.2. CONDITIONING

This section presents the various technologies known as ‘conditioning’ of RRSNF. Conditioning operations “produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, enclosure of the waste in containers and, if necessary, provision of an overpack” [21]. Available options for conditioning of RRSNF are theoretically the same as for spent fuel from commercial NPPs. In practice, however, available options depend heavily on the nature of the fuel, of which there are many varieties for RRs. Possible conditioning options include:

- Inactive part removed, fuel meat melting or compaction to reduce the volume, followed by specific conditioning for meeting the expected storage or disposal requirements;
- Fuel meat encapsulation in a matrix like glass or ceramics, with a well-known long term behaviour.

Conditioning options are currently under development, although there is no standard process available with a high technological readiness level which addresses a large spectrum of RRSNF types. Each fuel type needs a specific approach. Conditioning can also include chemical treatment (without fissile material removal), and there are several different spent fuel conditioning technologies in different stages of development. These developmental processes can be divided into two main categories [22]:

(a) Processes resulting in a metallic final product;
(b) Processes resulting in a glass or glass ceramic matrix final product.

The advantages of spent fuel conditioning are (a) that the spent fuel is transformed into a durable waste package suitable for disposal in a deep geological repository; (b) that the uranium enrichment is decreased, which could reduce proliferation concerns; and (c) that it creates a waste form from which it is more difficult to separate the plutonium from the spent fuel, thus lowering the proliferation risk and financial liability.

These options will not automatically terminate safeguards obligations, as the final conditioned waste may contain fissile materials. Storage options for conditioning products include engineered structures and casks, which in principle are suitable for the materials under consideration.

Conditioning operations should consider known or expected requirements for the next steps in radioactive waste management, including storage and disposal.

2.3. REPROCESSING

Reprocessing of RRSNF allows the separation of the valuable materials from the waste for the recycling of any remaining fissile material into fresh fuel and the optimization of the final waste form (both amount and composition) for disposal. Reprocessing is or has been used by several countries such as Australia, Belgium, France, Germany, Italy, Japan, Poland, Romania, the Russian Federation, the United Kingdom, and the United States of America. Nuclear materials in waste may be released from IAEA safeguards, subject to IAEA approvals. Additionally, the final waste form will be specifically designed to ensure safe storage during extended periods. Up to 99% of the activity is encapsulated into a stable matrix through vitrification of the fission products. For more information about RRSNF reprocessing, see Ref. [10].

As discussed in Section 5, States can consider developing their own reprocessing capabilities or using the capabilities offered by an international reprocessing service provider. As of 2021, only France and the Russian Federation are providing commercial reprocessing services.

2.3.1. RRSNF reprocessing in France

Orano has decades of reprocessing experience, having reprocessed more than 28 tonnes of RRSNF from various countries. Between the late 1990s and the end of 2018, more than 150 RRSNF transportation casks were received and unloaded at Orano in La Hague, corresponding to more than 5700 RRSNF assemblies. The reprocessing option offered by Orano is available for Al and silicide fuel types (MTR type and Al-clad type fuel) as well as uranium oxide and mixed oxide types. For any other RR fuel types, case-by-case analyses can be conducted by Orano to determine the technical feasibility of reprocessing.

2.3.1.1. Regulatory environment

A detailed description of French legislation, regulatory requirements and procedures for intergovernmental agreements involving RRSNF reprocessing services may be found in Ref. [10]. Regarding the management of waste resulting from used fuel reprocessing, French law[1] stipulates that:

- Shipment out of French territory of the foreign radioactive waste after reprocessing is mandatory, excluding effluents and operational waste, it being understood that plutonium and uranium are not waste and are therefore not subject to this mandatory export;
- A reprocessing contract, as it involves the entry of foreign radioactive waste and materials into French territory, requires an intergovernmental agreement signed between the client country and the service provider country (France). This agreement specifies the schedule of the contract, including the projected periods of spent fuel delivery, reprocessing and waste return, as well as the deadline for the last shipment of the waste out of French territory.

The material accounting system used by Orano La Hague as part of a reprocessing contract is the 'Système d'Expédition des Résidus' (EXPER system), which determines the equivalence of waste that needs to be returned to the country of origin after reprocessing. This system of allocation of radioactive waste from reprocessing is approved by the Nuclear Safety Agency and the Directorate General for External Security (i.e. the French foreign intelligence agency), in compliance with the European Directive 2011/70/EURATOM and the 2006 French Transparency on Nuclear Safety law. The equivalence is determined based on two units:

(a) The 'unité d'activité résiduelle' (UAR, residue activity unit) based on the neodymium content (in decigrams);
(b) The 'unité de masse résiduelle' (UMR, residue mass unit) based on the mass of the metallic structural components of the spent fuel (in kilograms).

The UAR and UMR are credited into accounts at the time of reprocessing, independently of any conditioning of the waste. They are then debited from the accounts at the time of shipment of the waste from the Orano La Hague site, and the incoming activity is considered to be returned to the country of origin when (i) the UMR account is set to zero, and (ii) the balance of the UAR account is close to 0.2% of its credit.

2.3.1.2. Waste management in the RR country after French reprocessing of the RRSNF

Research reactor organizations have several options for the management of post-reprocessing waste. So far, residues have been returned as waste conditioned into universal canisters. The fission products

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[1] French Decree No. 2008-209 of 3 March 2008 "rélatif aux procedures applicables au traitement des combustibles usés et des déchets radioactifs provenant de létranger" [concerning the procedures applicable to the treatment of spent nuclear fuel and radioactive waste from abroad].

and minor actinides are vitrified in a homogeneous glass matrix and conditioned in universal canisters for vitrified residues. This type of conditioning is very stable and ensures containment over thousands of years. Universal canisters allow relatively easy transport of radioactive residues and on-site handling conditions; standardization results in volume minimization in storage or disposal facilities, and high stability of the residues is demonstrated for the long term, along with exemption from IAEA safeguards. The options include:

- Return of the waste from reprocessing in universal canisters, placed in a TN 28 transportation cask or a TN 81/TN 85/CASTOR HAW28M transportation and storage cask. As of March 2019, the TN 28 is licensed in France, the United Kingdom, Belgium, the Netherlands and Japan, the TN 81 is licenced in France, Switzerland, Australia, Spain and the United Kingdom, and the TN 85 and CASTOR HAW28M are licensed in Germany.
- Return of the waste from reprocessing with form and quantity determined using an accountancy system other than the EXPER system. This system would need to be compatible with the EXPER system in order to be considered for waste calculation after reprocessing in France.
- For the return of small quantities of radioactive residues, there is a cask proposed for use: the TN MW cask, a light cask adapted for a large variety of waste (type, volume and activity from low level waste (LLW) to high level waste (HLW)) [23] and also a triple purpose cask designed for waste transportation, storage and disposal.

Such comprehensive domestic residues management is mainly implemented in countries with an industrial scale civilian nuclear power industry and/or with large scale spent fuel management plans, i.e.:

- The country may have a defined comprehensive national radioactive waste management programme, including reprocessing after nuclear power generation, and the returned universal canisters after RRSNF reprocessing are managed along with the greater universal canister stream returned from reprocessing of SNF arising from NPP operation (e.g. Belgium);
- Or the country is already implementing a clear and sustainable long term strategy for its RRSNF, with the help of foreign industrial partners (e.g. Australia).

The above technical options may not be practical for all RRSNF management strategies in certain circumstances; difficulty with waste management can be caused, for example, by public acceptance issues causing delays in the implementation of a disposal solution. In order to tackle these waste management issues, alternative waste management routes and options can be considered. For example, depending on the country's regulations, RR operating organizations could benefit from a range of residue type options, seeking a final waste inventory which would lead to easier operations at each stage of waste management (transport, storage and disposal) and require fewer regulatory constraints, resulting in a reduction of the estimated cost for final disposal.

2.3.2. RRSNF reprocessing in the Russian Federation

The Russian reprocessing complex RT-1 was commissioned in 1977. Since 2002, foreign RR operating organizations have shipped HEU RRSNF to the Russian Federation for reprocessing under the RRRFR programme. Additionally, several countries have shipped low enriched uranium (LEU) RRSNF under commercial agreements with Russian organizations.

The RT-1 plant can reprocess a wide range of RR fuel [24]. Reference [10] includes a list of the accepted fuel types compliant with the available licences. There is experience in extending the range of spent fuel reprocessing capability, provided that safe handling of the SFAs during transport, storage and reprocessing is proven and appropriate licences and approvals are obtained. Recently, the RT-1 plant has started reprocessing uranium carbide (UC), uranium–beryllium (U–Be), metal uranium and plutonium fuels.

Additional fuel processing capabilities are under consideration for the RT-1 plant: for example, in the 2020–2025 time frame the development of reprocessing capabilities for U–Zr is planned. In 2016, a new electrical furnace, EP-500/5, for HLW vitrification was commissioned at Federal State Unitary Enterprise Production Association (FSUE PA) Mayak, which enhances safety and improves the characteristics of the resulting vitrified HLW after spent fuel reprocessing. The new furnace incorporates technical improvements compared with the four operating furnaces installed between 1987 and 2010. The design includes new engineering solutions aimed at improving reliability and extending operating life. The new facility includes an electric furnace, a glass pouring chamber, and transportation and handling equipment. In addition, three storage compartments were built to house vitrified HLW.[2]

Depending on the origin of the spent fuel and the conditions of government-to-government agreements, the vitrified HLW is subject to final management in the Russian Federation or return to the country of the SNF export.

2.3.2.1. Regulatory environment

A detailed description of Russian legislation, regulatory requirements and procedures for intergovernmental agreements involving RRSNF reprocessing services may be found in Ref. [10].

Prior to the project initiation, a government-to-government agreement with the foreign country must be signed. This should identify the destination of the radioactive waste arising from reprocessing. Two options are possible: return of the radioactive waste to the country of SNF export or permanent disposal in the Russian Federation. In addition, the unified project documentation for spent fuel import should be prepared, and this should be put through the State's ecological review process before a foreign trade contract for operations with SFAs is signed.

When it is required to return the radioactive waste arising from reprocessing to the country of SNF export, the quantity of the radioactive waste to be returned is determined. For imports of spent fuel of foreign origin to the Russian Federation, the findings of the State's ecological review are additionally considered by a special commission appointed by the President of the Russian Federation.

A positive expert assessment of the project by the State's ecological expertise authority and a positive expert assessment of the project documents by the special commission (for spent fuel of foreign origin) enable the signing of a foreign trade contract for SNF handling in the Russian Federation (transportation, storage, reprocessing and management of the radioactive waste arising from reprocessing).

2.3.2.2. Reprocessing RRSNF without waste return

Russian federal law does not forbid the management of radioactive waste resulting from reprocessing of foreign-origin RRSNF in the Russian Federation, provided that government-to-government agreements with foreign countries include the relevant provisions. The countries participating in the RRRFR programme have the possibility of including management of the radioactive waste arising from reprocessing of Russian-origin HEU spent fuel in the Russian Federation in the foreign trade contract.

The radioactive waste resulting from foreign-origin SNF reprocessing is managed in the same way as other long lived HLW and ILW arising from domestic nuclear activities, in compliance with the provisions of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [3].

Over recent years, the Russian Federation has been setting up an underground radioactive waste isolation facility on the Nizhnekansk granitoid massif in Krasnoyarsk Krai, 6 km from the city of Zheleznogorsk and 4.5 km from the Yenisei river, for deep geological disposal of long lived heat generating vitrified HLW and long lived ILW (Fig. 16). The host rock, which is more than 2.5 billion years old, is composed of 80% granite gneiss and 20% dolerite.

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[2] New Vitrification Oven for Russia's Mayak, 21 July 2015 (https://www.nsenergybusiness.com/news/newsnew-vitrification-oven-for-russias-mayak-4631613/)

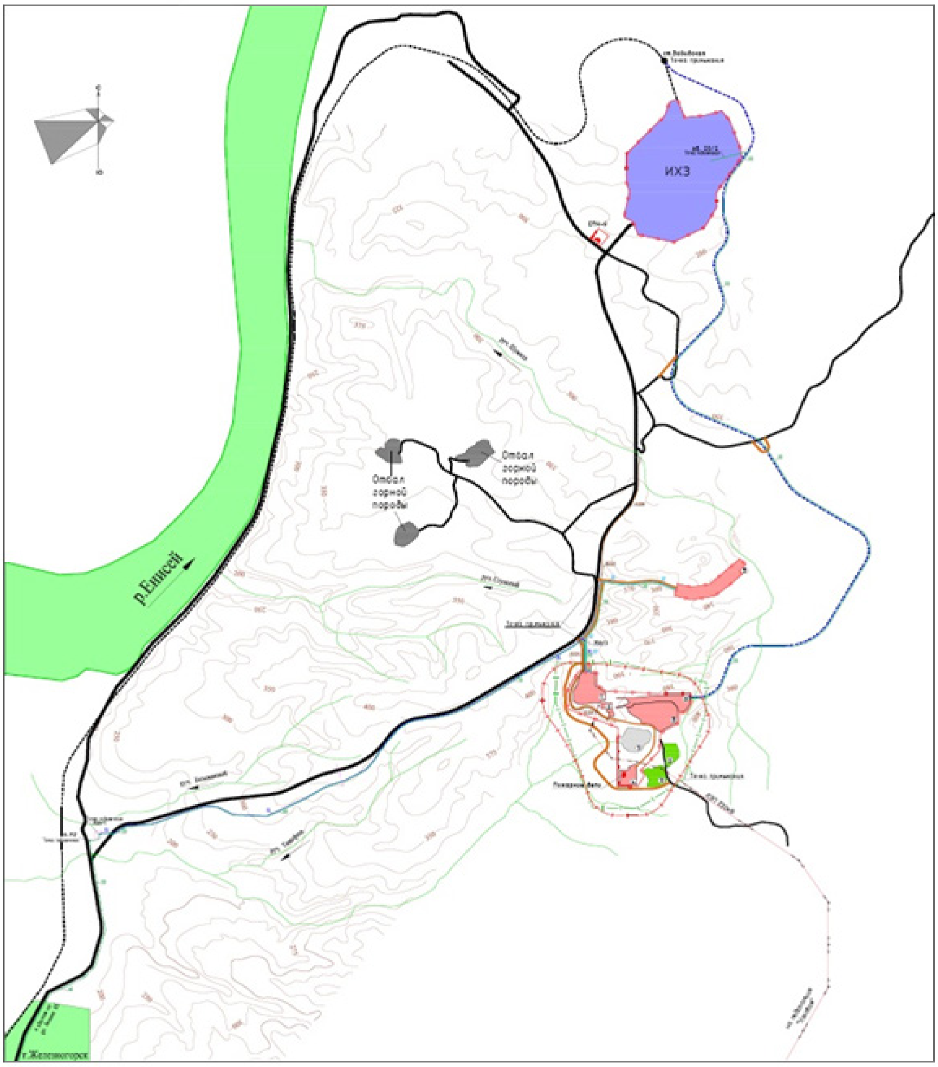

FIG. 16. Location of the underground radioactive waste isolation facility (courtesy of State Atomic Energy Corporation ROSATOM, Russian Federation).

The heat generating vitrified HLW enclosed in thick-walled canisters is planned for storage in vertical boreholes, 100 m deep, surrounded by a strong bentonite barrier. As for the long lived ILW, it will be stacked in containers in horizontal boreholes.

The first stage is setting up an underground research laboratory, Nizhnekansk Massif, for further exploration of the rock massif and justification of commercial application of the underground radioactive waste isolation facility (Fig. 17). The site selection process, including drilling of boreholes as deep as 700 m, began in 1992 and the location has been identified.

For more information on the management of spent fuel and radioactive waste in the Russian Federation, see Section I–12 of Annex I.

The Nizhnekansk Massif laboratory will incorporate the following underground facilities:

- Three shafts (servicing, engineering and air) with insets at depths of 450 m and 525 m;
- Horizontal boreholes delineating the area of the future underground facilities for the deep disposal of radioactive waste at a depth of 450 m;
- Exploratory boreholes for the Nizhnekansk Massif laboratory at depths of 450 m and 525 m;

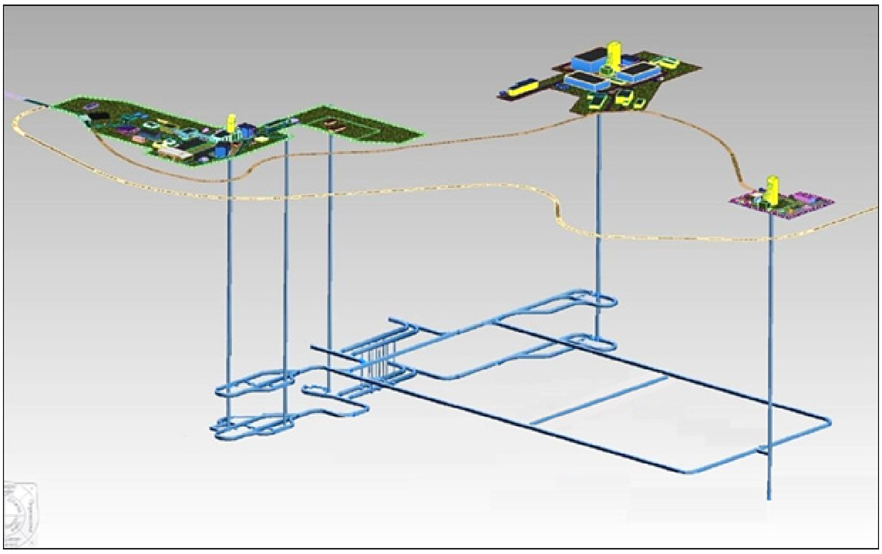

FIG. 17. The Nizhnekansk Massif underground research laboratory (courtesy of State Atomic Energy Corporation ROSATOM, Russian Federation).

— An additional cross-hole at a depth of 450 m for exploration of the rock massif in the area of the future underground facilities for the deep disposal of radioactive waste.

Once the Nizhnekansk Massif laboratory is set up, additional exploratory boreholes can be built to test alternative emplacements of radioactive waste. In 2016, the site and construction of the Nizhnekansk Massif laboratory was licensed. In 2017, a strategy for setting up the underground radioactive waste isolation facility in compliance with international underground laboratory research practices, and a strategic research master plan that envisions step-by-step research projects in 150 areas of activity, were developed.

2.4. TRANSPORTATION

SNF from RRs will likely need to be transported more than once following removal from wet storage in the reactor facility pool. From the pool it could go to dry storage near the reactor facility, centralized storage off the reactor site, a reprocessing facility or final disposal. This section provides details on transport modes, types of transport containers available, and general information that needs to be considered and understood when planning RRSNF transportation [10, 25].

In the early stages of RRSNF management strategy planning, it is necessary to determine whether the SFAs are leak-tight and properly and legibly marked. If there is any damage to the fuel assembly or the load-gripping elements, or there are significant deviations in geometry, appropriate transportation methods and containers have to be selected.

2.4.1. Transport modes

RRSNF can be transported to the management facility (e.g. storage, conditioning, reprocessing or disposal facilities) by road, rail, water, air or a combination of these modes. The United Nations Recommendations on the Transport of Dangerous Goods (UN Model Regulations) contain all the internationally applicable requirements for all classes of dangerous goods, including class 7, radioactive materials [26].

Transport route and mode options are selected depending on the following criteria:

- The geographical location of the RR and available transport infrastructure, including remoteness from the reprocessing (or storage or disposal) facility's country borders, probable transit countries and access to the sea;
- Interface requirements between the RR operating organization and the receiving organization (e.g. licensing and intergovernmental agreements);
- Packaging available for the shipment;
- Costs.

Specific requirements for the transport of radioactive material are established in IAEA Safety Standards Series No. SSR-6 (Rev. 1), Regulations for the Safe Transport of Radioactive Material [25].

2.4.2. Transport packages

Several types of transport packages are available:

- Transportation casks;
- Transportation and storage (also called dual purpose) casks;
- Transportation, storage and disposal (also called triple purpose) casks, under development.

A summary of commercially available RRSNF transportation packages is presented in Table 2.

There are several techniques for loading spent fuel, such as remotely controlled loading in air, underwater loading of submerged transport packages in the cooling pool, or a transfer cask with auxiliary equipment. Each combination of RR facility and transportation container needs to be evaluated to determine the best way to load the RRSNF into the container.

2.4.3. Dual purpose containers

As previously mentioned in the discussion of Australia's dry storage of reprocessing waste, there are dual purpose container options and they can be either cask based or canister based. The cask based system is an integral unit that serves all purposes for which the system is designed (e.g. transportation, storage, disposal). The canister based system consists of a sealed canister that contains the spent fuel. Some of these transports and storage containers are suited only for vitrified waste but not spent fuel. Typically, canister based systems use overpacks to house the canister during storage and transport. Cask based systems have generally been metal systems. For more details on dual purpose containers, see Ref. [27].

Table 3 displays the current status of dual purpose containers. Table 4 displays information about dual purpose containers that can be used only for vitrified waste.

2.5. MANAGEMENT OF DAMAGED RRSNF

Handling and management of damaged spent fuel may require further assessment and modified packaging or conditioning prior to transport for reprocessing, storage and final disposal. Damaged RRSNF can be stored wet or dry in an appropriate overpack container for containment of the material [28].

Since RRSNF conditioning assumes that spent fuel cladding integrity is the first containment barrier, for damaged fuel, there is a need to define a specific process for replacing the first containment barrier for conditioning activities.

In the case of damaged fuel which may lead to gaseous leaks, transfer/handling and reprocessing can be performed using specific tools and processes. Since reprocessing or conditioning damaged fuel

TABLE 2. SUMMARY OF AVAILABLE RRSNF PACKAGES (ADAPTED FROM Ref. [10])

Package	Service provider	Countries/regions where the container is licensed	Transport mode
TUK-19	Sosny Research and Development Company	Kazakhstan Latvia Libya Poland Romania Russian Federation Serbia Uzbekistan	Road Rail Water Air
ŠKODA VPVR/M	ÚJV Řež, a.s. Sosny Research and Development Company	Belarus Bulgaria Czech Republic Hungary Poland Russian Federation Serbia Ukraine	Road Rail Water
TUK-128 (TUK-135)	Sosny Research and Development Company FSUE PA Mayak	Russian Federation	Road Rail
TUK-32	Sosny Research and Development Company FSUE PA Mayak	Russian Federation	Rail
TUK-145/C	Sosny Research and Development Company	China* Ghana* Hungary Nigeria Russian Federation Uzbekistan Viet Nam	Road Rail Water Air
TN MTR 68, 44, RHF	Orano TN	Australia Belgium Denmark France Italy Portugal United States of America Venezuela	Road Rail Water
TN MTR 52, 52S, 52SV2	Orano TN	Australia Belgium Denmark France Portugal United States of America	Road Rail Water

TABLE 2. SUMMARY OF AVAILABLE RRSNF PACKAGES (ADAPTED FROM Ref. [10]) (cont.)

Package	Service provider	Countries/regions where the container is licensed	Transport mode
TN LC	Orano TN	France United States of America	Road Rail Water
TN 17/2	Orano TN	Belgium France Italy Netherlands Sweden	Road Rail Water
NAC-LWT	NAC International	Asia European Union South America United States of America	Road Rail Water
ROBATEL R72	ROBATEL Industries	France Germany Switzerland Denmark Sweden Spain	Road
ROBATEL R82	ROBATEL Industries	United Kingdom (pending)	Road Rail
ROBATEL R83	ROBATEL Industries	Netherlands	Road

Note: Cask providers may offer to design and produce casks for a specific RRSNF inventory and may also give assistance in licensing.

* With new miniature neutron source reactor (MNSR) basket (TUK-145/C-MNSR).

TABLE 3. SUMMARY OF DUAL PURPOSE CASKS FOR RRSNF

Package	Service provider	Countries	Transport mode
ŠKODA VPVR/M	ÚJV Řež, a.s. Sosny Research and Development Company	Belarus Bulgaria Czech Republic Hungary Poland Russian Federation Serbia Ukraine	Road Rail Water Air

TABLE 3. SUMMARY OF DUAL PURPOSE CASKS FOR RRSNF (cont.)

Package	Service provider	Countries	Transport mode
TUK-128 (TUK-135)	Sosny Research and Development Company FSUE PA Mayak	Russian Federation	Road Rail
Latin America cask project [6][a]	–	Argentina Brazil Chile Columbia Peru Mexico	–
Castor MTR3[b]	Gesellschaft fur Nuklear Service GmbH (GNS)	Germany	Road Rail Inland Water
TN MTR 85	Orano TN	Germany	Road Rail
HI-STAR 100[c]	Holtec International	South Africa United States of America	Road Rail Water

Note: Cask providers may offer to design and produce casks for a specific RRSNF inventory and may also give assistance in licensing.

[a] Under development.

[b] Licenced for transport and storage in 2019. First loading of a Castor MTR3 with SFAs from the FRM II research reactor in Germany is planned for 2021.

[c] Licenced for SNF from pressurized water reactors or boiling water reactors, but a redesigned rack could be considered to accommodate RRSNF.

–: Not applicable.

TABLE 4. SUMMARY OF DUAL PURPOSE CASKS FOR VITRIFIED WASTE

Package	Service provider	Countries/region	Transport mode
TN 81	Orano TN	France Switzerland Australia Spain United Kingdom	Road Rail Water
CASTOR HAW28M	Gesellschaft fur Nuklear Service GmbH (GNS)	Germany	Road Rail
TN 85	Orano TN	Germany	Road Rail

could lead to contamination, the following precautions may be required, determined by the facility safety basis, such as:

- Receipt at the conditioning/reprocessing plant may require specific operations;
- Conditioning/reprocessing may require an adapted process.

If some fuel assemblies are found to be damaged it may be necessary to develop new spent fuel canisters for use in the shipping containers or modify other standard spent fuel handling practices. There are established and internationally accepted procedures for storage, reprocessing, transport and disposal [7].

2.6. GEOLOGICAL DISPOSAL

Disposal is the final stage of RRSNF management whatever the chosen strategy. The final radioactive waste (conditioned RRSNF or waste from reprocessing) ultimately needs to be emplaced into an appropriate facility without the intention of retrieval. However, some countries may choose to keep open the option to retrieve the waste [29]. This section describes available options for disposal in geological formation of conditioned RRSNF and waste from reprocessing.

Disposal facilities use a combination of natural and engineered barriers to contain radionuclides within the engineered barriers, as well as to delay and retard their releases until their activity has decayed to acceptable levels [30]. The disposal facility is sited, designed, constructed and operated to isolate the waste from any surface based disturbances and to ensure that the host formation and the disposal facility's engineered barriers comply with the safety requirements, using the guidance provided in IAEA Safety Standards Series No. SSG-14, Geological Disposal Facilities for Radioactive Waste [31].

2.6.1. Main features

Mature concepts for geological disposal of conditioned RRSNF and waste from reprocessing exist and are beginning to be licensed. The IAEA safeguards will continue to apply on spent fuel disposed of in geological repositories. The IAEA safeguards terminate on nuclear material contained in waste from commercial reprocessing upon the IAEA determination that such material has been consumed or has been diluted in such a way that it is no longer usable for nuclear activity relevant to safeguards or has become practicably irrecoverable (see Section 2.3).

ILW and HLW need to be isolated from the biosphere for tens or hundreds of thousands of years. The relevant timescale and specific need for containment and isolation depend on the specific waste properties. It is not possible to guarantee this level of isolation by facilities at the surface or at a depth of some tens of metres. These types of waste require disposal in a stable geological formation at a site and depth that can provide isolation and containment for the needed timescale. IAEA Safety Standards Series No. SSR-5, Disposal of Radioactive Waste [30], establishes the safety requirements to ensure this isolation and containment. IAEA Safety Standards Series No. GSG-1, Classification of Radioactive Waste [32], sets out a general scheme for classifying radioactive waste that is based primarily on considerations of long term safety and thus, by implication, disposal of the waste. It identifies the conceptual boundaries between different classes of waste and links the waste class (e.g. LLW, ILW or HLW) to the type of disposal facility that can provide for its long term safety [33].

For generic information about disposal in geological formations, see IAEA-TECDOC-1934, Underground Disposal Concepts for Small Inventories of Intermediate and High Level Radioactive Waste [34].

2.6.2. Examples of geological disposal options

Several countries have developed, or are in the process of designing, geological repositories for radioactive wastes. Some of these are briefly described below.

2.6.2.1. Disposal facilities and concepts

Designs for mined deep geological disposal repositories have been developed for a range of geological environments such as salt, crystalline rock or clay formations. The Waste Isolation Pilot Project (WIPP) facility is a geological disposal facility in the United States of America at a depth of around 650 m in a salt formation where transuranic waste — i.e. waste that includes a mix of LLW and ILW — has been disposed of since 1999 (Fig. 18) [35].

The Onkalo facility is a deep geological disposal facility licensed for construction in Finland, at a depth of around 520 m in a crystalline host formation, for the disposal of spent fuel declared as waste, including RRSNF (Fig. 19) [36]. The French National Radioactive Waste Management Agency (Andra) has designed and sited a deep geological disposal facility for HLW and long lived ILW in a clay formation in France, at a depth of approximately 500 m [37]. A licence application process is currently under way (Fig. 20).

The above examples of mined deep geological disposal facilities are intended for the disposal of a large inventory of ILW, HLW or spent fuel declared as waste. The costs associated with developing, siting and licensing, constructing, operating and eventually closing these facilities are high, and range from the billions to several tens of billions of euros.

2.6.2.2. Disposal options for small waste inventories

States managing RRSNF with no nuclear power programme have a relatively small SNF inventory compared with countries with nuclear power reactors. For small waste inventories, however, constructing a deep geological repository is likely to be an uneconomical solution. Construction costs of a comparatively simple geological repository can reach from several tens to hundreds of millions of euros. Thus, there

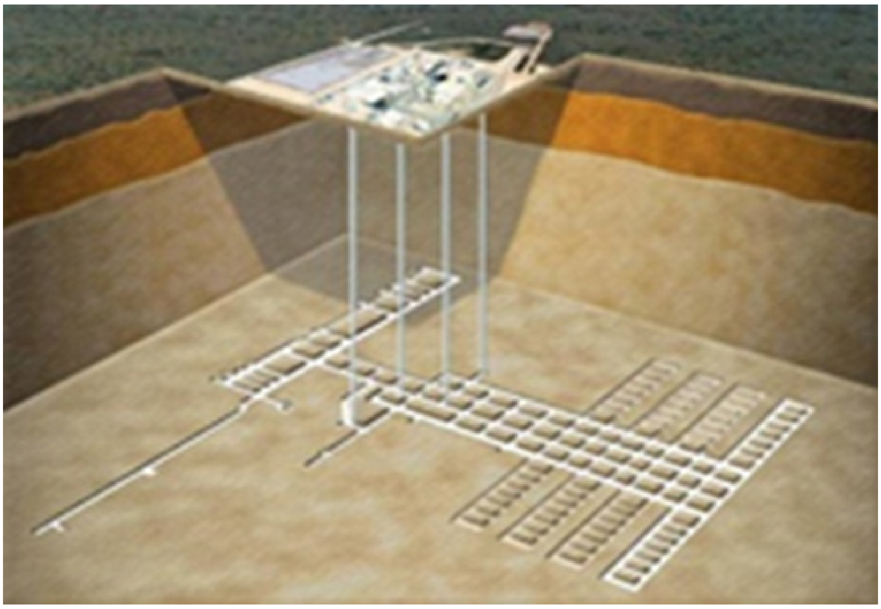

FIG. 18. Schematic illustration of the WIPP facility in New Mexico, United States of America (courtesy of the United States Department of Energy (USDOE)).

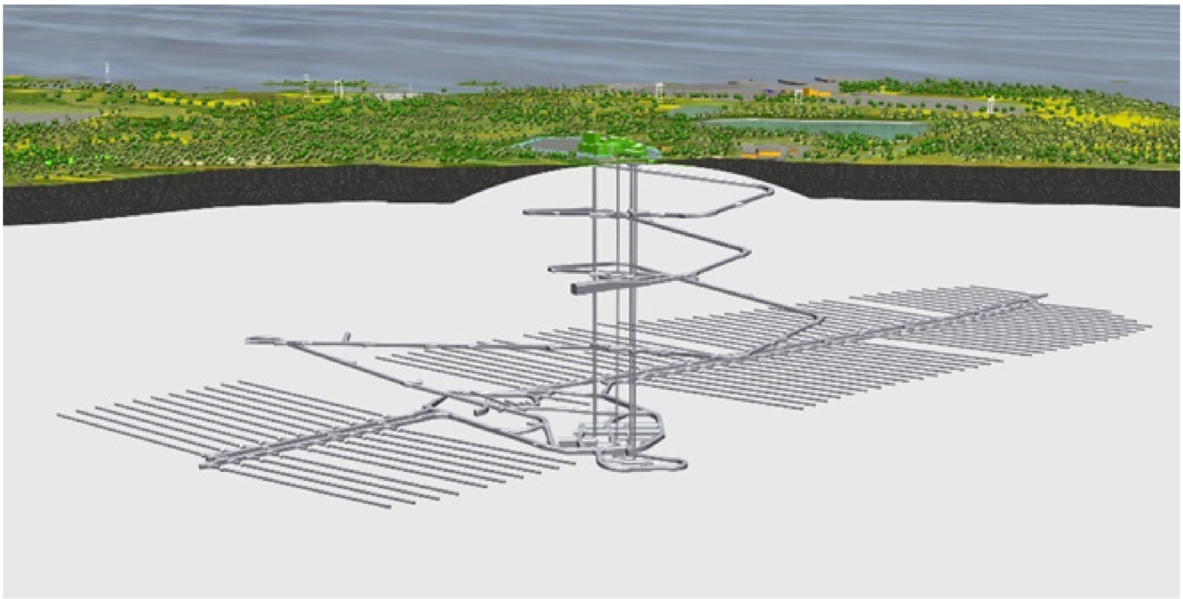

FIG. 19. Schematic illustration of the Onkalo spent fuel disposal facility project in Finland (courtesy of Posiva Oy).

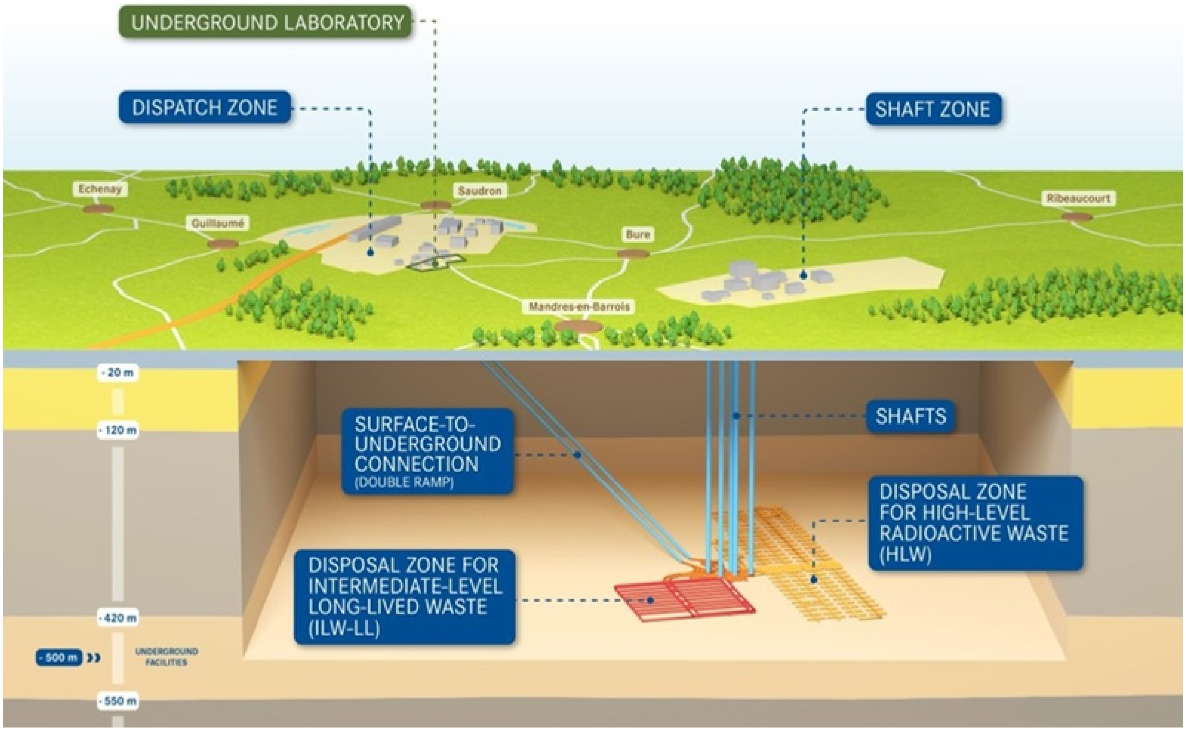

FIG. 20. Schematic illustration of the Centre Industriel de Stockage Géologique (CIGÉO) concept design for a ILW and HLW disposal facility project in France (courtesy of Andra).

is a significant incentive to not simply duplicate the deep geological disposal concept, but to look for alternative disposal concepts.

In considering any alternatives, however, the costs for the development and safety analysis of these new solutions must also be included in the cost estimate for each alternative. In this case the graded approach refers to the hazard potential from that inventory, not only the volume.

One potential approach would be to use a suitable, already existing underground excavation, for example from a mine no longer operating. Knowledge of the overall mining activity and the current geological condition of the location is needed to evaluate the suitability of this option; the costs for required backfill and stabilization activities need to be included in the decision. A similar approach would be creating access to an underground formation from the side of a hill or mountain — as was done at Bataapati (Hungary) and as was explored at the Zuricher Weinland [38]. Costs for tunnelling are conventionally known and are assumed to be of the order of €10 million per kilometre.

Another economically interesting disposal option for small waste inventories is in a borehole, which is a cylindrical excavation, made by a drilling device [39]. After lowering a waste package down the borehole, the borehole is filled with a buffer material to fill the annular space around the waste packages and, usually, to ensure that the waste packages are not stacked directly on top of one another. Long term safety is achieved by a combination of the natural barrier around the boreholes and the engineered barrier, which is mostly made up by the waste package and the backfill material.

Boreholes for disposal of disused sealed radioactive source inventories have been extensively studied, and some States are currently progressing towards implementing this system (Fig. 21). In this concept, boreholes are approximately 26 cm in diameter, and can be drilled using standard water and mineral resource exploration techniques. Depending on site-specific properties, the disposal zone would typically be in a geological formation at tens to hundreds of metres deep. The overall project costs, from initial studies over licensing to implementation, would be several million euros.

Mined geological repositories do not envisage depths beyond a thousand metres. However, boreholes can stretch to depths beyond this distance, often within the crystalline basement rock formation (Fig. 22). Considering deep borehole disposal therefore expands the range of locations suitable for disposal.

The safety strategy consists of isolating the waste in an environment where the groundwater is unlikely to communicate with the biosphere. Constructing such boreholes is possible with today's drilling technology, but it remains to be demonstrated and licenced that waste (including RRSNF) can be safely emplaced in such deep boreholes and that they can be sealed and closed. A demonstration project is currently under preparation by the USDOE [40].

(a) (b) (c)

FIG. 21. Borehole disposal of disused sealed radioactive sources: the sources are conditioned by placement into dedicated capsules (a), followed by containerization (b), before they are placed in a borehole (c).

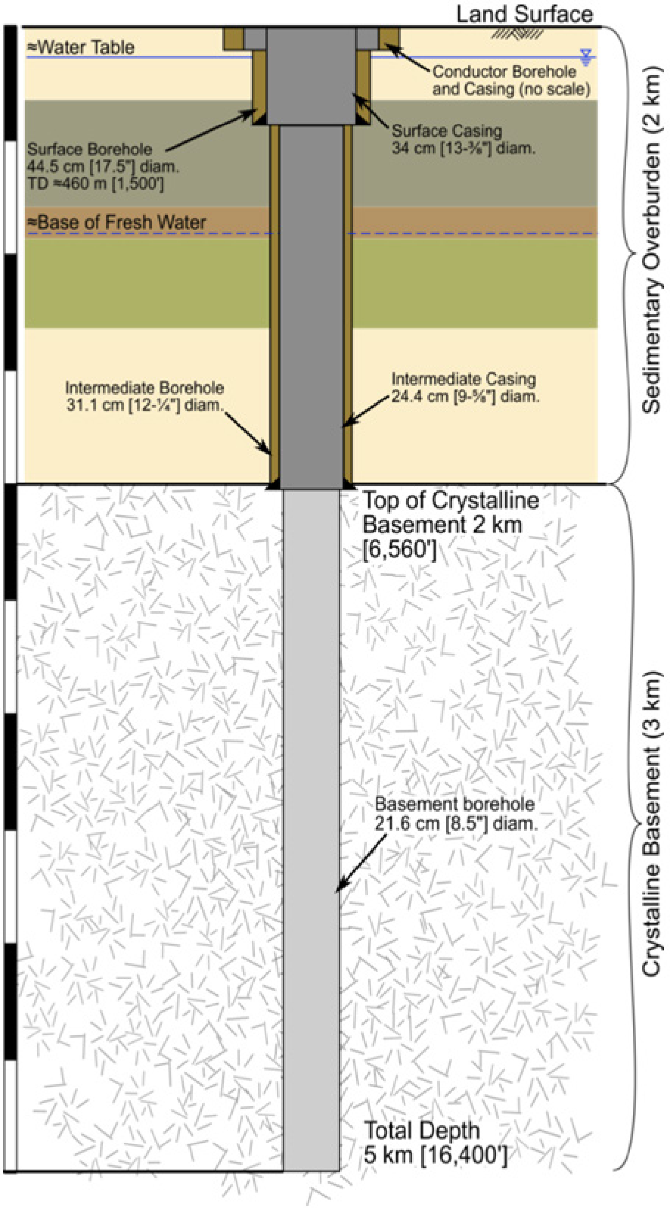

FIG. 22. Deep borehole disposal concept (courtesy of USDOE [40]).

2.7. FUEL RETURN PROGRAMMES

Commencing in the 1990s, in an effort to eliminate civilian use of HEU fuel in RRs, the Russian Federation and the United States of America initiated programmes to allow the return of US-origin and Russian-origin HEU fuel to the country of origin [41]. The IAEA has fully supported these programmes since their inception [11]. The IAEA has organized several interregional training courses and holds annual ‘lessons learned’ meetings on the subject. The courses provide participants with the technical, organizational and administrative information needed to prepare RRNSF for shipment.

While the RRRFR programme does not have a defined end date, the original FRRSNF acceptance programme of the United States of America programme ended in May 2019. To demonstrate commitment to non-proliferation goals, however, a portion of the FRRSNF acceptance programme was extended through May 2029. Proposed receipts will be considered on a case-by-case basis and undertaken only when there is clear justification to do so [42]. From a State's perspective, this option may be attractive because it transfers the responsibility for final disposal of the RRSNF to the country of origin. While there are still some bilateral agreements that will allow the return of HEU and some LEU to the country of origin, States cannot rely on the indefinite availability of these return programmes as a long term RRSNF strategy.

A similar programme to minimize the HEU use in miniature neutron source reactors (MNSRs)[3] was launched by China and the United States of America, who at the 2016 Nuclear Security Summit committed to work together through the IAEA to support the conversion of MNSRs in Ghana and Nigeria as soon as possible. The Ghana and Nigeria MNSRs were converted to LEU fuel in 2017 and 2018, respectively, and both HEU cores were returned to the country of origin. China has agreed to accept return of the HEU MNSR cores, upon the request of respective countries, to convert all remaining Chinese-origin MNSRs worldwide.

There is no restriction to the fuel supply contract containing an option for the buyer to return the RRSNF to the country where the fuel was enriched and manufactured, subject to a negotiated intergovernmental agreement. Many States may find it attractive to negotiate such a return agreement; however, this is not a standard arrangement.

3. SPENT FUEL MANAGEMENT STRATEGIES AND SCENARIOS

All RRSNF management starts in the reactor facility, typically in wet storage. A complete RRSNF management strategy will have a final disposal situation (either as fuel or waste from reprocessing). The steps in between vary and can include storage, transportation, processing or conditioning, and multiple steps of similar types may be incorporated. Member States participating in the CRP considered in total 11 options for managing their spent fuels, as follows:

- Option 0. On-reactor-site storage. This is essentially the 'do nothing' option and is not suitable for long term storage because the reactor facility will ultimately be decommissioned and the fuel will have to be removed from the facility. Additionally, long term wet storage can lead to fuel cladding degradation, creating a radiological contamination problem.
- Option 1. Direct disposal. This involves moving the spent fuel directly from the reactor pool storage to the final disposal facility. This option is not likely to be implemented because the disposal facilities being developed are not intended to accept spent fuel without some form of conditioning or encapsulating.
- Option 2. Conditioning, storage, disposal [43]. Fuel is sent from the reactor pool to be conditioned (e.g. structural parts are cut to minimize waste volume, fuel assembly is encased in a stabilizing container or matrix), then placed in away-from-reactor storage before being sent to the final disposal facility.
- Option 3. Storage, conditioning, storage, disposal. This is the same as option 2, however, there is an additional storage period prior to conditioning.
- Option 4. Storage, direct disposal. Fuel is moved from the reactor pool and placed in storage away from the reactor (could be wet or dry), then moved to final disposal. As with option 1, this is not viewed as a probable option.

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[3] US–China Joint Statement on Nuclear Security Cooperation, 31 March 2016 (http://www.nss2016.org/document-center-docs/2016/3/31/us-china-joint-statement-on-nuclear-security-cooperation)

- Option 5. Storage, reprocessing, storage, disposal. Fuel is moved away from the reactor facility into storage away from the reactor (wet or dry), then taken to a reprocessing facility. The waste product from reprocessing is then moved to a storage facility away from the reactor before disposal.
- Option 6. Reprocessing, storage, disposal. This is the same as option 5 except the fuel is moved directly from the reactor into the reprocessing facility.
- Option 7. Fuel return. Fuel is returned to the country of origin (i.e. the country where the nuclear material was enriched), which takes responsibility for the final disposal. While this does not meet the criteria of a State retaining responsibility for the fuel during its whole lifetime, it is acceptable if the receiving State is willing to assume that responsibility. This needs to be negotiated with the country providing the fuel during the purchase negotiations, then followed up throughout the RR's operating lifetime to ensure that fuel return will continue to be possible. All agreements should be in place before the final decision is made on the fuel management strategy.
- Option 8. Conditioning, disposal. Spent fuel is conditioned prior to placement in the final disposal site. It is the same as option 2, except there is no storage after conditioning.
- Option 9. Storage, conditioning, disposal. Fuel is moved away from the reactor facility, stored, then moved to a conditioning facility prior to the final disposal. It is the same as option 3, except there is no storage after conditioning.
- Option 10. Storage, reprocessing, disposal. This is the same as option 5 except there is no storage after reprocessing.
- Option 11. Reprocessing, disposal. The fuel is moved directly from the reactor facility to a reprocessing facility, then the waste product from the reprocessing is moved directly to the final disposal site. It is the same as option 6, except there is no storage after reprocessing.

A single flow chart of the spent fuel management life cycle is shown in Fig. 23.

As stated above, option 0 is not considered an acceptable option for final RRSNF management. Options 8 and 9 are similar to options 2 and 3, without the storage stage prior to disposal. Similarly, options 10 and 11 are similar to options 5 and 6, without the storage stage prior to disposal. Therefore, these 11

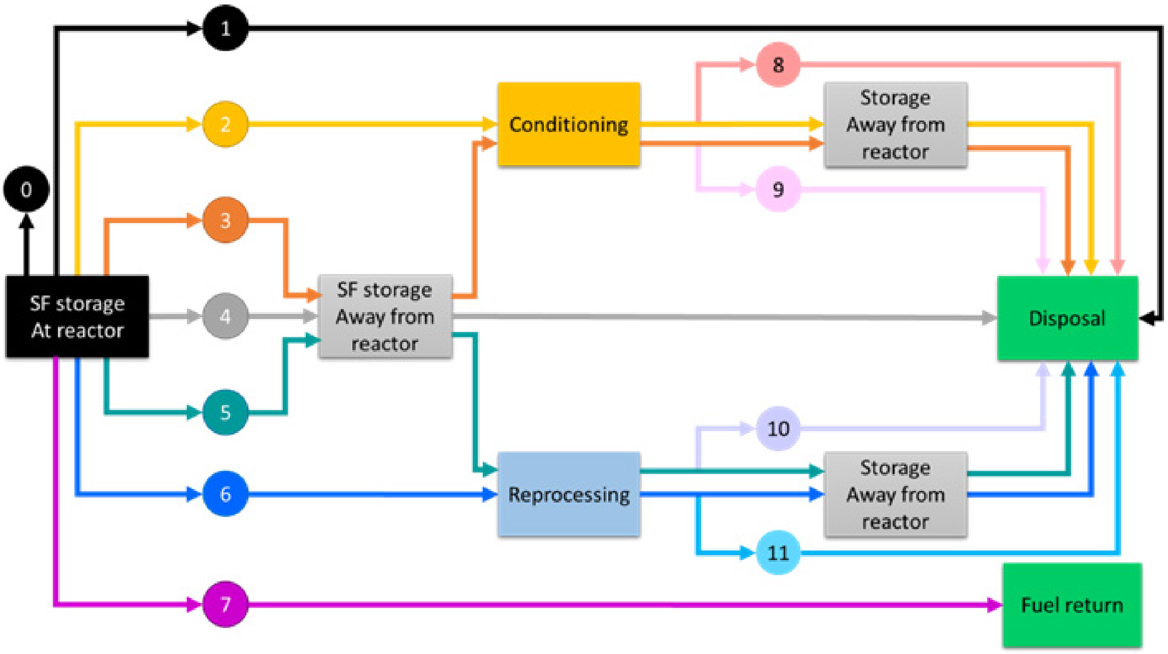


FIG. 23. RRSNF management scenario options.

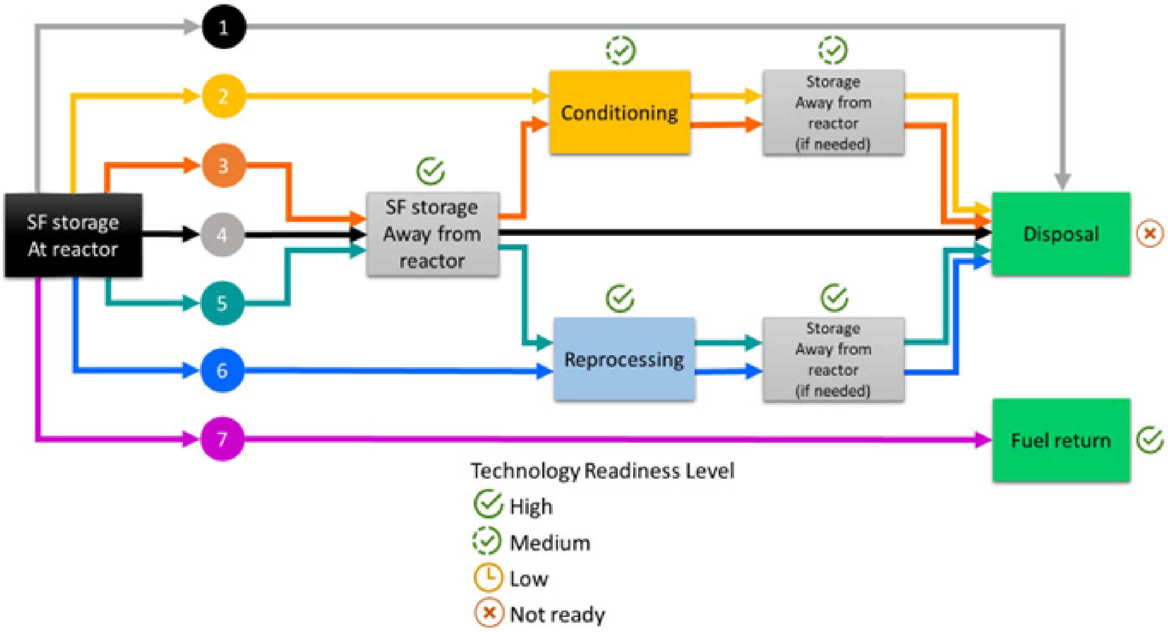


FIG. 24. RRSNF management options and available strategies.

options can be simplified to the seven probable options shown in Fig. 24, with an optional storage prior to disposal. Figure 24 also shows the technology development state of each RRSNF management stage.

For options 5 and 6, the reprocessing stage can be done either in a domestic facility or in an international one. Furthermore, if the reprocessing is done internationally, the radioactive waste from reprocessing can be managed (storage and disposal) by either the original RR country or by the reprocessing country, depending on the contractual arrangements.

4. FACTORS FOR EVALUATING RRSNF OPTIONS

The stated goal of this CRP was to develop a comprehensive set of options for management of the RRSNF. Possible spent fuel management scenarios were introduced in Section 3, themselves a specific sequence of technical management steps introduced in Section 2. The CRP goal is further to develop tools for informing decision makers about the advantages and disadvantages of each scenario.

This section introduces non-economic factors that could influence the viability, and probability of success, of implementing any given RRSNF management scenario. Full awareness of these factors and of their potential to impact on any or all steps, associated intermediate decisions and the overall duration of implementing a chosen scenario, should be considered a prerequisite to choosing and committing to any such scenario.

As discussed in Section 3, scenarios must meet the identified requirements to provide for required levels of safety, security and safeguards; any scenarios that do not meet these minimum requirements will not be considered further. Assessment of the advantages and disadvantages of each scenario will focus on both their likelihood of being implementable within a given national framework and the associated resources needs. Comparative cost assessments directly associated with each of the scenarios' activities (and overall duration) can be performed, and the assessment tools introduced in Section 5 present specific cost estimation approaches.

The non-economic factors further discussed in this section do not directly impact on the cost assessment. They do, however, impact on the life cycle cost, as they are fundamental to a Member State's ability to implement a given scenario. Adverse risks can broadly be associated with each of these factors, in case they present an obstacle to such implementation. Risk assessments and the associated implications for cost estimates are difficult to quantify, although, clearly, risks associated with lengthy delays in implementing a scenario or a specific step (e.g. due to a lack of adequate legal basis or the absence of a mandate conveyed by a political decision) can significantly impact on life cycle costs. Rather than attempting more detailed uncertainty assessments to capture the potential implications of those risks, factors likely to impact on the implementation of a scenario are discussed below and are considered in a qualitative manner using the decision making tools presented in Section 5.

The following is a list of general factors that is based on the Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems [44] developed in the frame of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO); specifically, the INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Infrastructure [45]. The INPRO methodology lists items needed for the sustainability of nuclear energy systems, and the following elements were identified as applicable to determining RRSNF options:

- Legal and regulatory considerations;
- Industrial and technical considerations;
- Political support;
- Public acceptance;
- Human resources;
- Environmental impact considerations;
- Regional and international partnerships.

These non-economic factors, discussed in more detail in Sections 4.1 to 4.7, should be taken into consideration as a group when making an informed decision. In Section 5, a methodology for a related decision-support process for RRSNF is discussed, and the non-economic factors are numerically incorporated into the decision tool. It is also possible to consider these factors subjectively as an overlay to a detailed cost estimate. Typically, the economics of choosing a particular scenario and strategy for RRSNF disposal is the most important consideration, but the other non-economic criteria discussed in Sections 4.1 to 4.7 should be considered as part of a comprehensive strategy.

Based on these non-economic considerations, certain options may be positively or negatively impacted.

4.1. LEGAL AND REGULATORY CONSIDERATIONS

Each State is free to choose its nuclear fuel cycle policy, including whether to use a closed or open fuel cycle, as well as its waste and spent fuel management strategy. In turn, it is highly advisable for it (a) to establish a national legislative, regulatory and organizational framework for spent fuels and radioactive waste management; (b) to establish and maintain a competent and independent authority in the field of spent fuel and radioactive waste management safety; and (c) to ensure that adequate financial resources will be available for the management of spent fuel and radioactive waste.

Therefore, the options could be affected by national and international legal issues. Laws regarding spent fuel management may eliminate certain options and will inform which aspects of the options could be affected by the legal framework. Options that are not currently compliant with a country's laws can be used as a basis for making a case to change the law. The legal and regulatory framework comprises two aspects: (i) legal requirements set out in nuclear related legislation, referred to as nuclear law and including related regulations and guides; and (ii) the related institutional infrastructure, including regulatory authorities that oversee the implementation of nuclear law and ensure that legal commitments are met. Some of this framework includes international legal commitments for a country, such as the Treaty on the Non-Proliferation of Nuclear Weapons [46] and the related safeguards agreements and protocols, and conventions, such as the Convention on Nuclear Safety [47] and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [3].

To cover the first aspect of a nuclear legal framework, States need to consider whether the (existing or planned) laws cover all areas necessary for the selected options in accordance with international standards, whether important international nuclear legal arrangements are in place and whether the regulations and guidelines are complete and adequate.

To cover the second aspect of a nuclear legal framework, State's competent authorities for regulating various aspects of the options (i.e. nuclear, environmental, commercial, international trade, etc.) need to be identified and evaluated for adequacy. As examples, the following factors should be considered:

- What is the status of the national legal framework with respect to the RRSNF options? Such as:
  - International nuclear liability conventions [48, 49, 50];
  - Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [3];
  - Treaty on the Non-Proliferation of Nuclear Weapons [46] (and associated safeguards agreements and additional protocols);
  - Convention on the Physical Protection of Nuclear Material [51] and the 2005 Amendment thereto [52];
  - International Convention for the Suppression of Acts of Nuclear Terrorism [53].
- What is the status of national regulatory authorities with the below responsibilities, and what considerations should be taken into account for each option?
  - Nuclear safety and radiation protection;
  - Environmental protection;
  - Control of operation, radioactive waste management and decommissioning;
  - Emergency preparedness and response;
  - Nuclear security and non-proliferation.

4.2. INDUSTRIAL AND TECHNICAL CONSIDERATIONS

Consideration should be given to the level of technological and industrial capacity development that would be required to implement an option. The industrial and technical capacity of a country should be adequate to support the different options, projected throughout their complete life cycles. Options that require more extensive investment in new facilities and development of technologies can be viewed negatively because they can entail risks (e.g. delay, other-than-expected outcomes), but they may also be viewed as positive because they represent opportunities for investment in national infrastructure and technological capacity. The industrial support infrastructure could be provided either by local, regional, national and/or international arrangements. As examples, the following factors should be considered:

- Is there suitable equipment (trucks, cranes or other construction and maintenance equipment)?
- What national industrial base and technical infrastructure is available to support each option (roads, bridges, ports, emergency response and fabrication facilities)?
- Does an option add value to or place a demand on the national industrial base?
- Is the participation of national industry in the different options a discriminator between them?
- Have potential sites in the country for the respective storage options been considered?

4.3. POLITICAL SUPPORT

The organizations responsible for RRSNF disposal need to describe the options and strategies so that they are understandable by the government and political agents. This will allow them to outline the national need for a waste management strategy and practical ways for meeting this strategy. They should be able to clearly explain why each option is being considered and outline the process by which the government will come to a decision and how stakeholders can provide input to the decision making. Since there will be different issues and attitudes related to each option in a specific country, political equities and support will likely be different for each option. As examples, the following factors should be considered:

- Is there active opposition in a current political party, or in one expected to gain power?
- Has progress been made in the siting of end-state waste management facilities?
- Is there a system for resolving public concerns?
- Does the legal system allow intervener activities to unduly delay projects once a construction permit has been issued?
- Are there policy considerations that eliminate some options?
- Does the public perception of risks of the different options differ significantly? (If decision makers are elected, will public perception sway their choices?)
- Is there political support for the expected outcome?
- Do the stakeholders and decision makers operate within an approved political direction?
- How important is it for the decision makers to support the option?
- What is the government policy regarding each alternative?
- Does one option provide more benefits (as perceived by politicians) to society or have political ramifications?

4.4. PUBLIC ACCEPTANCE

Closely related to political support is the fact that public opinion will likely play a significant role in the selection of RRSNF management options for a country. As such, the various scenarios may have different degrees of public acceptance and public sensitivity. Public perception of the options being considered should be thoroughly investigated and understood, to enable a government policy commitment to support those options. Public opinion will be affected by the information provided, the frequency of the information communicated and the level of public participation in the decision-support process. Public acceptance issues related to waste management vary from country to country, so there is no general ‘one size fits all’ approach to dealing with this issue. In some countries, public opposition has stopped or delayed the site selection or construction of disposal facilities for radioactive waste. The public may have concerns about contamination to the environment from radioactivity and the potential for widespread contamination, and about the perception that there is no safe way to manage spent nuclear fuel and radioactive waste.

A large part of public opinion on nuclear matters relates to perception of risk. Risk is defined as the product of the consequence multiplied by the probability of occurrence. This mathematical definition is widely accepted by experts and scientists; however, public perception of risk is not as easily quantified. Additionally, although probabilistic risk assessment is commonly used by experts in many fields to quantify risk, this is not well understood by the public. The following factors have been found to affect the perception and acceptance of a risk by an individual [54]:

- Trust in the institutions (e.g. the national regulator and the RR owner) controlling nuclear safety and security.
- The voluntary nature of the risk: imposition of a decision on individuals who could be affected is a significant multiplier of perceived risk. The amplification of risk perception could be so high that it prevents real communication about the risks and benefits of a project.

- Degree of control: people are more concerned about their control of risks (e.g. nuclear energy or flying in a plane versus driving cars or smoking cigarettes).
- Benefit/reward: the acceptance of risk by an individual or group is increased if there are associated direct benefits to the individual or group.
- Knowledge and familiarity: a risk is perceived to be more significant if it is not well understood or familiar. Experience has shown that public knowledge strongly influences the perception of risk.
- Potential for catastrophic results: accidents that cause multiple fatalities at a single time are perceived as a higher risk compared to the same number of fatalities from scattered or random accidents (e.g. plane crashes versus car accidents).

Based on the above, there is a clear need to provide relevant and understandable information to local communities and to provide opportunities for public participation in decision making. The processes used for public communication and participation would be expected to differ from one country to another; however, it is expected that governments participate with the relevant public and private organizations. As examples, the following factors should be considered:

- Is information being provided to the public?
- Is the information being provided sufficient according to national requirements, considering international practice?
- Is there a process that allows the public to provide input?
- What is the risk perception of the different options by the public?
- If the public perception is negative for an option, does the government have the tools to change the public perception to a degree that will allow the option to proceed?
- Does the public participate in decision making processes between alternatives?
- What is the public perception of each alternative and do they prefer one acceptable alternative over another?
- Are there established and effective pathways in place to inform the public of the impact of this option?
- Does the public perceive that the government is committed to the long term responsibility of the option?

4.5. HUMAN RESOURCES

Sufficient human resources, both in terms of knowledge and quantity, should be available to achieve each proposed option. It is essential that an adequate number of qualified staff are available at the respective facilities, government and regulatory authorities. It is important to understand the human resource requirements related to the different options, since skilled and trained personnel are needed for successful implementation. This includes not only the entities performing the tasks, but also other institutions involved, such as regulatory bodies and government ministries. It should be considered whether any training and expertise will be required to implement some options. As examples, the following factors should be considered.

- Are adequate human resources available to establish and operate each alternative?
- Are these resources enough, according to international experience?
- Are human resources available for operation, maintenance and decommissioning if required by an option?
- If not, are there plans for developing needed human resources and does this differ for each option?
- Are there systems in place to replace and develop new skills as needed?
- Can the skills be imported or developed within the country, and how does this differentiate between the options?

4.6. ENVIRONMENTAL IMPACT

Every RRSNF management scenario will need to be evaluated for compliance with environmental regulations. The costs due to environmental impacts, such as remediation, will have to be included in the cost analysis (in the form of decommissioning and land use costs). However, there may be impacts (such as on habitats or on human environments) and public perceptions that are not captured by the cost analysis. As examples, the following factors should be considered:

- What are the specific environmental regulations that apply to the different options?
- What are the agencies that are responsible for enforcing environmental regulations?
- Are there technical specialists available that understand the national environmental policy sufficiently to determine its impact on the different options?
- What is the public perception/acceptance of the different options from an environmental standpoint?
- Are there non-governmental organizations (NGOs) that may use the environmental impact as a tool to block any of the options?

4.7. REGIONAL AND INTERNATIONAL PARTNERSHIPS

Existing or planned regional and international partnerships can have a direct impact on the domestic resources and infrastructure required to implement individual options. Some partnerships can reduce the infrastructure needed for an option. For example, if the laws and regulations that affect nuclear and radiological activities are harmonized between two countries, then this lowers the barriers to implementing the respective option. This harmonization between markets can benefit technology suppliers and users and will likely require international licensing agreements; some agreements already exist, such as those reflected in international conventions, standards and guides. If there are existing institutional relationships between governments or between industries, this can also minimize the infrastructure needed to implement certain options. As examples, the following factors should be considered:

- Have regional and international arrangements been considered in terms of their impact on:
  - The institutional infrastructure?
  - The industrial infrastructure?
  - The social and political infrastructure?
  - The human resource requirements?
- Have the appropriate international norms and standards been adopted?
- Have laws, regulations and licensing structures been harmonized with the necessary regional and international partners?
- Has the host government entered into the appropriate regional and international partnerships that support the options?

5. DECISION-SUPPORT FRAMEWORK TOOLS

A key output of this CRP is a methodology comprising integrated decision-support and costing tools, to assist States in developing their RRSNF management strategies. Two electronic, Excel based, decision-support tools were developed: (a) Back end Research Reactor Integrated Decision making Evaluation (BRIDE), which includes the cost estimation comparative input module BASCET; and (b) a cost analysis tool, Fuel Cycle Cost Estimation for Research Reactors in Excel (FERREX). BRIDE allows

States to quantitatively compare the available technologies and thereby determine the best strategy for their situation, before FERREX is used to determine detailed cost estimates for the chosen strategy.

A tutorial with examples of the applications of these tools has been developed in a presentation format and is available for download.

5.1. OVERVIEW AND USE OF THE MODELS

BRIDE is a multiattribute utility methodology and can be used by a State to compare options for RRSNF disposal, combining non-economic factors with a cost estimate to determine the optimum option. It supports the two highlighted steps in the decision workflow shown in Fig. 25. The steps comprise screening of an initial scenario set to eliminate scenarios that are not viable and weighing the remaining scenarios against cost and several non-economic factors to arrive at a preferred scenario. BRIDE is structured such that the strengths and potential weaknesses of each scenario, along with measures that can remediate weaknesses, are identified during the evaluation.

Before the use of BRIDE and FERREX, users must identify all plausible RRSNF management strategies. From this group, the most relevant and feasible scenarios are selected for further evaluation. BRIDE and FERREX can be applied to any scenario, and may involve RRSNF storage, conditioning, reprocessing and disposal, as discussed in Section 3.

The BRIDE analysis is applied to the reduced set of scenarios. Comparative cost analyses are developed using BASCET and a group of State experts is convened for a structured discussion about costs and non-economic factors, as presented in Section 4.

The main purpose and objective of the FERREX model is to provide a bottom-up cost estimate and cost optimization for the preferred option for management of the back end of the RRSNF cycle, as identified by the BRIDE tool. The cost estimate from FERREX provides the total cost data for the preferred option in the standardized hierarchical structure of the International Structure for Spent Fuel Cycle Costing of Research Reactors (ISFC).

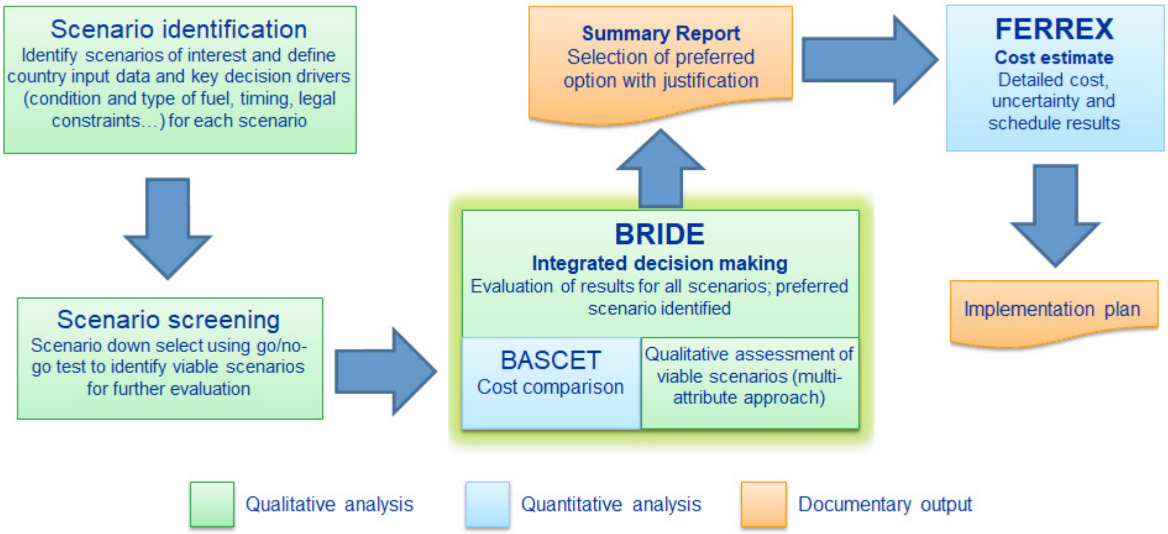


FIG. 25. Decision workflow for the back end of the RR fuel cycle.

5.2. BRIDE

BRIDE is an expert based evaluation. The selection and diversity of the experts are crucial to the quality of the results. The expert participants in this tool should be constructive and have relevant backgrounds, for example senior RR and SNF managers, strategy and funding decision makers, and regulators. The diversity of the expert panel will minimize any bias in the integration of the non-economic factors.

The most important product of a BRIDE analysis is likely to be the summary report of the participants' discussions during the BRIDE expert elicitation. Use of a qualified facilitator would optimize the benefit of this activity. While this publication focuses on the mechanics of the numerical scoring part of a BRIDE analysis, discussion points raised by the experts, such as strategies' strengths and weaknesses, are significant outcomes of the BRIDE workflow.

If a State is interested in applying this methodology, it is advised to contact the IAEA Research Reactor Section for assistance in the facilitation of the BRIDE tool. The following conditions will result in an optimal implementation:

- The State has a complete understanding and awareness of its responsibilities regarding RRSNF;
- The State has initiated or has decided to initiate an RRSNF management strategy;
- The State has the required legal and institutional infrastructure in place to make a decision regarding its RRSNF management strategy;
- The State has basic cost estimates for the RRSNF management steps.

The three parts of the BRIDE tool discussed here are scenario definition, application of BASCET to determine approximate scenario costs, and application of BRIDE to evaluate scenarios and arrive at a preferred scenario. BRIDE and the BASCET module are distributed in a single spreadsheet workbook. The full tutorial on BRIDE is available for download; Fig. 26 shows a simple flow chart of the tabs in the workbook and the inputs to each tab. As indicated in Fig. 25 above, the green tabs are part of the qualitative analysis and the blue tabs are the BASCET module (i.e. the quantitative analysis).

The BRIDE tool is set up in the tab 'FacilitatorPage', where the names and detailed descriptions of the scenarios to be considered are entered, as well as the number of experts participating in the analysis.

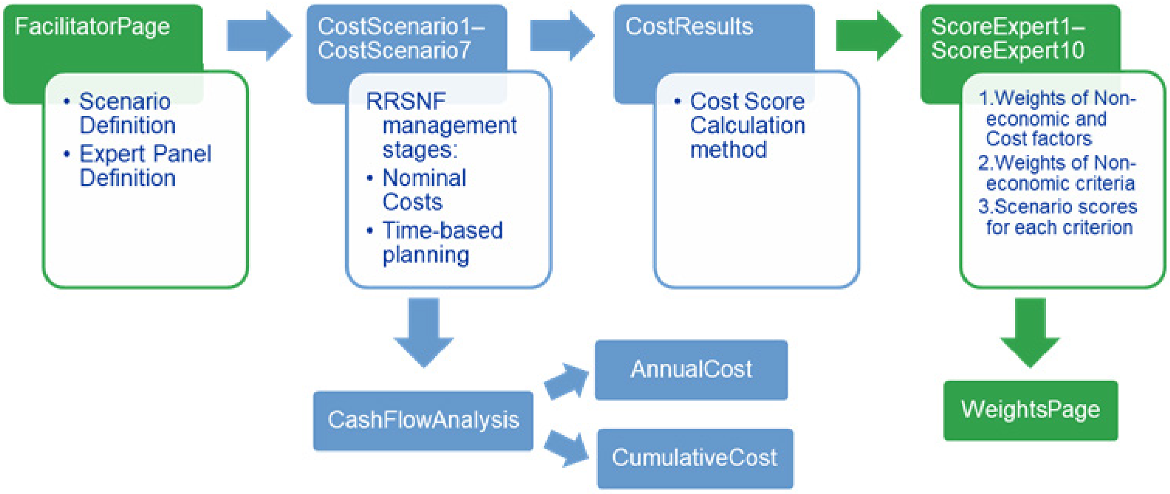


FIG. 26. Flow chart of the tabs and inputs for the BRIDE tool.

The cost and time planning estimates for each scenario are entered in the tabs 'CostScenario1' to 'CostScenario7'. The results of the cost comparison can be seen in the tabs 'CashFlowAnalysis', 'AnnualCost', 'CumulativeCost' and 'CostResults'.

The experts assign weights and scores to each scenario, which are input into each 'ScoreExpert' tab. The average of the experts' assigned weights is displayed in the 'WeightsPage' tab.

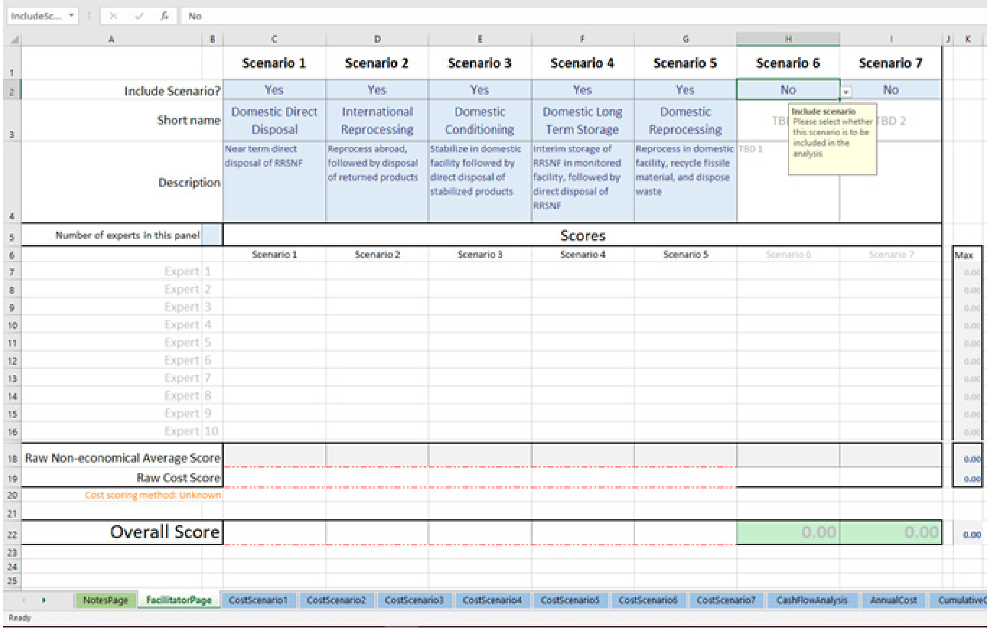
When all the inputs have been entered, the results of the BRIDE implementation and the preferred option are displayed back in the FacilitatorPage.

5.2.1. Scenario definition

BRIDE is currently configured to analyse up to five scenarios in parallel; more scenarios can be added, but adding scenarios increases the complexity of the comparison and analysis. BRIDE is distributed with five default scenarios already entered in the FacilitatorPage, as shown in Fig. 27. These default scenarios are illustrated in Fig. 28 and detailed in Table 5. Concise descriptions of the default scenarios are given, but these descriptions may be customized in the FacilitatorPage for a given Member State's situation.

As a first step, users of BRIDE must develop country-specific versions of these scenarios prior to discussion and analysis using the BRIDE methodology. This country-specific development process can involve the following:

- — Eliminating scenarios that are clearly not relevant;
- — Customizing relevant scenarios to account for country-specific elements (e.g. making a copy of a default scenario in order to allow comparison of two interim storage options);
- — Developing timelines and defining the basic characteristics of facilities and services that would be part of each relevant scenario;
- — Preparing cost data for each scenario (see the discussion on BASCET in Section 5.2.2).



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	
Include Scenario?	Yes	Yes	Yes	Yes	Yes	No	No	
Short name	Domestic Direct Disposal	International Reprocessing	Domestic Conditioning	Domestic Long Term Storage	Domestic Reprocessing	TB	TBD 2	
Description	Near term direct disposal of RRSNF	Reprocess abroad, followed by disposal of returned products	Stabilize in domestic facility followed by direct disposal of stabilized products	Interim storage of RRSNF in monitored facility, followed by direct disposal of RRSNF	Reprocess in domestic facility, recycle fissile material, and dispose waste	TBD 1		
Number of experts in this panel	Scores							
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Max
Expert 1								0.0
Expert 2								0.0
Expert 3								0.0
Expert 4								0.0
Expert 5								0.0
Expert 6								0.0
Expert 7								0.0
Expert 8								0.0
Expert 9								0.0
Expert 10								0.0
Raw Non-economical Average Score								0.00
Raw Cost Score								0.00
Cost scoring method: Unknown								
Overall Score						0.00	0.00	0.00

Include scenario
Please select whether this scenario is to be included in the analysis

FIG. 27. The BRIDE tool's FacilitatorPage tab showing the default inputs with which it is distributed.

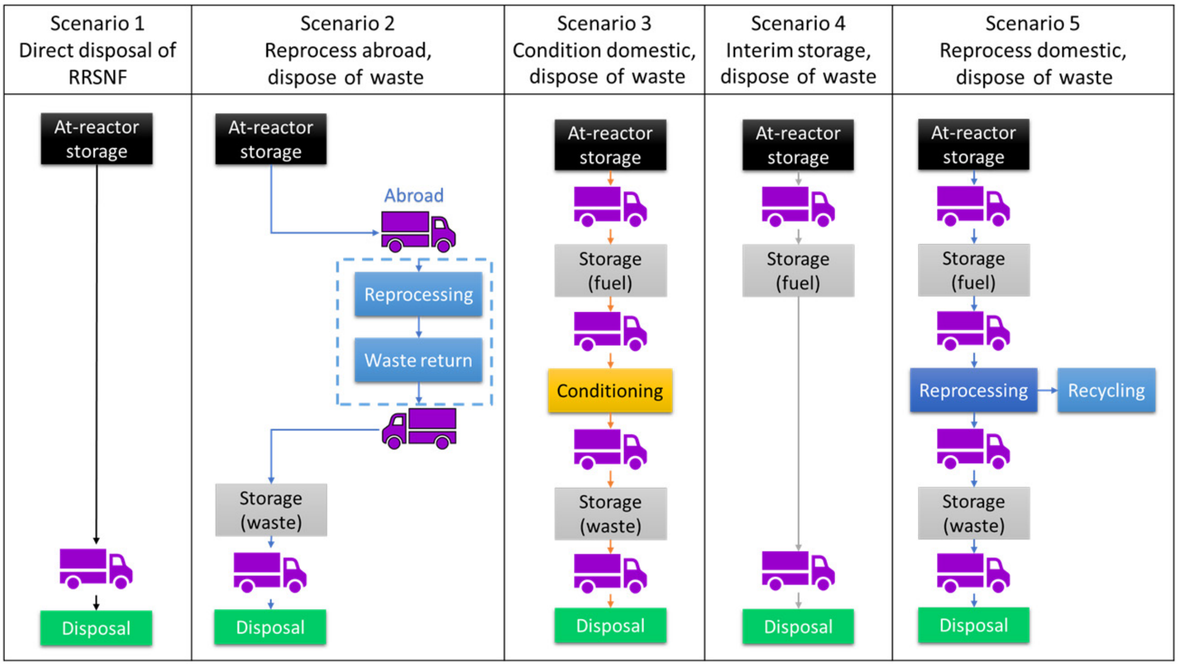


FIG. 28. Flow chart of default scenarios in BRIDE.

5.2.2. BASCET: cost analysis and tracking

This section describes the input and output for the BASCET module of the BRIDE screening and analysis tool. Developing a comparative cost estimate ahead of time will increase confidence in the selection of the preferred option. The values input into the example scenarios are for demonstration purposes only and do not necessarily correspond to actual costs. The cost information corresponding to each scenario in BASCET should be estimated and revised by experts as part of the scenario development. For detailed instructions on how to develop the input values for BASCET, refer to the tutorial presentation available for download.

The cost structures (e.g. facilities constructed, services purchased) defined in the BASCET module are shown in Fig. 29 and correspond to the management stages of the five default scenarios in Table 5. The cost analysis and tracking of the considered scenarios starts on the tabs ‘CostScenario1’ through ‘CostScenario7’ (see Fig. 26), where the estimated cost of each considered scenario is calculated. The input areas for a given scenario are shown in Fig. 29, divided into two input sections and one section for results. For a better visualization of results, all costs are by default considered in thousands of euros.

The first input section comprises the nominal and capital costs, in columns C, D and I, and the second input section comprises the time planning, in columns G, H and K. The cost categories are given as ‘Domestic’ and ‘International’, corresponding to costs incurred within the country and costs incurred with international contractors, respectively. At the bottom of both the Domestic and International categories are the total summations of both nominal and standard deviation.

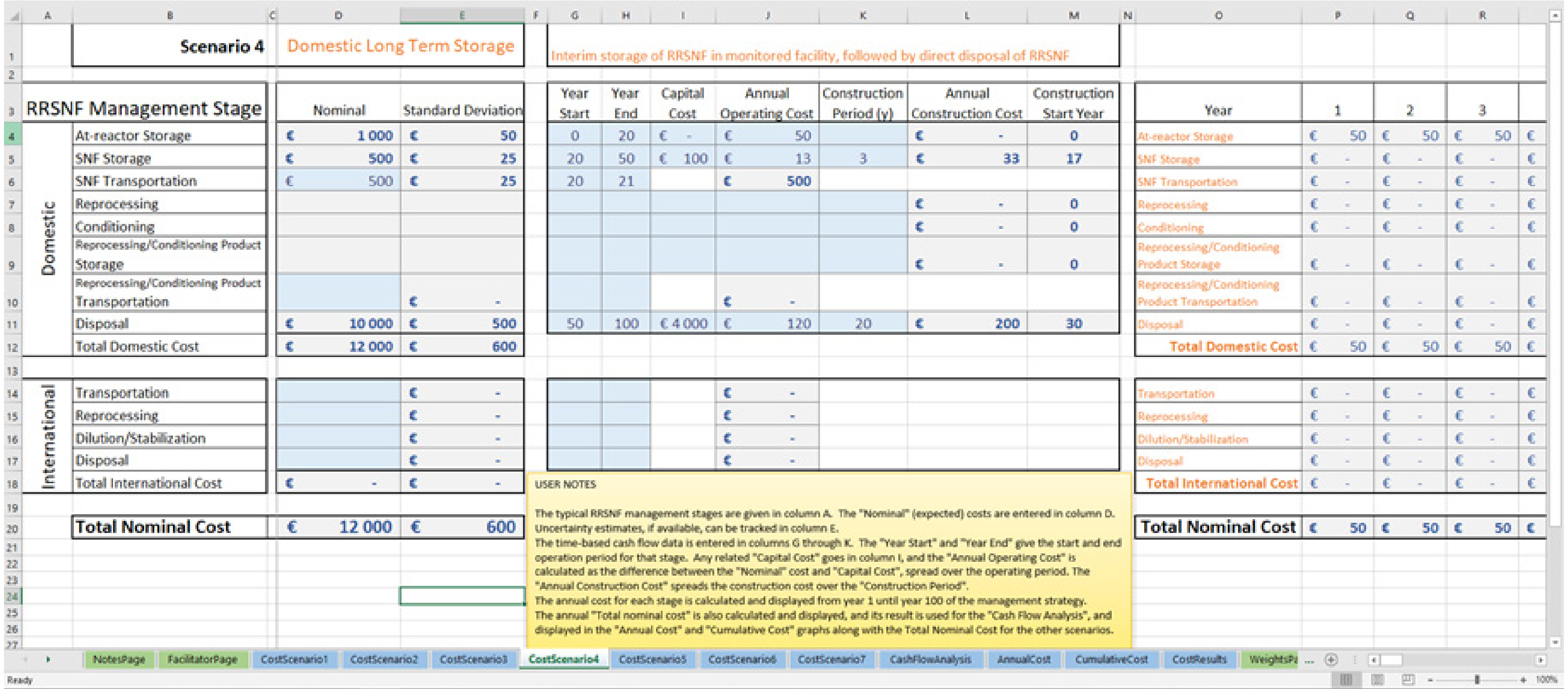
Domestic cost categories are:

- At-reactor Storage: storage of RRSNF at the reactor site;
- SNF Storage: storage at a non-reactor site in preparation for future steps;
- SNF Transportation: transportation from the reactor site to the interim site;
- Reprocessing: chemical treatment, potentially including reprocessing;
- Conditioning: dilution, stabilization or other physical treatment;

TABLE 5. DESCRIPTION OF DEFAULT SCENARIOS IN BRIDE

RRSNF management stages		Default BRIDE scenario				
		1 Direct disposal of RRSNF	2 Reprocess abroad, dispose of waste	3 Condition and stabilize domestically, dispose of waste	4 Interim storage, direct disposal of RRSNF	5 Reprocess domestically, dispose of waste
At-reactor storage		Yes	Yes	Yes	Yes	Yes
Transportation to storage		–	–	Yes	Yes	Yes
Storage (fuel)		–	–	Yes	Yes	Yes
Transportation to facility		–	Yes	Yes	–	Yes
Abroad	Reprocessing	–	Yes	–	–	–
	Waste return	–	Yes	–	–	–
Conditioning		–	–	Yes	–	–
Recycling		–	–	–	–	Yes
Transportation to storage		–	Yes	Yes	–	Yes
Storage (waste)		–	Yes	Yes	–	Yes
Transportation to disposal		Yes	Yes	Yes	Yes	Yes
Disposal		Yes	Yes	Yes	Yes	Yes
Scenario description		RRSNF remains at reactor site(s) until the repository is ready. RRSNF is directly disposed of without resorting to a storage facility.	Fuel is shipped abroad for reprocessing and waste is returned. Waste is placed in an appropriate storage facility until a repository is ready to receive it.	A conditioning and stabilization (physical transformation but not chemical separation of RRSNF) facility is built inside the country. RRSNF is conditioned at this facility and waste products are disposed of. Storage may be needed before and/or after conditioning.	A storage facility is constructed to store RRSNF once the reactor(s) are decommissioned and until an in-country RRSNF disposal facility is completed. May entail several decades of monitored storage.	A reprocessing facility is built inside the country. Fissile material recovered from RRSNF processed at this facility is recycled and waste disposed of. Storage may be needed before and/or after reprocessing.

–: Not applicable.



Scenario 4 | Domestic Long Term Storage | Interim storage of RRSNF in monitored facility, followed by direct disposal of RRSNF

	RRSNF Management Stage	Nominal	Standard Deviation	Year Start	Year End	Capital Cost	Annual Operating Cost	Construction Period (y)	Annual Construction Cost	Construction Start Year
Domestic	At-reactor Storage	€ 1 000	€ 50	0	20	€ -	€ 50		€ -	0
	SNF Storage	€ 500	€ 25	20	50	€ 100	€ 13	3	€ 33	17
	SNF Transportation	€ 500	€ 25	20	21		€ 500			
	Reprocessing								€ -	0
	Conditioning								€ -	0
	Reprocessing/Conditioning Product Storage								€ -	0
	Reprocessing/Conditioning Product Transportation		€ -				€ -			
	Disposal	€ 10 000	€ 500	50	100	€ 4 000	€ 120	20	€ 200	30
	Total Domestic Cost	€ 12 000	€ 600							
International	Transportation		€ -				€ -			
	Reprocessing		€ -				€ -			
	Dilution/Stabilization		€ -				€ -			
	Disposal		€ -				€ -			
	Total International Cost	€ -	€ -							
	Total Nominal Cost	€ 12 000	€ 600							

Year	1	2	3
At-reactor Storage	€ 50	€ 50	€ 50
SNF Storage	€ -	€ -	€ -
SNF Transportation	€ -	€ -	€ -
Reprocessing	€ -	€ -	€ -
Conditioning	€ -	€ -	€ -
Reprocessing/Conditioning Product Storage	€ -	€ -	€ -
Reprocessing/Conditioning Product Transportation	€ -	€ -	€ -
Disposal	€ -	€ -	€ -
Total Domestic Cost	€ 50	€ 50	€ 50
Transportation	€ -	€ -	€ -
Reprocessing	€ -	€ -	€ -
Dilution/Stabilization	€ -	€ -	€ -
Disposal	€ -	€ -	€ -
Total International Cost	€ -	€ -	€ -
Total Nominal Cost	€ 50	€ 50	€ 50

USER NOTES

The typical RRSNF management stages are given in column A. The "Nominal" (expected) costs are entered in column D. Uncertainty estimates, if available, can be tracked in column E.
The time-based cash flow data is entered in columns G through K. The "Year Start" and "Year End" give the start and end operation period for that stage. Any related "Capital Cost" goes in column I, and the "Annual Operating Cost" is calculated as the difference between the "Nominal" cost and "Capital Cost", spread over the operating period. The "Annual Construction Cost" spreads the construction cost over the "Construction Period".
The annual cost for each stage is calculated and displayed from year 1 until year 100 of the management strategy.
The annual "Total nominal cost" is also calculated and displayed, and its result is used for the "Cash Flow Analysis", and displayed in the "Annual Cost" and "Cumulative Cost" graphs along with the Total Nominal Cost for the other scenarios.

FIG. 29. Input areas for scenario cost estimates in the BASCET module of BRIDE.

- Reprocessing/Conditioning Product Storage: storage of reprocessed or conditioned material in preparation for future steps;
- Reprocessing/Conditioning Product Transportation: transportation from the treatment facility to the storage site;
- Disposal: final disposal of the material, including transportation.

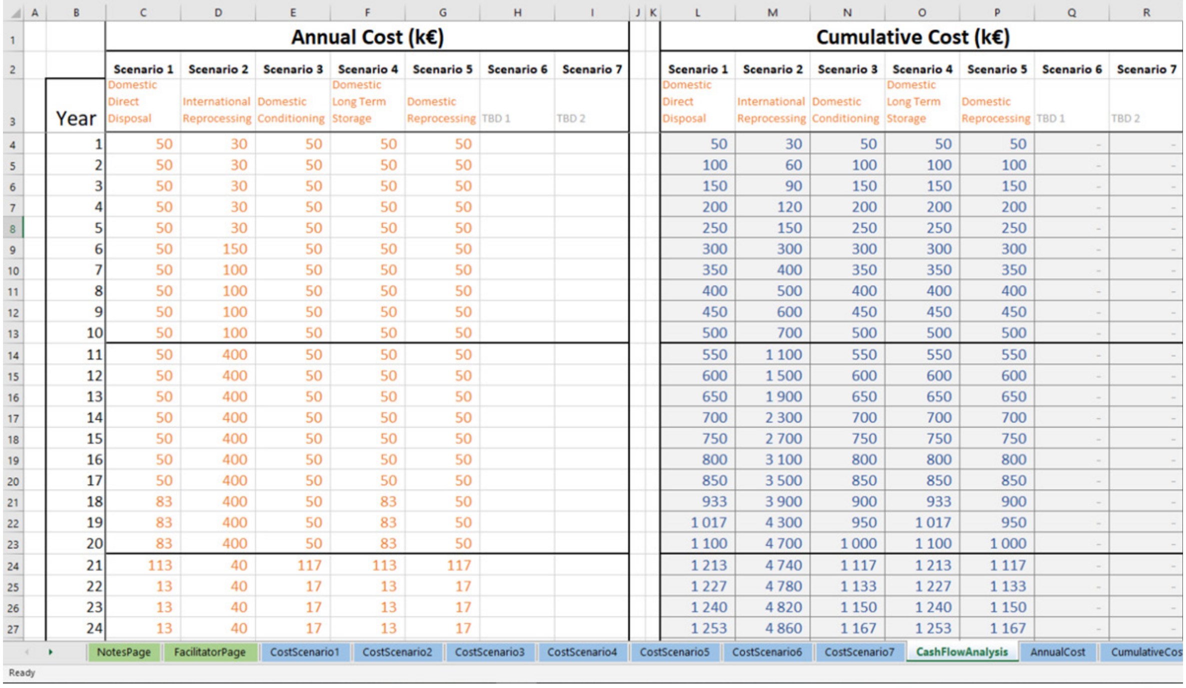
International cost categories are:

- Transportation: transportation from a domestic storage site to the contractor site;
- Reprocessing: service cost of reprocessing;
- Dilution/Stabilization: service cost of dilution/stabilization;
- Disposal: service cost of disposal of negotiated material.

In the time planning input section, the ‘Year Start’ column gives the year of the initial cost incurred for the cost category in that row. This table uses the convention of ‘end of year’. For example, a process that begins now (or continues from the past) and runs for five years into the future would be entered as starting at year 0 and ending at year 5. As a result of the time planning, the yearly costs that will be incurred, per cost category, for the next 100 years are automatically calculated and displayed in the section for results, from column O to column DK. Figure 29 shows only three years of annual costs for clarity.

The timeline information for each scenario is automatically transferred to the CashFlowAnalysis tab, as shown in Fig. 30, for a total of 100 years; for clarity, Fig. 30 shows only the years up to year 25.

The CashFlowAnalysis tab shows two tables. The table on the left, Annual Cost, pulls the total annual cost (columns O–DK) from each CostScenario tab, resulting from the timeline definition. The table on the right calculates the cumulative cost that will have been incurred by the end of each year. These two tables are then plotted in the AnnualCost and CumulativeCost tabs, respectively (Figs 31 and 32).



Annual Cost (k€)

Year	Scenario 1 Domestic Direct Disposal	Scenario 2 International Reprocessing	Scenario 3 Domestic Conditioning	Scenario 4 Domestic Long Term Storage	Scenario 5 Domestic Reprocessing	Scenario 6 TBD 1	Scenario 7 TBD 2
1	50	30	50	50	50		
2	50	30	50	50	50		
3	50	30	50	50	50		
4	50	30	50	50	50		
5	50	30	50	50	50		
6	50	150	50	50	50		
7	50	100	50	50	50		
8	50	100	50	50	50		
9	50	100	50	50	50		
10	50	100	50	50	50		
11	50	400	50	50	50		
12	50	400	50	50	50		
13	50	400	50	50	50		
14	50	400	50	50	50		
15	50	400	50	50	50		
16	50	400	50	50	50		
17	50	400	50	50	50		
18	83	400	50	83	50		
19	83	400	50	83	50		
20	83	400	50	83	50		
21	113	40	117	113	117		
22	13	40	17	13	17		
23	13	40	17	13	17		
24	13	40	17	13	17		

Cumulative Cost (k€)

Scenario 1 Domestic Direct Disposal	Scenario 2 International Reprocessing	Scenario 3 Domestic Conditioning	Scenario 4 Domestic Long Term Storage	Scenario 5 Domestic Reprocessing	Scenario 6 TBD 1	Scenario 7 TBD 2
50	30	50	50	50	-	-
100	60	100	100	100	-	-
150	90	150	150	150	-	-
200	120	200	200	200	-	-
250	150	250	250	250	-	-
300	300	300	300	300	-	-
350	400	350	350	350	-	-
400	500	400	400	400	-	-
450	600	450	450	450	-	-
500	700	500	500	500	-	-
550	1 100	550	550	550	-	-
600	1 500	600	600	600	-	-
650	1 900	650	650	650	-	-
700	2 300	700	700	700	-	-
750	2 700	750	750	750	-	-
800	3 100	800	800	800	-	-
850	3 500	850	850	850	-	-
933	3 900	900	933	900	-	-
1 017	4 300	950	1 017	950	-	-
1 100	4 700	1 000	1 100	1 000	-	-
1 213	4 740	1 117	1 213	1 117	-	-
1 227	4 780	1 133	1 227	1 133	-	-
1 240	4 820	1 150	1 240	1 150	-	-
1 253	4 860	1 167	1 253	1 167	-	-

FIG. 30. *The CashFlowAnalysis tab in the BASCET module.*

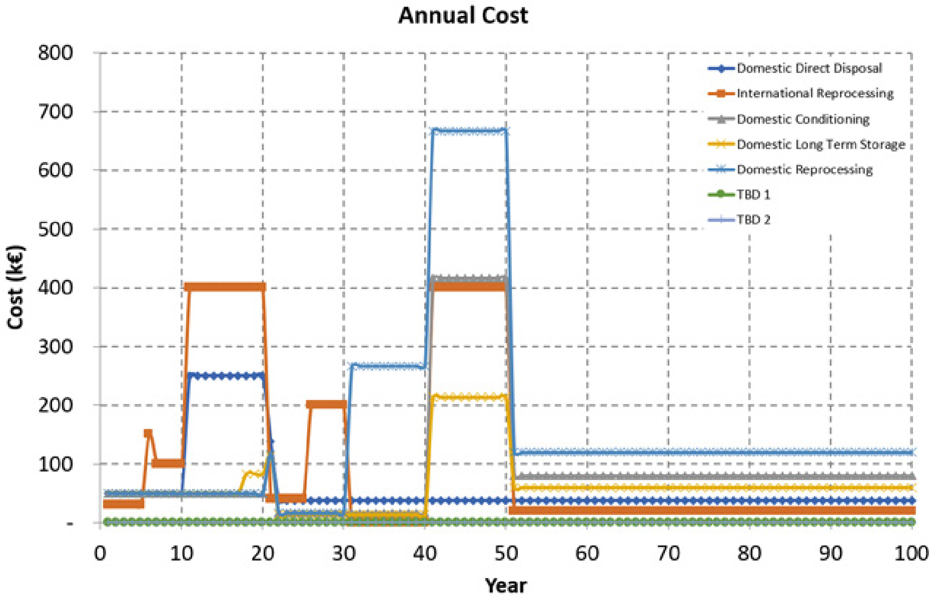


FIG. 31. AnnualCost tab in the BASCET module.

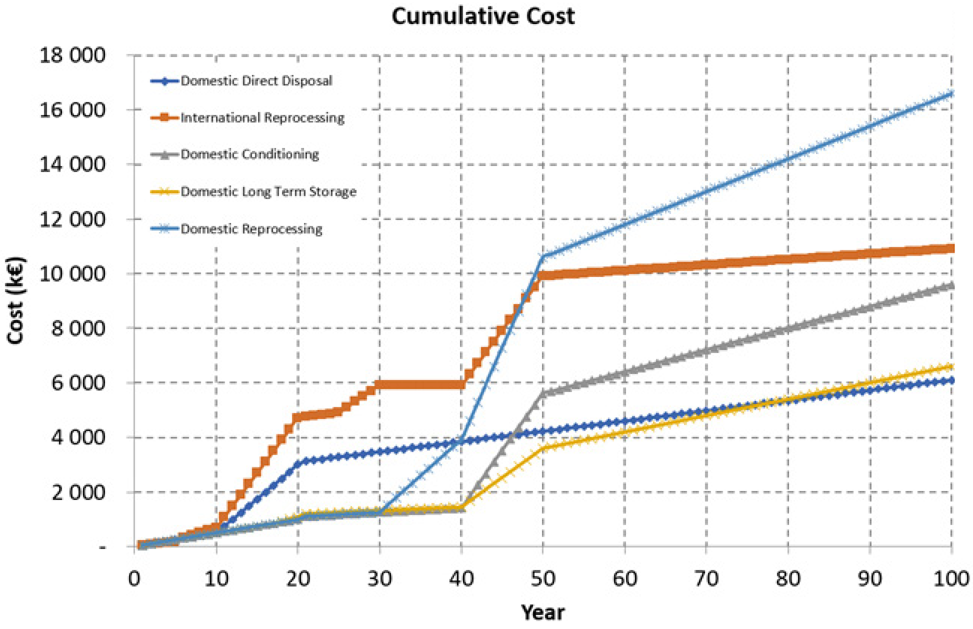


FIG. 32. CumulativeCost tab in the BASCET module.

The CostResults tab pulls the total nominal costs for each scenario and compares them numerically using a 1–10 score. Two types of scoring methods are available for this comparison: linear or logarithmic. In both methods, the least expensive scenario is assigned the best 'Cost Score', 10, and the most expensive scenario is assigned the worst Cost Score, 1. To determine the Cost Score of the remaining scenarios, a linear or logarithmic interpolation is automatically made. The order of the scores is identical in the two methods, but the logarithmic option provides more separation between the cheaper scenarios and the high cost scenarios. This method is particularly useful when there is an option that stands out of the range of the others. For example, in Fig. 33 there is a scenario that is significantly more expensive than the other three; the distinction between the 'cheap' scenarios is better in the logarithmic scoring than in the linear scoring.

5.2.3. Scenario analysis and comparison

This section describes a summary of the BRIDE analysis involving the expert panel. Detailed instructions on how each input is entered into the corresponding tab are found in the tutorial presentation available for download.

Each of the experts on the panel should have an 'Expert Scoring Handout', which is also available for download. With the facilitator's guidance, experts assign weights and scores.

5.2.3.1. Weight assignment

First, each expert assigns the weight of the non-economic factors against the cost factor. The heaviest factor (either cost or non-economic) is assigned a weight of 10, representing the biggest impact on the decision. The other factor is assigned a weight relative to the heaviest. For example, weight assignments of 10 and 5 would indicate that one of the factors (weight of 5) has half as much impact on the decision as the other (weight of 10).

Second, setting the cost factor aside, each expert assigns the weight of each non-economic criterion (described in Section 4) against the other non-economic criteria. The heaviest non-economic criterion (i.e. the criterion with the highest priority) is assigned a weight of 10. The remaining criteria are assigned weights from 0 to 10, relative to the heaviest. For example, the weight assignment in Fig. 34 indicates that the most influential criterion is 'Environmental Impact'. The 'Regional and International Partnerships' and 'Public Acceptance' criteria have equal impact on the decision (receiving the same weight of 7), but are not as important as 'Political Support' (receiving a weight of 9).

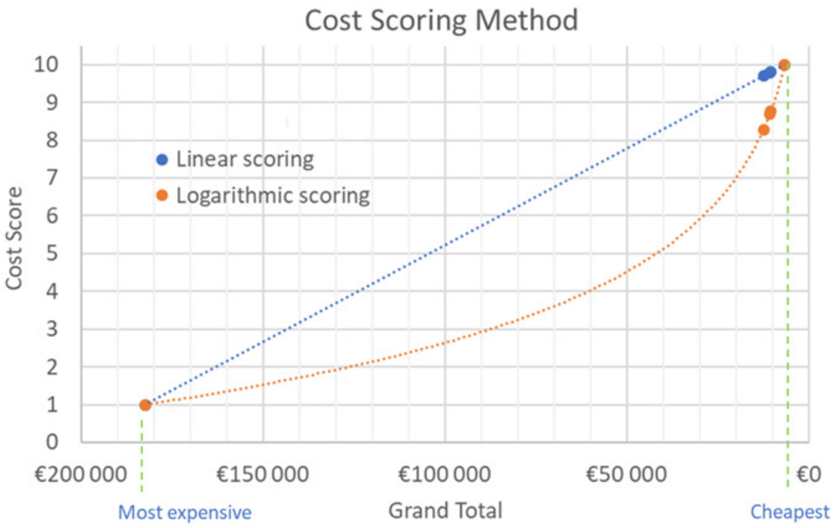
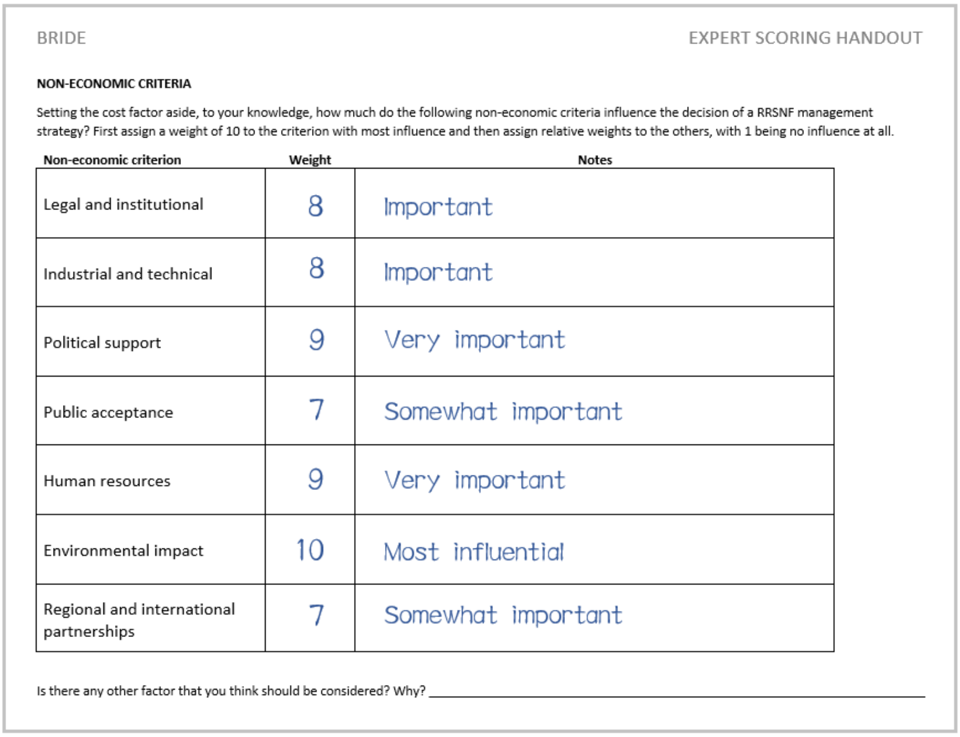


FIG. 33. The two options for cost scoring in the BASCET module: linear and logarithmic.



BRIDE EXPERT SCORING HANDOUT

NON-ECONOMIC CRITERIA

Setting the cost factor aside, to your knowledge, how much do the following non-economic criteria influence the decision of a RRSNF management strategy? First assign a weight of 10 to the criterion with most influence and then assign relative weights to the others, with 1 being no influence at all.

Non-economic criterion	Weight	Notes
Legal and institutional	8	Important
Industrial and technical	8	Important
Political support	9	Very important
Public acceptance	7	Somewhat important
Human resources	9	Very important
Environmental impact	10	Most influential
Regional and international partnerships	7	Somewhat important

Is there any other factor that you think should be considered? Why? ____________

FIG. 34. Expert Scoring Handout page 2, showing an example of weight assignments for non-economic criteria.

The Expert Scoring Handout includes a space for each participant to take notes, since recording the observations of, and discussions between, participants during this weighting exercise is crucial to BRIDE implementation.

When the weight assignments of all the experts on the panel have been entered into the BRIDE tool, the WeightsPage tab displays the average of these values (Fig. 35). The averaged weights thus represent the expert panel's opinion as a group and are used for the calculation of the final results.

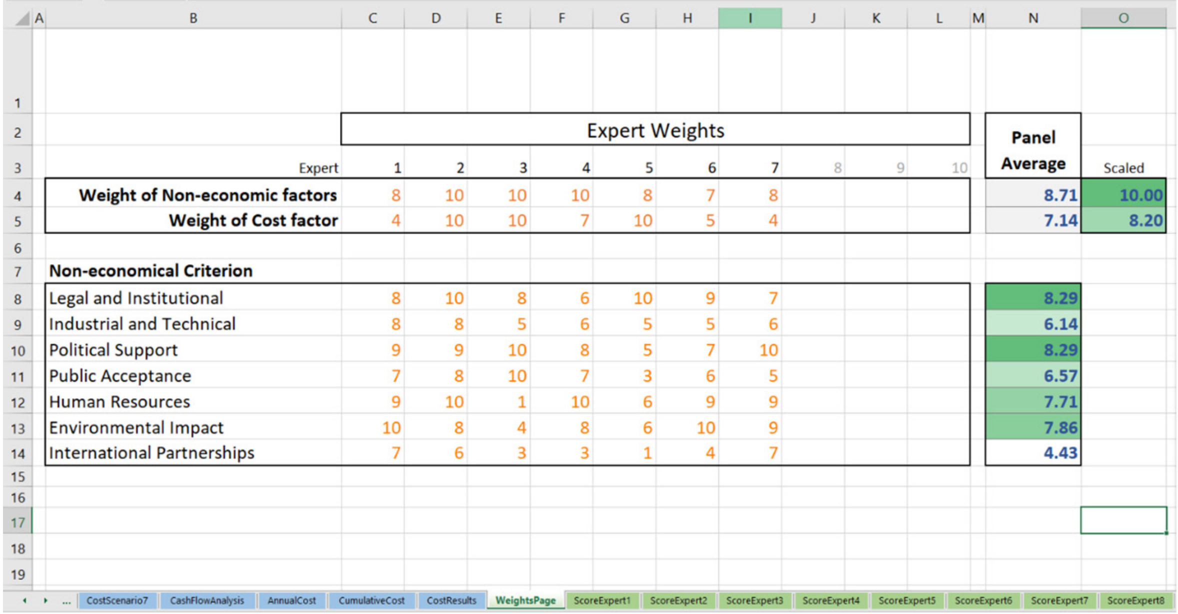
For the weight of the non-economic factor compared with the cost factor, the panel's average is scaled: the factor with the highest averaged value is assigned a scaled weight of 10. The other factor is linearly fit relative to a 1–10 scale, following a simple cross-multiplication.

In the example shown in Fig. 35, the panel considers that the factor with more weight is the non-economic factor, which has an averaged weight of 8.71. This is assigned a scaled weight of 10, representing that this is the most important factor in the decision. Then, the panel's average cost factor weight of 7.14 is scaled relative to the other one, following a simple cross-multiplication:

$$\frac{10}{8.71} = \frac{\text{Scaled Weight}}{7.14}$$

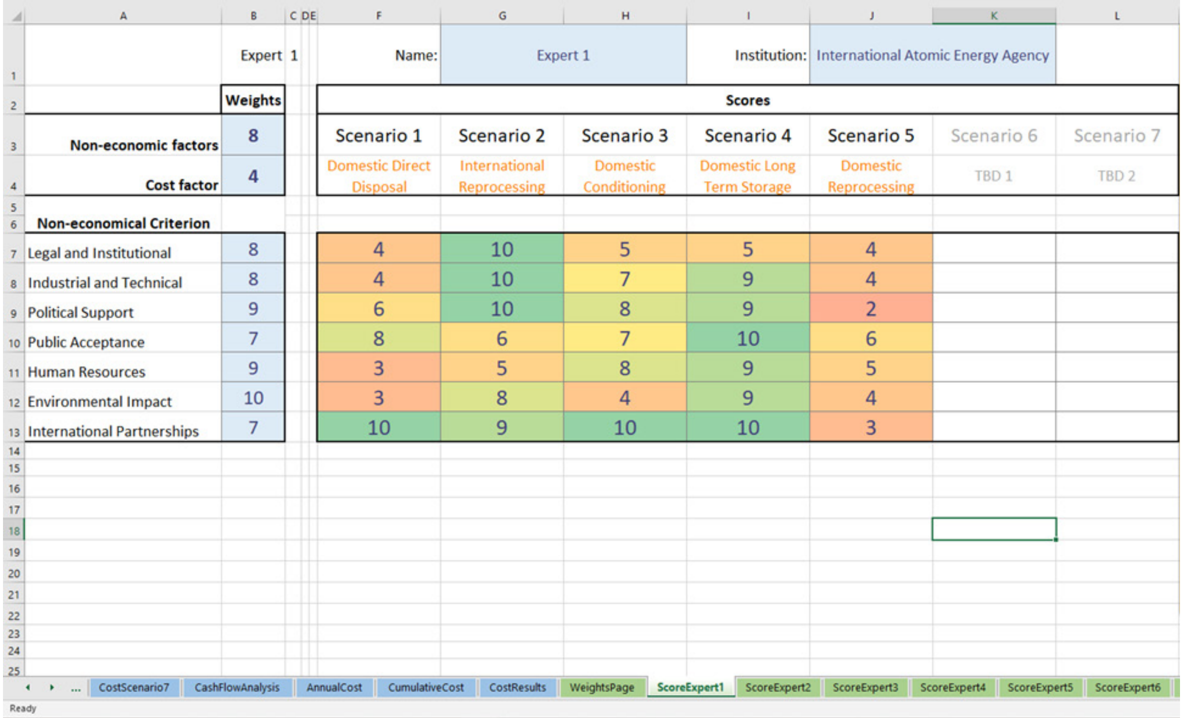
5.2.3.2. Score assignment

Setting the prioritization of non-economic factors aside, each expert assigns a score to each non-economic criterion for each scenario. The sets of questions in Section 4 may be used as a guide to help assign the scores for each criterion. The scores are first written in the Expert Scoring Handout, and then after discussion and exchange of key ideas they are entered into the BRIDE tool, as shown in Fig. 36.



	Expert Weights										Panel Average	Scaled
Expert	1	2	3	4	5	6	7	8	9	10		
Weight of Non-economic factors	8	10	10	10	8	7	8				8.71	10.00
Weight of Cost factor	4	10	10	7	10	5	4				7.14	8.20
Non-economical Criterion												
Legal and Institutional	8	10	8	6	10	9	7				8.29	
Industrial and Technical	8	8	5	6	5	5	6				6.14	
Political Support	9	9	10	8	5	7	10				8.29	
Public Acceptance	7	8	10	7	3	6	5				6.57	
Human Resources	9	10	1	10	6	9	9				7.71	
Environmental Impact	10	8	4	8	6	10	9				7.86	
International Partnerships	7	6	3	3	1	4	7				4.43	

FIG. 35. WeightsPage tab, showing the individual experts' weight assignments and the panel average.



Expert 1 Name: Expert 1 Institution: International Atomic Energy Agency

	Weights	Scores						
		Scenario 1 Domestic Direct Disposal	Scenario 2 International Reprocessing	Scenario 3 Domestic Conditioning	Scenario 4 Domestic Long Term Storage	Scenario 5 Domestic Reprocessing	Scenario 6 TBD 1	Scenario 7 TBD 2
Non-economic factors	8							
Cost factor	4							
Non-economical Criterion								
Legal and Institutional	8	4	10	5	5	4		
Industrial and Technical	8	4	10	7	9	4		
Political Support	9	6	10	8	9	2		
Public Acceptance	7	8	6	7	10	6		
Human Resources	9	3	5	8	9	5		
Environmental Impact	10	3	8	4	9	4		
International Partnerships	7	10	9	10	10	3		

FIG. 36. ScoreExpert1 input tab, showing the expert's assigned weights on the left and scores on the right.

It is important that in the scoring exercise, each expert considers both vertical comparison (all factors within one scenario) and horizontal comparison (one factor among all scenarios).

When scores are entered in the BRIDE tool, the colour code will identify the highest scores in green and the lowest scores in red, enabling a visual interpretation of any given expert's scoring. For example, in Fig. 36 a preference for scenario 4 may be visually inferred from the majority of green cells, indicating high scores.

After scores have been entered by all the experts on the panel, discussions and observations may lead to revision and refinement of the scoring, and experts may wish to change their scores and weights before displaying the final results.

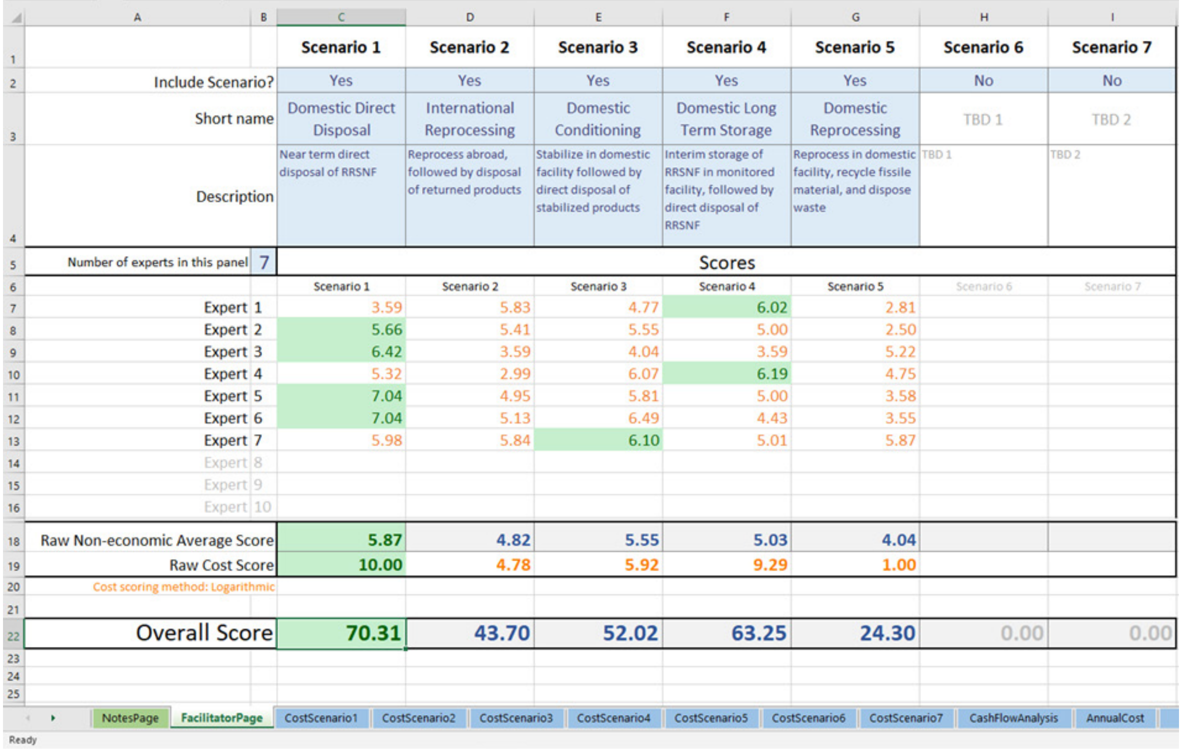
5.2.4. Results of BRIDE implementation

For each expert, each scenario's scores are pulled from the ScoreExpert tab and weighted against the panel average for each non-economic criterion, and then normalized to 10 according to the following formula:

$$\text{Raw Score} = \frac{\sum_j \text{Score of Criterion}_j \times \text{ Panel Average for Criterion}_j}{7 \text{ criteria } \times 10}$$

The results of the raw score are given for each expert for each scenario in rows 7–16 of the FacilitatorPage (Fig. 37). These weighted scores are averaged over the scores of the expert panel to obtain the 'raw non-economic average score' for each scenario, displayed in row 18.

Row 19 pulls the cost scores calculated by the linear or logarithmic scoring methods, described in Section 5.2.2.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Include Scenario?	Yes	Yes	Yes	Yes	Yes	No	No
Short name	Domestic Direct Disposal	International Reprocessing	Domestic Conditioning	Domestic Long Term Storage	Domestic Reprocessing	TBD 1	TBD 2
Description	Near term direct disposal of RRSNF	Reprocess abroad, followed by disposal of returned products	Stabilize in domestic facility followed by direct disposal of stabilized products	Interim storage of RRSNF in monitored facility, followed by direct disposal of RRSNF	Reprocess in domestic facility, recycle fissile material, and dispose waste	TBD 1	TBD 2
Number of experts in this panel 7	Scores						
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Expert 1	3.59	5.83	4.77	6.02	2.81		
Expert 2	5.66	5.41	5.55	5.00	2.50		
Expert 3	6.42	3.59	4.04	3.59	5.22		
Expert 4	5.32	2.99	6.07	6.19	4.75		
Expert 5	7.04	4.95	5.81	5.00	3.58		
Expert 6	7.04	5.13	6.49	4.43	3.55		
Expert 7	5.98	5.84	6.10	5.01	5.87		
Expert 8							
Expert 9							
Expert 10							
Raw Non-economic Average Score	5.87	4.82	5.55	5.03	4.04		
Raw Cost Score	10.00	4.78	5.92	9.29	1.00		
Cost scoring method: Logarithmic							
Overall Score	70.31	43.70	52.02	63.25	24.30	0.00	0.00

FIG. 37. FacilitatorPage tab displaying final results and preferred option.

Finally, the raw non-economic average score for each scenario is weighted against the non-economic factor weight, added to the raw cost score weighted against the cost factor weight, and divided by the number of factors (two: the non-economic factor and the cost factor):

$$\text{Overall Score} = \frac{\left(\text{Raw non-economic score} \times \text{weight of non-economic}\right) + \left(\text{Raw cost score} \times \text{weight of cost}\right)}{2}$$

The ‘overall score’ for each scenario is displayed in row 22. The highest possible overall score is 100, and the green cell in this row highlights the scenario with the highest score (i.e. the preferred option). This is the final result and completes the BRIDE analysis.

5.3. FERREX

FERREX is a detailed costing tool for estimating spent fuel management costs from the bottom up, including such attributes as variable labour rates, time delays in performing the work and inflation rates. The FERREX model is based on CERREX [55], which was developed by IAEA Member States to assist with decommissioning cost estimations [56, 57].

5.3.1. Introduction to ISFC structure

The International Structure for Decommissioning Costing of Nuclear Installations (ISDC) is recommended by the Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency (OECD/NEA), the IAEA and the European Commission as a standardized structure for the calculation and presentation of the results for decommissioning costing projects [58]. For this CRP, the International Structure for Spent Fuel Cycle Costing of Research Reactors (ISFC) was developed and represents an analogy to the ISDC. It should be used like the ISDC general platform to provide a standardized structure, integrating typical activities for the relevant RRSNF strategies or options to be included in the costing project.

The back end of the RR fuel cycle activities identified in the ISFC is structured hierarchically into three levels, with the first and second levels being aggregates of the activities in the third level (see Fig. 38). The advantages of using the standardized ISFC structure are primarily that it includes a systematic checklist of activities, offers a common understanding of cost items and a tool for comparison, and provides consistency of results.

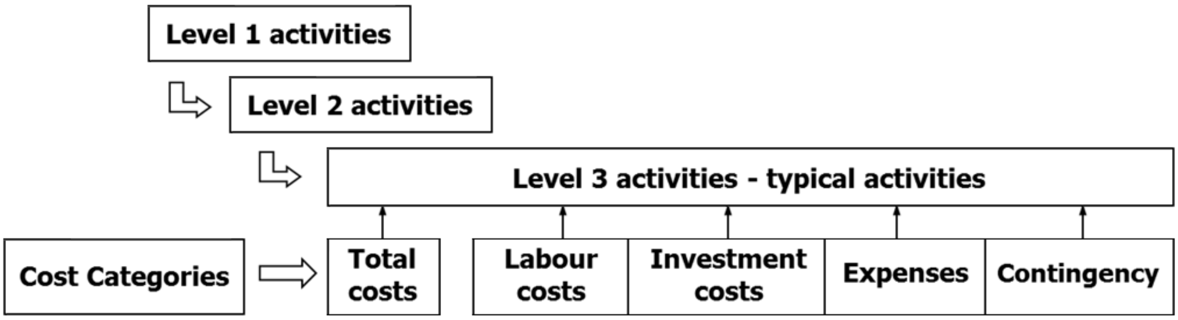


FIG. 38. Structure of ISFC showing cost categories.

Moreover, activities lower than a Level 3 in the ISFC system can be modified by the user, based on the required level of detail of each project. At Level 1, 11 principal activities are identified as follows:

(1) Preparation of spent fuel management options;
(2) Spent fuel management activities at the reactor building;
(3) Long term storage activities;
(4) Spent fuel return programmes;
(5) Spent fuel reprocessing;
(6) Spent fuel conditioning;
(7) Disposal of the spent fuel and/or fuel related radioactive waste;
(8) Packaging and transport of spent fuel and/or fuel related radioactive waste;
(9) Management and support activities;
(10) Research and development;
(11) Miscellaneous costs.

The calculated costs associated with each ISFC activity are subdivided according to the four cost categories in place in the ISDC [58]:

- Labour costs, which include all payments to employees, for example, social security, health insurance and overheads;
- Investment costs, which include capital, equipment and material costs;
- Expenses, which include all payments related to spent fuel management activities, not identified as labour and investment costs, for example, consumables, spare parts, electricity costs, insurances, taxes and authorizations;
- Contingency, which provides flexibility for cost fluctuations and unanticipated costs within the scope of the costing project.

5.3.2. FERREX model

The cost estimating principles for FERREX are:

- A bottom-up approach, which collects the data at the level of elementary activities. This approach applies the principle that the project is divided into discrete and measurable units of work activities (e.g. time based or activity based).
- Use of defined cost categories (i.e. labour costs, investments, expenses and contingency) as defined in Section 5.3.1.
- Costs are calculated for elementary activities as follows:
    - Inventory dependent costs, associated mainly with the number of fuel assemblies and related to for example, fuel assembly characterization, storage, stabilization, reprocessing or disposal;
    - Time dependent costs, associated with the duration of the activity, as well as the composition of the relevant workgroup, (e.g. management and support activities, safety, security and quality assurance);
    - Fixed costs occurring once in the lifetime of a project (e.g. capital procurement, design and engineering, permits, external services and consultancies);
    - Contingency costs (i.e. a percentage assigned to each elementary activity based on previous costing experience).

5.3.3. Input data for FERREX

FERREX is initiated through the input of data, which are divided into two groups:

- RRSNF inventory, including the number of fuel assemblies and their characteristics;
- Calculation parameters:
  - Unit factors: workforce (staff hours per unit), investments and expenses (costs per unit). The unit factors are defined for the various activities (according to ISFC categories) that are relevant to the scenario being estimated. The unit factors are key inputs for calculation of inventory dependent activities;
  - Inputs for time dependent activities: duration of the activity and composition of the workgroup;
  - Fixed or time dependent investments or expenses;
  - Contingencies;
  - General calculation parameters (e.g. labour rates, level of overheads, currency, working hours per day, week and year).

For detailed instructions on how to define and input these parameters into the three ISFC levels of the FERREX tool, please refer to the tutorial presentation available for download.

5.3.4. Output data from the FERREX model

The following outputs are available for the user in the FERREX model for further management, analysis and optimization of the back end of RR fuel cycle management options and strategies:

- Tables presenting the total values of costs and required workforce for the activities defined in ISFC Level 3, Level 2 (aggregating the results from Level 3) and Level 1 (aggregating the results from Level 2);
- Schedule of annual activities by cost;
- Cash flow data, distributed on a yearly scale for the whole duration of the spent fuel management project.

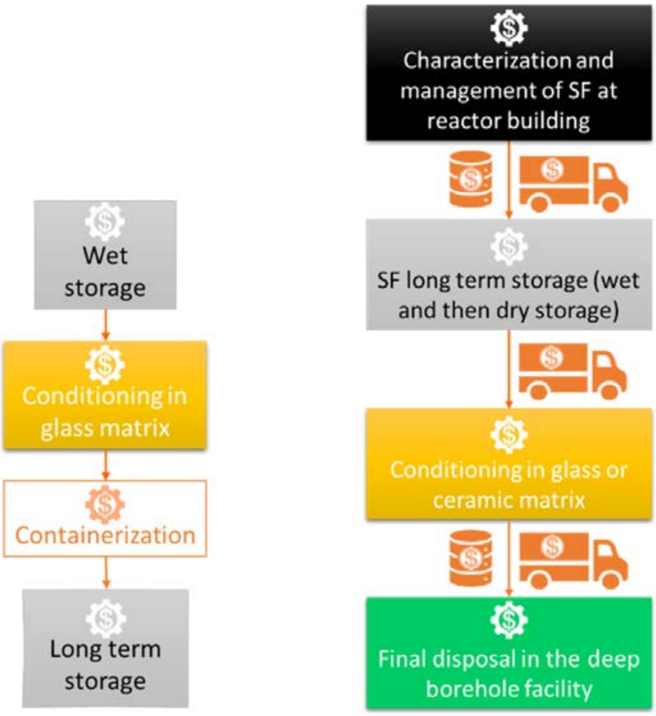
5.3.5. FERREX case study — Malaysia

The Malaysian Nuclear Agency used FERREX to estimate the cost of a preferred scenario — disposal in a borehole —for disused sealed radioactive sources. For this case study, hypothetical deep geological borehole disposal is chosen as the final destination of the fuels. The associated activities were conditioning, packaging, transportation and disposal. It is assumed that 130 fuel canisters are generated from the conditioning of spent fuel using glass or a glass ceramic matrix.

Two estimates for this scenario were generated: (1) a process comprising wet storage, conditioning and stabilization in a glass matrix, containerization and long term storage (Fig. 39 (a)); and (2) an extended process including the additional steps of characterization, fuel management at the reactor building and final disposal. Figure 39 (b) depicts the process steps for the second scenario.

The conditions or assumptions adopted in this cost estimation are as follows:

- Some of the equipment required for the handling of the spent fuel has already been procured and the equipment is fully operable. Therefore, the cost of this equipment is not included in the cost estimates. Examples of this equipment include the transfer cask, underwater fuel surveillance equipment and plasma rig.
- The spent fuel pool storage facility is in operation and the cost of its development is also not included in the total estimates.
- Although FERREX allows for three levels of data input, the Malaysian costs are populated only at Levels 1 and 2.



(a) (b)

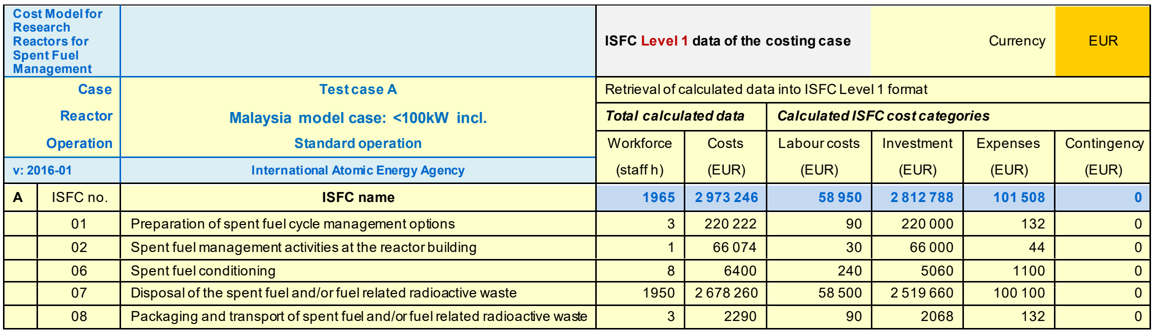
FIG. 39. Stages in the preferred scenario for (a) the first and (b) second cost estimation.

As depicted in Fig. 40, for the first estimate only five out of eleven Level 1 cost elements were filled in the FERREX spreadsheet, resulting in an estimate of €2.97 million. The details for each cost element are presented in Fig. 41, representing the Level 3 data. It should be noted that the costs for siting and construction of the geological disposal facility are not incorporated into this estimate due to unavailability of data.

For the second estimate, the following additional cost elements were introduced:

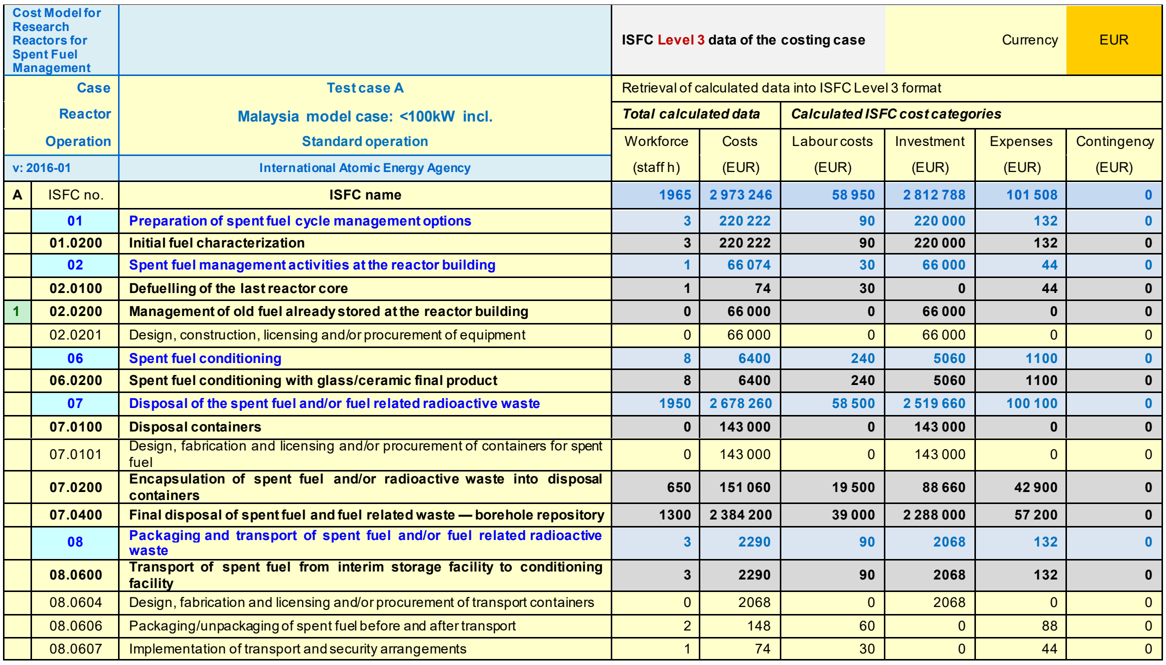
- Long term storage activities;
- Design and siting of repository (borehole);
- Construction and licensing of repository;
- Operation of repository — disposal of spent fuel;
- Relevant transport elements;
- Management and support activities.

The second cost estimate was €26.3 million. Figures 42 and 43 depict Level 1 and Level 3 revised cost data, respectively.



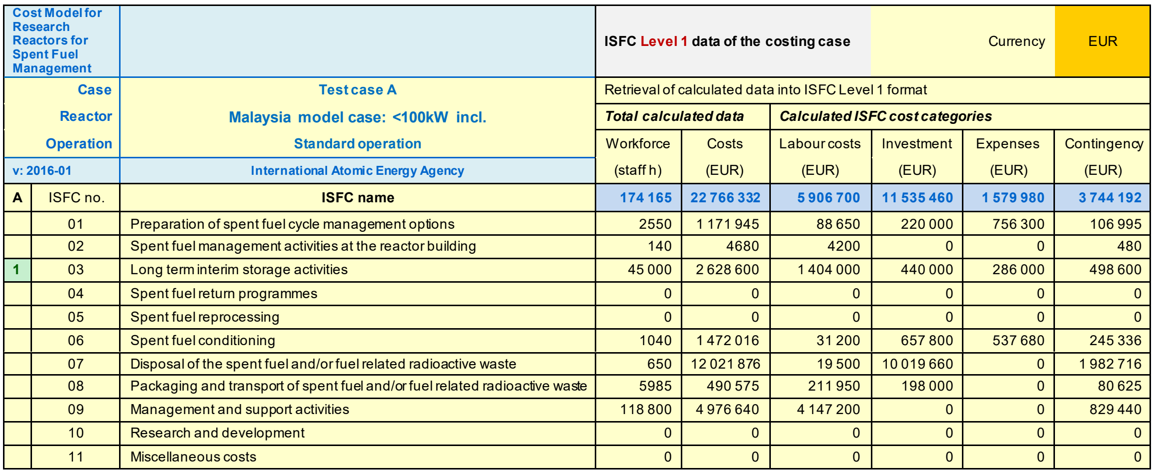
Cost Model for Research Reactors for Spent Fuel Management			ISFC Level 1 data of the costing case				Currency	EUR
Case		Test case A	Retrieval of calculated data into ISFC Level 1 format					
Reactor		Malaysia model case: <100kW incl.	Total calculated data		Calculated ISFC cost categories			
Operation		Standard operation	Workforce	Costs	Labour costs	Investment	Expenses	Contingency
v: 2016-01		International Atomic Energy Agency	(staff h)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)
A	ISFC no.	ISFC name	1965	2 973 246	58 950	2 812 788	101 508	0
	01	Preparation of spent fuel cycle management options	3	220 222	90	220 000	132	0
	02	Spent fuel management activities at the reactor building	1	66 074	30	66 000	44	0
	06	Spent fuel conditioning	8	6400	240	5060	1100	0
	07	Disposal of the spent fuel and/or fuel related radioactive waste	1950	2 678 260	58 500	2 519 660	100 100	0
	08	Packaging and transport of spent fuel and/or fuel related radioactive waste	3	2290	90	2068	132	0

FIG. 40. Summary of the FERREX Level 1 results for the first cost estimation.



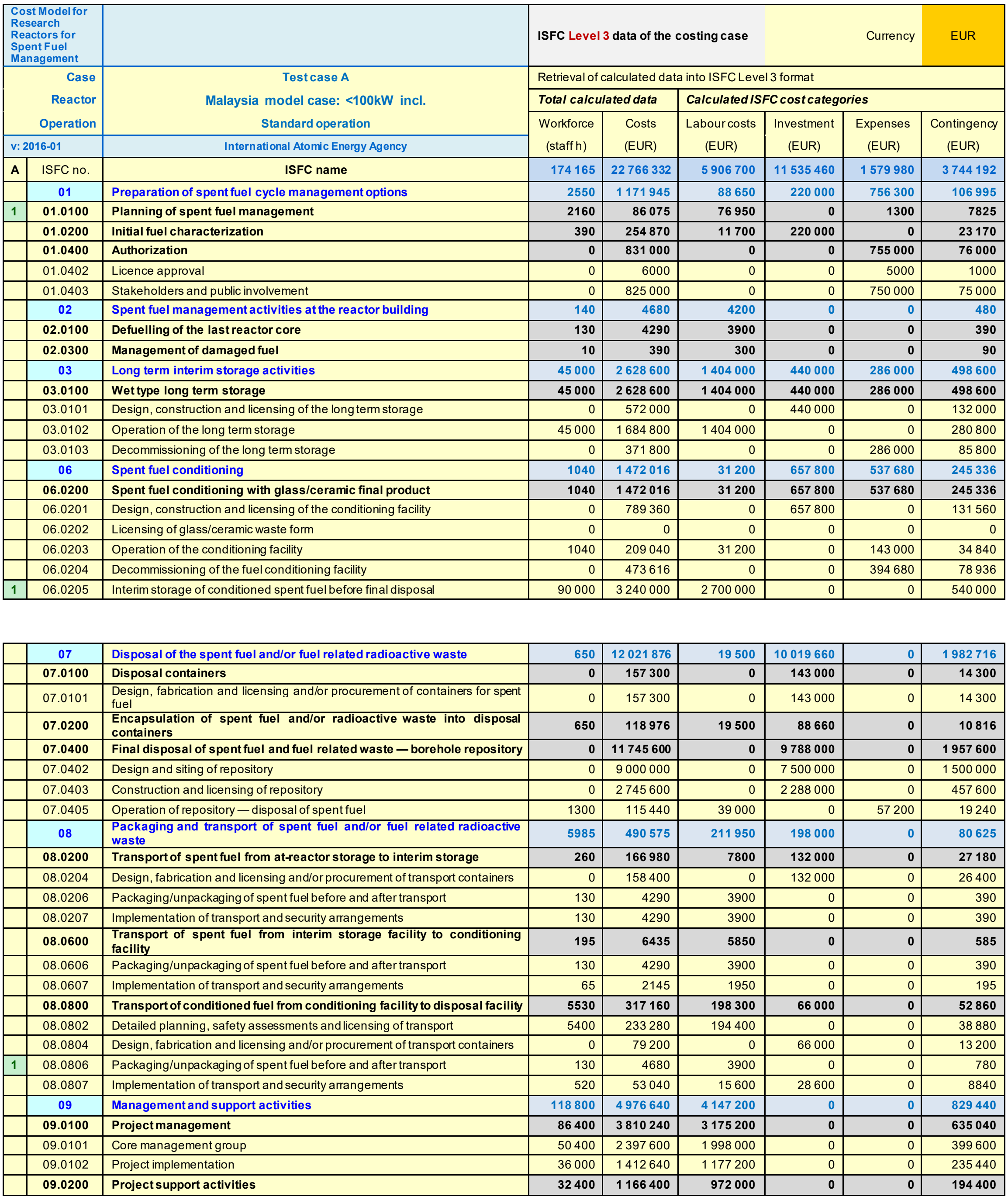
Cost Model for Research Reactors for Spent Fuel Management			ISFC Level 3 data of the costing case				Currency	EUR
Case		Test case A	Retrieval of calculated data into ISFC Level 3 format					
Reactor		Malaysia model case: <100kW incl.	Total calculated data		Calculated ISFC cost categories			
Operation		Standard operation	Workforce	Costs	Labour costs	Investment	Expenses	Contingency
v: 2016-01		International Atomic Energy Agency	(staff h)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)
A	ISFC no.	ISFC name	1965	2 973 246	58 950	2 812 788	101 508	0
	01	Preparation of spent fuel cycle management options	3	220 222	90	220 000	132	0
	01.0200	Initial fuel characterization	3	220 222	90	220 000	132	0
	02	Spent fuel management activities at the reactor building	1	66 074	30	66 000	44	0
	02.0100	Defuelling of the last reactor core	1	74	30	0	44	0
1	02.0200	Management of old fuel already stored at the reactor building	0	66 000	0	66 000	0	0
	02.0201	Design, construction, licensing and/or procurement of equipment	0	66 000	0	66 000	0	0
	06	Spent fuel conditioning	8	6400	240	5060	1100	0
	06.0200	Spent fuel conditioning with glass/ceramic final product	8	6400	240	5060	1100	0
	07	Disposal of the spent fuel and/or fuel related radioactive waste	1950	2 678 260	58 500	2 519 660	100 100	0
	07.0100	Disposal containers	0	143 000	0	143 000	0	0
	07.0101	Design, fabrication and licensing and/or procurement of containers for spent fuel	0	143 000	0	143 000	0	0
	07.0200	Encapsulation of spent fuel and/or radioactive waste into disposal containers	650	151 060	19 500	88 660	42 900	0
	07.0400	Final disposal of spent fuel and fuel related waste — borehole repository	1300	2 384 200	39 000	2 288 000	57 200	0
	08	Packaging and transport of spent fuel and/or fuel related radioactive waste	3	2290	90	2068	132	0
	08.0600	Transport of spent fuel from interim storage facility to conditioning facility	3	2290	90	2068	132	0
	08.0604	Design, fabrication and licensing and/or procurement of transport containers	0	2068	0	2068	0	0
	08.0606	Packaging/unpackaging of spent fuel before and after transport	2	148	60	0	88	0
	08.0607	Implementation of transport and security arrangements	1	74	30	0	44	0

FIG. 41. Summary of the FERREX Level 3 results for the first estimation.



Cost Model for Research Reactors for Spent Fuel Management			ISFC Level 1 data of the costing case				Currency	EUR
Case		Test case A	Retrieval of calculated data into ISFC Level 1 format					
Reactor		Malaysia model case: <100kW incl.	Total calculated data		Calculated ISFC cost categories			
Operation		Standard operation	Workforce	Costs	Labour costs	Investment	Expenses	Contingency
v: 2016-01		International Atomic Energy Agency	(staff h)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)
A	ISFC no.	ISFC name	174 165	22 766 332	5 906 700	11 535 460	1 579 980	3 744 192
	01	Preparation of spent fuel cycle management options	2550	1 171 945	88 650	220 000	756 300	106 995
	02	Spent fuel management activities at the reactor building	140	4680	4200	0	0	480
1	03	Long term interim storage activities	45 000	2 628 600	1 404 000	440 000	286 000	498 600
	04	Spent fuel return programmes	0	0	0	0	0	0
	05	Spent fuel reprocessing	0	0	0	0	0	0
	06	Spent fuel conditioning	1040	1 472 016	31 200	657 800	537 680	245 336
	07	Disposal of the spent fuel and/or fuel related radioactive waste	650	12 021 876	19 500	10 019 660	0	1 982 716
	08	Packaging and transport of spent fuel and/or fuel related radioactive waste	5985	490 575	211 950	198 000	0	80 625
	09	Management and support activities	118 800	4 976 640	4 147 200	0	0	829 440
	10	Research and development	0	0	0	0	0	0
	11	Miscellaneous costs	0	0	0	0	0	0

FIG. 42. Summary of the FERREX Level 1 results for the second estimation.



Cost Model for Research Reactors for Spent Fuel Management			**ISFC Level 3 data of the costing case**				Currency	EUR
Case		**Test case A**	Retrieval of calculated data into ISFC Level 3 format					
Reactor		**Malaysia model case: <100kW incl.**	***Total calculated data***		***Calculated ISFC cost categories***			
Operation		**Standard operation**	Workforce	Costs	Labour costs	Investment	Expenses	Contingency
v: 2016-01		**International Atomic Energy Agency**	(staff h)	(EUR)	(EUR)	(EUR)	(EUR)	(EUR)
A	ISFC no.	**ISFC name**	**174 165**	**22 766 332**	**5 906 700**	**11 535 460**	**1 579 980**	**3 744 192**
	01	**Preparation of spent fuel cycle management options**	**2550**	**1 171 945**	**88 650**	**220 000**	**756 300**	**106 995**
1	**01.0100**	**Planning of spent fuel management**	**2160**	**86 075**	**76 950**	**0**	**1300**	**7825**
	01.0200	**Initial fuel characterization**	**390**	**254 870**	**11 700**	**220 000**	**0**	**23 170**
	01.0400	**Authorization**	**0**	**831 000**	**0**	**0**	**755 000**	**76 000**
	01.0402	Licence approval	0	6000	0	0	5000	1000
	01.0403	Stakeholders and public involvement	0	825 000	0	0	750 000	75 000
	02	**Spent fuel management activities at the reactor building**	**140**	**4680**	**4200**	**0**	**0**	**480**
	02.0100	**Defuelling of the last reactor core**	**130**	**4290**	**3900**	**0**	**0**	**390**
	02.0300	**Management of damaged fuel**	**10**	**390**	**300**	**0**	**0**	**90**
	03	**Long term interim storage activities**	**45 000**	**2 628 600**	**1 404 000**	**440 000**	**286 000**	**498 600**
	03.0100	**Wet type long term storage**	**45 000**	**2 628 600**	**1 404 000**	**440 000**	**286 000**	**498 600**
	03.0101	Design, construction and licensing of the long term storage	0	572 000	0	440 000	0	132 000
	03.0102	Operation of the long term storage	45 000	1 684 800	1 404 000	0	0	280 800
	03.0103	Decommissioning of the long term storage	0	371 800	0	0	286 000	85 800
	06	**Spent fuel conditioning**	**1040**	**1 472 016**	**31 200**	**657 800**	**537 680**	**245 336**
	06.0200	**Spent fuel conditioning with glass/ceramic final product**	**1040**	**1 472 016**	**31 200**	**657 800**	**537 680**	**245 336**
	06.0201	Design, construction and licensing of the conditioning facility	0	789 360	0	657 800	0	131 560
	06.0202	Licensing of glass/ceramic waste form	0	0	0	0	0	0
	06.0203	Operation of the conditioning facility	1040	209 040	31 200	0	143 000	34 840
	06.0204	Decommissioning of the fuel conditioning facility	0	473 616	0	0	394 680	78 936
1	06.0205	Interim storage of conditioned spent fuel before final disposal	90 000	3 240 000	2 700 000	0	0	540 000
	07	**Disposal of the spent fuel and/or fuel related radioactive waste**	**650**	**12 021 876**	**19 500**	**10 019 660**	**0**	**1 982 716**
	07.0100	**Disposal containers**	**0**	**157 300**	**0**	**143 000**	**0**	**14 300**
	07.0101	Design, fabrication and licensing and/or procurement of containers for spent fuel	0	157 300	0	143 000	0	14 300
	07.0200	**Encapsulation of spent fuel and/or radioactive waste into disposal containers**	**650**	**118 976**	**19 500**	**88 660**	**0**	**10 816**
	07.0400	**Final disposal of spent fuel and fuel related waste — borehole repository**	**0**	**11 745 600**	**0**	**9 788 000**	**0**	**1 957 600**
	07.0402	Design and siting of repository	0	9 000 000	0	7 500 000	0	1 500 000
	07.0403	Construction and licensing of repository	0	2 745 600	0	2 288 000	0	457 600
	07.0405	Operation of repository — disposal of spent fuel	1300	115 440	39 000	0	57 200	19 240
	08	**Packaging and transport of spent fuel and/or fuel related radioactive waste**	**5985**	**490 575**	**211 950**	**198 000**	**0**	**80 625**
	08.0200	**Transport of spent fuel from at-reactor storage to interim storage**	**260**	**166 980**	**7800**	**132 000**	**0**	**27 180**
	08.0204	Design, fabrication and licensing and/or procurement of transport containers	0	158 400	0	132 000	0	26 400
	08.0206	Packaging/unpackaging of spent fuel before and after transport	130	4290	3900	0	0	390
	08.0207	Implementation of transport and security arrangements	130	4290	3900	0	0	390
	08.0600	**Transport of spent fuel from interim storage facility to conditioning facility**	**195**	**6435**	**5850**	**0**	**0**	**585**
	08.0606	Packaging/unpackaging of spent fuel before and after transport	130	4290	3900	0	0	390
	08.0607	Implementation of transport and security arrangements	65	2145	1950	0	0	195
	08.0800	**Transport of conditioned fuel from conditioning facility to disposal facility**	**5530**	**317 160**	**198 300**	**66 000**	**0**	**52 860**
	08.0802	Detailed planning, safety assessments and licensing of transport	5400	233 280	194 400	0	0	38 880
	08.0804	Design, fabrication and licensing and/or procurement of transport containers	0	79 200	0	66 000	0	13 200
1	08.0806	Packaging/unpackaging of spent fuel before and after transport	130	4680	3900	0	0	780
	08.0807	Implementation of transport and security arrangements	520	53 040	15 600	28 600	0	8840
	09	**Management and support activities**	**118 800**	**4 976 640**	**4 147 200**	**0**	**0**	**829 440**
	09.0100	**Project management**	**86 400**	**3 810 240**	**3 175 200**	**0**	**0**	**635 040**
	09.0101	Core management group	50 400	2 397 600	1 998 000	0	0	399 600
	09.0102	Project implementation	36 000	1 412 640	1 177 200	0	0	235 440
	09.0200	**Project support activities**	**32 400**	**1 166 400**	**972 000**	**0**	**0**	**194 400**

FIG. 43. Summary of the FERREX Level 3 results for the second estimation.

6. SUMMARY AND RECOMMENDATIONS

This publication will assist Member States in developing their RRSNF management strategies, and summarizes the work performed within the CRP. It describes options for RRSNF management and proposes a standard approach to identify a preferred option using integrated Excel based decision-support and costing tools (BRIDE and FERREX). BRIDE allows Member States to compare the available technologies and thereby determine the best strategy for their situation. One of the unique aspects of BRIDE is that it incorporates non-economic factors along with comparative costs, allowing Member States to emphasize the factors most important to their decision. FERREX can then be used to develop a bottom-up cost estimate for the preferred option. The publication includes case studies that were performed by the CRP participants, to illustrate the variety of scenarios that can be evaluated and to demonstrate use of the tools.

In addition, the annexes present country-specific RRSNF strategies and case studies from CRP participants.

BRIDE is used in three stages: (i) definition of possible scenarios; (ii) comparison of scenario costs; and (iii) use of the multiattribute utility methodology by an expert group to evaluate the available scenarios and identify a preferred scenario. BRIDE is distributed in a single workbook.

After the development and testing of the tools with examples from Member States, members of the CRP concluded that these tools are valuable in supporting Member States' analysis and strategic decision making.

Future work related to this publication will involve the IAEA assisting Member States in applying the tools to develop their RRSNF management strategies. Detailed tutorials have been produced to assist in the use of the tools and are available for download. Furthermore, Member States are strongly encouraged to request support and training in the use of the tools.

To disseminate information and increase awareness on the CRP outputs and to facilitate widespread use of the BRIDE and FERREX tools, both workshops and technical meetings can be considered. These can include (i) training workshops at IAEA Headquarters; (ii) regional workshops; and (iii) expert missions as requested by the Member States. The members of the CRP have agreed to be available as resources in the future development and dissemination of the tools.

For Member States that already operate RRs, there may be value in holding joint decommissioning and spent fuel management workshops. Radioactive waste management technologies are common to both processes and the same personnel may work on both, thus allowing the two aspects to be planned together.

In line with IAEA Nuclear Energy Series No. NP-T-5.1, Specific Considerations and Milestones for a Research Reactor Project [59], the CRP participants recommended that new RR projects in Member States should include spent fuel management in the life cycle design, planning and cost stages.

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Annex I

CURRENT RRSNF MANAGEMENT STRATEGIES IN PARTICIPATING MEMBER STATES

Each of the countries participating in the CRP have contributed information about the current status of their RRSNF management strategies, as examples to other countries that have not yet decided on their own RRSNF management strategies.

I–1. ARGENTINA

Argentina currently has five RRs in operation and one under construction [I–1]. The operational RRs are RA-0, RA-1, RA-3, RA-4 and RA-6; the one under construction is RA-10.

RA-1 is located at CNEA's Constituyentes Atomic Centre in Buenos Aires province. It is an open tank reactor with a 40 kW thermal power rating and a 19.71% enriched uranium core. The RA-1 reactor produced the first radioisotopes for medical and industrial applications in Argentina. In addition, it pioneered the training of personnel required for the construction of three NPPs in Argentina.

The RA-0 reactor went critical in 1958 to assist in checking experimental data for startup of the RA-1, RA-2 (now dismantled) and RA-3 reactors. In the early 1970s, it was installed in the National University of Córdoba. The facility normally operates for four hours per day for research and training purposes.

The main technical features of RA-0 are:

- Typical thermal power of 1 W and up to 10 W for short periods of time;
- 19.71% enriched UO_2 fuel (co-extruded graphite-UO_2 rod with Al cladding);
- Cooled and moderated by demineralized light water;
- Graphite reflector;
- Four Cd plate control rods.

The RA-3 reactor, a pool type reactor, is located at the Ezeiza Atomic Centre near Buenos Aires. The RA-3 originally operated as a 3 MW reactor using HEU and was converted to LEU in 1989. The RA-3 reactor currently operates at 10 MW (as of 2018).

The main technical features of RA-3 are:

- Maximum thermal power of 10 MW;
- 19.75% enriched U_3O_8 fuel;
- Cooled and moderated by demineralized light water;
- Graphite reflector;
- Four Ag–In–Cd coarse regulation control rods.

The RA-4 reactor was installed at the National University of Rosario in November 1972. It is a homogeneous reactor with a maximum power of 1 W. Its core comprises a circular plate arrangement with a graphite reflector. The plates are made of a homogeneous mixture of U_3O_8 (<20% enriched) and polyethylene. The reactor was specifically designed for education and training and only operates for four hours per day.

The RA-6 reactor is located at the Bariloche Atomic Centre in the southwest of Argentina and was commissioned in October 1982. Originally designed as an education and training reactor to support nuclear engineering and research at the Balseiro Institute, the RA-6 has provided other scientific and training services in its lifetime. It provides for research and development in reactor physics and nuclear engineering, education and training, boron neutron capture therapy, neutron activation analysis, neutron radiography, instrumentation and control testing, and materials irradiation.

The main technical features of RA-6 are:

- Pool type reactor with a maximum thermal power of 1 MW;
- 19.7% enriched uranium silicide MTR type fuel;
- A maximum thermal flux of 1.5×10^{13} $cm^{-2} \cdot s^{-1}$;
- Cooled and moderated by demineralized light water;
- Graphite reflector;
- Four Ag–In–Cd coarse regulation control rods and one fine regulation control rod.

The RA-10 is a new multipurpose RR that is currently under construction; as of October 2020, the overall construction completion rate is 62%. The RA-10 reactor will replace the RA-3 reactor and support the increasing national and regional demands for radioisotopes. The RA-10 is a 30 MW thermal power reactor and is designed to achieve high performance neutron production. The reactor is an open pool design with a compact core with MTR LEU fuel assemblies, consisting of uranium silicide fuel plates with Al cladding. The expected fuel consumption is around 40 fuel elements per year.

I–1.1. RRSNF strategies

Argentina's RRSNF strategy is focused on MTR spent fuel design, with an inventory of approximately 1000 spent fuel elements with Al cladding and a dispersion type core [I–2]. The main contributors to the inventory are the RA-3 and RA-10 (once in operation) reactors. The two main characteristics of this type of RRSNF are its enrichment (19.7% ^{235}U) and its cladding material, which has poor durability under wet conditions (if the quality of the water is not controlled to specification).

The spent fuel inventory of the RA-3 is not an immediate concern because of the availability of an existing wet storage facility (FACIRI), described in Section 2.1.1.2, where there is adequate capacity to store the spent fuel up to the end of life of the reactor. The RA-6 also has a storage pool with adequate capacity to store spent fuel from the RA-6 and the new RA-10 for at least ten years.

A suitable RRSNF strategy is required to be available by around 2025. CNEA commenced planning in 2013 to evaluate different scenarios/strategies for a long term RRSNF management strategy, which particularly includes consideration of issues such as national policy changes (e.g. budget reduction). The strategy review will also consider:

(a) Stabilization/conditioning of SNF for disposal without the additional generation of radioactive waste streams (including dilution).
(b) Domestic processing of SNF for final disposal.
    (i) Processing (physical, chemical or physicochemical) of SNF followed by the treatment and conditioning of the radioactive waste stream.
    (ii) Dissolution of SNF followed by the separation of two streams of radioactive wastes: U or Pu and the remaining material. Treatment and conditioning of both streams.
    (iii) Dissolution of SNF followed by recovery of U or Pu and other radionuclides of interest for reuse plus treatment and conditioning of radioactive wastes.
(c) Foreign processing of SNF. Radioactive wastes remain in the processing country or are returned in a monolithic stable waste form, suitable for final disposal.
(d) Direct disposal of SNF. Deep borehole technology; co-disposal with ILW; encapsulation of RRSNF (with the need for isotopic dilution to be evaluated).

Except for strategy (c) above, which is an immediately available possibility, the other options are under different stages of review. In addition to the above strategies, Argentina has decided to carry out detailed analysis of the present and past activities related to the options under consideration, including:

- Fabrication of irradiation targets for the installation for production of ^{99}Mo from fission (U–Al alloy with 90% enriched uranium, with Al cladding) and separation of the ^{99}Mo produced from the irradiated targets. This activity started in 1985 and the use of HEU ceased in 2000 when CNEA started using a new LEU target (uranium silicide compound with Al cladding with an enrichment of 19.7% ^{235}U).
- Development of a method to recover, purify and down blend the irradiated HEU, formerly used for the proposed ^{99}Mo production. The objective was to reuse the uranium by reducing the enrichment to 19.7%, producing new targets. For this activity a dedicated installation was prepared and licensed.
- Recovery and reuse of the irradiated LEU to fabricate the irradiation targets previously mentioned. This processing is in an ongoing state.
- Basic studies of a method for conditioning the spent fuel in a stable ceramic matrix.

It is expected that a national decision on the RRSNF strategy will be made by 2030.

I–2. AUSTRALIA

Australia has operated three RRs, of which two have been shut down. The first RR, HIFAR, a 10 MW reactor, operated from 1958 to 2007. HIFAR operated on HEU fuel for much of its lifetime, converting to LEU fuel shortly before its shutdown. It is currently under decommissioning.

The second reactor, Moata, designed in the mid-1950s, operated at 100 kW between 1961 and 1995 using HEU fuel. It was initially used for research and training, and later for activation analysis and neutron radiography. It was fully decommissioned in 2010.

The third reactor, OPAL, is a 20 MW RR that first went critical in August 2006 and has an expected operational lifetime of at least 40 years. The OPAL reactor operates on LEU fuel.

Each of the three reactors, operated by ANSTO, have a slightly different spent fuel management regime, largely dependent on the reactor design and the availability of ancillary storage facilities. A brief description of the back end spent fuel management systems is detailed below.

I–2.1. HIFAR spent fuel management

I–2.1.1. Storage

The HIFAR spent fuel was stored in a cooling tank (deionized water) located within the reactor containment building for an initial period of one month to allow decay of the short lived radionuclides and remove some residual decay heat. Following this, volume reduction was achieved by the removal of the non-fuel plugs (by mechanical shearing). The sheared assemblies were then transferred to a storage pool located in another building adjacent to the HIFAR reactor area using a shielded dual purpose shear/transport flask.

Additional volume reduction occurred in this storage pool, using circular motorized saws to remove the excess non-fuel Al ends. This pool had storage capacity for 390 spent fuel elements, or six years' storage capacity. The storage pool acted as preparation and as a buffer storage area during spent fuel shipments for reprocessing overseas.

The wet storage pool (Fig. I–1) was commissioned in 1961 and is still in operation today, storing high activity Co-60 sources. The pool has a reinforced concrete structure set into a sandstone bedrock with a stainless steel liner. The pond compartments are of the same construction. The pond floor is 0.3 m thick concrete, lined with 3.2 mm stainless steel. The pond walls are made of 0.3 m thick concrete, lined with 1.6 mm stainless steel.

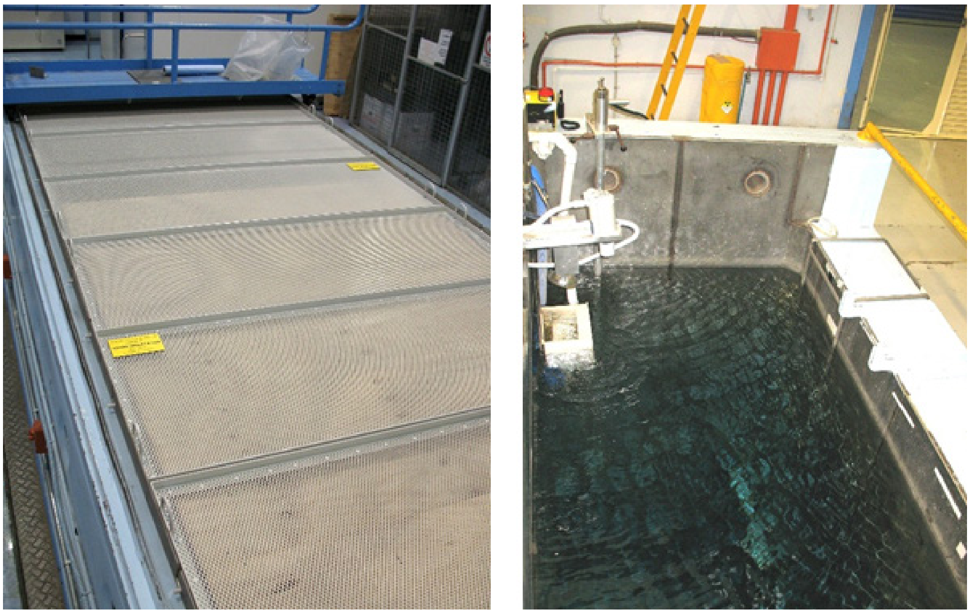

FIG. I–1. Wet storage facility (courtesy of ANSTO).

There are two narrow dipstick tubes which run in the interspace between the liner and concrete walls to the base of the concrete pool. The dipstick tubes in each compartment run through a small triangular vertical channel to the base of the pond floor. The dipstick tubes act as a leak collection/detection system, similar to the leak detection/collection systems incorporated into the design of other international spent fuel storage ponds to enable removal of potential water leakage.

The water chemistry in the pool is controlled using a bag filter and diatomaceous earth pool filter for removing surface dust/particulates, and a water demineralization circuit for maintaining water purity. Water is taken from the pond by the water demineralization system pump, and passed through cartridge filters, a fully sealed ultraviolet treatment system (for disinfection) and an ion exchange column, before being returned. Using this method, the water quality is maintained to high standards to prevent corrosion of the items stored within the pool.

There are three interchangeable ion exchange columns, which contain a mixture of nuclear grade anionic and cationic resins (28 L in total). There are normally two exchange columns fitted to the pond recirculation pipework at any one time. The third column is a portable stand-alone unit of the same capacity (mounted on a skid with its own pump, cartridge filter and pressure indicator), which can be put into service as required. The two more permanently fixed columns operate on a duty/standby basis (manual changeover); the duty column is isolated and removed when the conductivity or water activity levels rise, and the standby column is put directly into service. The availability of the third portable column provides operational redundancy and ensures that there are two columns ready for service should one be removed for maintenance, resin removal or refilling.

Water quality is tested monthly. Acid or alkaline water can cause corrosion. High conductivity indicates the presence of salts that could cause corrosion. Contamination shows that a stored item may be damaged and an investigation should be undertaken to identify the source of activity. Contamination and high conductivity can be reduced by changing over the ion exchange column. Limits for testing are:

— Conductivity <20 μS/cm (normal range is 1–10 μS/cm);
— Maximum gross alpha level is 0.02 kBq/L;
— Maximum gross beta level is 1.0 kBq/L (normal range is <0.5 kBq/L);
— 5 < pH < 9.

A gamma radiation detector is installed near the pond to monitor the radiation in the area. This has an audible alarm which is activated when the dose rate reaches a preset level.

The HIFAR cropped fuel was kept in wet storage for a minimum of three years prior to removal and placement into a dry in-ground storage facility. The fuel was moved in a specially designed flask, the general purpose flask (Fig. I–2), to the dry storage facility. The general purpose flask, weighing more than 10 tonnes, is constructed of steel and lead.

The dry storage facility is a purpose-built single level store (Fig. I–3) and is constructed as a steel-framed and clad structure built on a concrete slab floor, laid on bedrock. The building has a steel roof with a row of reinforced glass windows set high in the walls and is naturally ventilated. The building is enclosed by a fenced area which is accessed only through a locked gate.

The spent fuel is stored within deep stainless steel tubes. The tubes are drilled 15.2 m deep into the sandstone bedrock and lined with 140 mm ID sealed stainless steel containment tubes. When full, each hole has the capacity to hold 11 spent fuel storage cans with two spent fuel elements per can. There are 50 such storage tubes originally used for the storage of spent fuel, with a capacity to store up to 1100 spent fuel elements. There is a shielding plug at the top of every tube which is made of steel and is approximately 500 mm long.

The top end of each containment liner is surrounded by an outer collar shield, which is bolted to the concrete floor with steel packing being used to ensure that the top of the shield is flush with the surface of the floor. The containment liner is bolted to the outer shield to provide an integral containment for the storage vessels. A sealing gasket is positioned on the flange of the containment liner, the inner shield put into position and bolted to the outer liner through the flange of the containment liner. The inner shield has a passageway drilled from the top into a distribution groove to allow the liner to be purged and filled with dry nitrogen to reduce the risk of corrosion during storage. The storage tubes have some of their length below the groundwater table. A groundwater ingress and pump out monitoring system is in place to remove any groundwater ingress if the situation arises.

FIG. I–2. General purpose flask (courtesy of ANSTO).

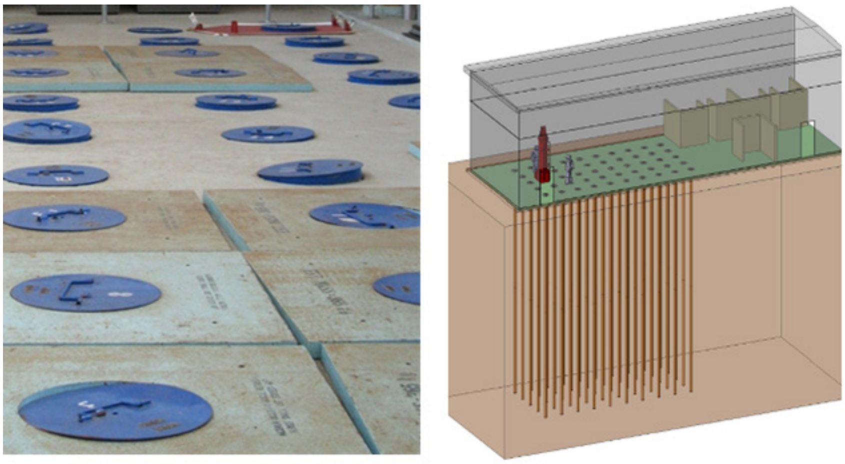
(a) (b)

FIG. I–3. *(a) Top view and (b) below ground diagram of deep storage tubes (courtesy of ANSTO).*

I–2.1.2. Reprocessing

There were four HIFAR spent fuel shipments to France, conducted between 1999 and 2004, for a total of 1288 SFAs. The reprocessing of ANSTO's fuel in France was conducted over several years and completed in 2014. ANSTO received an equivalent amount of radioactive waste from the reprocessing that met Australia's ILW requirement of <2 kW/m^3 heat output.

Planning for the return of the reprocessed waste to Australia commenced five years in advance of the scheduled 2015 return, with the contract to manufacture the TN 81 dual purpose transport storage cask. Orano supplied manufacturing data files for all of the vitrified waste canisters and technological wastes (cemented ILW) that were returned to Australia. These manufacturing data files were independently audited. A best match fit of activity resulted in 20 vitrified waste canisters being allocated to Australia. The maximum capacity of the TN 81 is for 28 canisters. Information was also supplied on the chemical and radiological characteristics of the vitrified residue, including the average heat output per canister; methodology for calculation of equivalent and measurement of actual activities; and vitrification plant operation. Most of this information was supplied to the Australian regulator, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

Several approvals were obtained from ARPANSA:

- Facility operating licence for an interim waste store at ANSTO;
- Import permit for radioactive materials;
- Validation of certificate of compliance for the TN 81;
- Shipment approval (including transport safety plan) for the road transport of the TN 81 and contents along Australian roads;
- Security plan approval (both this and shipment approval must be in place prior to transport)[1].

Approvals were also obtained from other Australian State and federal agencies:

- Approval that the nuclear action (transport of reprocessed waste) under the Environment Protection and Biodiversity Conservation Act 1999 did not need a referral under the Act;

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[1] The vitrified waste was treated as an aggregate Category 1 radioactive source, since nuclear material is not safeguarded due to its irrecoverable, low level of incorporation.

- Roads and Maritime Services approval for sensitive (radioactive) cargo and route approval for oversize road transport;
- ANSTO operational safety assessments;
- Extension of Comcover (Australian Government insurer) indemnity to ILW return operations.

Transport logistics planning started 18–24 months prior to the transport. The maritime transport and land transport within France were managed by Orano. ANSTO's responsibility was for the unloading of the ILW at the Australian port and land transport to the interim waste store at ANSTO. Many local approvals were required to set up a crane at the port of arrival, in addition to the port operator, logistics contractor and ANSTO safety assessment reviews of all port operations.

The TN 81 is both oversized and overweight (~2.75 m diameter, 6.5 m long, 130 tonnes) for normal road transport. Permits had to be obtained to allow the load to transit along the chosen route, with special attention to axle loadings, turning circles, mass limits of bridges or overpasses and heights of underpasses. The crane, 12-axle hydraulic trailer and heavy haulage front loaders are specialized equipment, which needed to be booked in advance of the operation to ensure availability. Erection of the crane at the port was commenced two days prior to the arrival of the ship and cargo. Trailers and trucks were deployed to the port the day before. Security and radiation contamination clearance surveys were conducted on trucks and trailers stationed at the port.

On the day of arrival of the cargo, the harbour was closed to commercial and recreational use, so that the ship could be escorted in securely. Timing of arrival is critical, since the exclusion zone for the harbour must be set up and timed, and advertised in advance of the arrival of the cargo. Closure of the harbour is a security measure that has operational benefits in that the tugs bringing in the ship have a clear pathway to the port without navigating other boats or ships in the area. The transport operation was conducted at night, to minimize disruption to local and commercial traffic (Figs I–4 and I–5).

An intergovernmental working group with representatives from State and federal agencies was formed to implement the transport of the TN 81 from the port of arrival to ANSTO. The working group comprised New South Wales (NSW) Police, Roads and Maritime Services, Traffic Management Centre, Fire and Rescue NSW, Ambulance NSW, NSW Health, Port Authority of NSW, NSW Ports, Australian Federal Police and the Australian Maritime Safety Authority. The first meeting of this group was 11 months before the shipment's arrival.

These agencies agreed on the protocol and arrangement of the primary and support convoys and discussed operational interfaces before and during the transport operation. The date of the shipment arrival and transport was kept 'need to know' for as long as possible. However, with an exercise of this nature, it proved impossible to maintain information security around the date and location of arrival. Careful negotiations took place with issue-motivated groups such as Greenpeace to facilitate access to secure areas of the port. This allowed controls to be placed on their protest activities while providing an

FIG. I–4. Port loading operations (courtesy of ANSTO).

FIG. I–5. TN 81 cask loaded and ready for transport (courtesy of ANSTO).

opportunity for them to obtain footage of the transport vessel entering the port, without interfering with the progress of the operation.

The first radioactive waste shipment back to Australia was in 2015. Prior to arrival, ANSTO prepared its site and trained its personnel to receive the TN 81.

An internal route assessment was performed at ANSTO to ascertain the best entry route to the site. Additionally, the 12-axle trailer required to spread the load on Australian roads was too long to negotiate roads within the site, and it was decided that the TN 81 would be shifted to a smaller 7-axle trailer.

A gantry crane system was used to perform the trailer exchange. The ‘arms’ from the four-point lifting system used at the port were attached to the gantry lifting devices. The 12-axle trailer was driven underneath the gantry; the arms were attached to the lifting points (trunnions) on the TN 81; the TN 81 and transport frame were lifted, the 12-axle trailer removed and the 7-axle trailer driven under the suspended TN 81 for repositioning (Fig. I–6).

The TN 81 truck/trailer configuration was driven into the interim waste store (Fig. I–7).

In preparation for testing the lifting procedures in the interim waste store, a wooden mock-up of the TN 81 was manufactured. This was used to test the crane operations and train personnel prior to the receipt of the TN 81 (Fig. I–8). The benefits of the operational readiness activities were:

- Familiarity and awareness of process for the project team;
- Communication of responsibilities and management of expectations (all internal and external stakeholders involved);

FIG. I–6. TN 81 cask transfer from external to internal transport for interim storage at the ANSTO site (courtesy of ANSTO).

- — Training (staff sent to Zwilag facility (Switzerland) to witness TN 81 handling and subject matter experts invited to ANSTO);
- — Practice (mock-up items, which are to scale, were built);
- — Review and testing of work instructions;
- — Dedicated staff (e.g. approval from line managers important to ensure availability for training);
- — Preparation (early delivery of ancillary equipment enabled inventory checks and set-up prior to cask arrival).

FIG. I–7. TN 81 cask moved to interim waste store at ANSTO (courtesy of ANSTO).

(a)

(b)

FIG. I–8. TN 81 (a) cask unloading and (b) testing training (courtesy of ANSTO).

I–2.2. Moata spent fuel management

The Moata fuel assemblies were moved using a shielded transfer flask consisting of a 178 mm thick steel box measuring 508 mm × 432 mm × 1194 mm and weighing 2000 kg. The fuel assemblies are stored in a four-by-four array of steel-lined vertical holes set in a concrete-filled cavity located near the reactor's biological shield (Fig. I–9). A duplicate dry storage block is also sited near the biological shield. Each hole is stepped from a 1 m section at the base, which holds the fuel assembly to a section containing a 1.6 m long shield plug. The block containing the fuel assemblies is covered by a steel plate fitted with a seal and air sampling valve. The empty fuel storage block is covered with an unsealed, padlocked steel plate.

Between 1961and 1995, 177 Moata fuel plates were irradiated to a combined burnup of 26.1 MWd. The spent fuel was kept in a dry nitrogen atmosphere to minimize corrosion. In 2010, the Moata reactor was fully decommissioned (Fig. I–10), and all the spent HEU fuel was sent back to the United States of America, along with HIFAR HEU fuel.

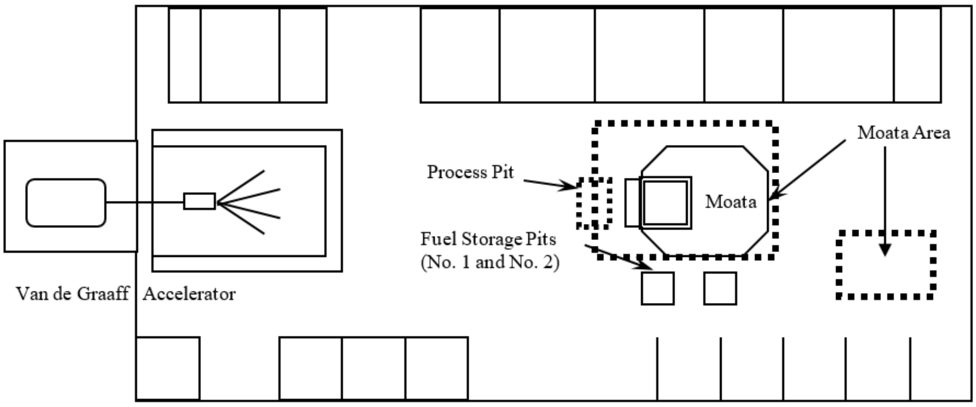

FIG. I–9. Moata reactor and ancillary plant layout (courtesy of ANSTO).

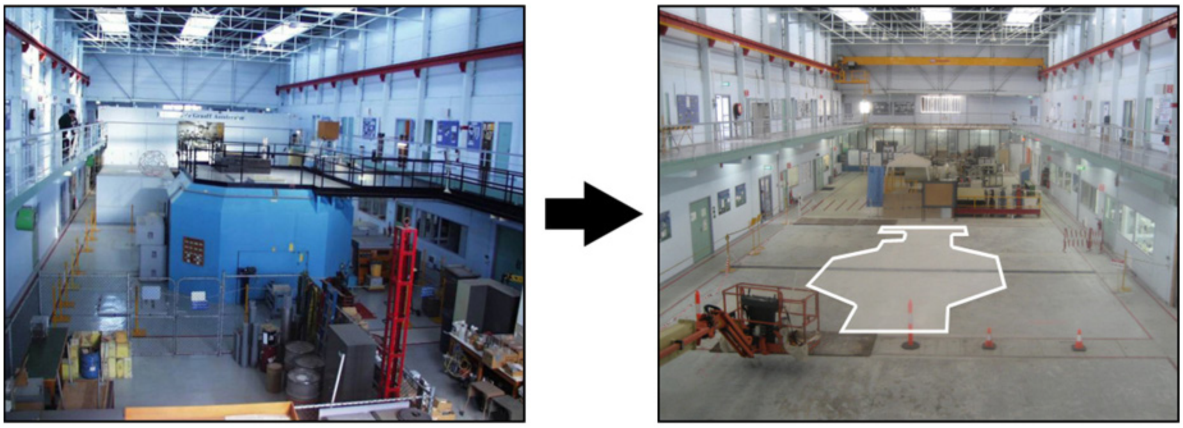

FIG. I–10. Moata decommissioning — before and after (courtesy of ANSTO).

I–2.3. OPAL spent fuel management

I–2.3.1. Storage

The OPAL reactor is an open pool design (comprising dual ponds — the reactor pool and a spent fuel storage/service pool). The reactor pool contains the fuel core (16 LEU aluminium silicide fuel elements), irradiation facilities and the neutron guides. An adjacent pool (storage/service), joined to the reactor pool via a transfer channel, provides a storage capacity for 330 SFAs (ten years' reactor operating capacity). The OPAL reactor uses about 30 fuel assemblies per year. Once used, the fuel assemblies are transferred from the reactor pool to the storage/service pool via a transfer channel separating the two pools. The spent fuel can be stored in the storage/service pool until the pool reaches capacity (after ten years). The OPAL reactor is designed for the spent fuel to be removed from the service pool, via wet loading into a shielded transport cask for dry storage or shipment for reprocessing. One spent fuel loading/transport cask that is suitable for use in the OPAL service pool is the French designed TN MTR cask. The TN MTR transportation cask is suitable for the OPAL fuel design, especially for transportation to the Orano reprocessing facility at La Hague. This cask can contain several types of basket, generic or specialized, according to the RRSNF. The TN MTR cask can be loaded at the RR site either under water or using a dry transfer system from pool to cask.

I–2.3.2. Reprocessing

The spent fuel strategy for the OPAL reactor is overseas reprocessing. ANSTO has an ongoing contract with Orano (France) to ship its spent fuel to the Orano La Hague reprocessing facility on a regular campaign basis. The reprocessing contract stipulates that the fissile material will remain in France and be recycled in civilian reactors and the vitrified waste will be returned to Australia as ILW using a dual purpose transport/storage cask (TN 81).

About 30 spent fuel elements are generated each year and are placed in storage in a storage pool located adjacent to the reactor pool (containing the fuel core). The storage pool has a capacity for ten years of OPAL operation. Shipments of spent fuel for reprocessing (in France) are planned to occur about every seven years, in accordance with the storage pool capacity, as well as for cost effective shipment from Australia to France and to align with the reprocessing capacity of the La Hague facility for uranium silicide spent fuel.

During spent fuel shipments the transport casks are lowered into the storage pool during scheduled reactor shutdowns. The spent fuel is then loaded (underwater) into the casks while the reactor is at power, allowing normal reactor operations to continue. The loaded casks are then removed from the reactor during the next scheduled shutdown.

The regular shipments to France for reprocessing ensure that the ten year storage pool capacity for spent fuel is maintained without the need to move spent fuel out of wet storage into other externally located wet or dry storage facilities. This decision was also a condition placed on the OPAL licence by the regulator to ensure that ANSTO had a viable back end solution for the management of its spent fuel.

The first OPAL spent fuel shipment to France was completed in September 2018 with 236 spent fuel elements loaded in four TN MTR casks arriving safely at the La Hague reprocessing facility. The second shipment is planned for 2025. Thereafter, shipments are forecast to occur every six to seven years. The shipments and return of the reprocessed waste are contingent on the intergovernmental agreement between Australia and France being in place, which was finalized in early 2018.

It is anticipated that the reprocessed waste on return will be placed in the Australian National Radioactive Waste Management Facility (NRWMF). The NRWMF is planned to be operational by 2025 for near surface disposal of LLW and above ground storage of ILW for a period of at least 50 years. The reprocessed vitrified returned waste (in stainless steel canisters) is classified as ILW, so the canisters will be placed in a dual transport/storage cask (TN 81) and stored at the NRWMF awaiting final disposal.

I–3. BRAZIL

Brazil has four operating RRs and one planned RR. The operational RRs are IEA-R1, IPR-R1, Argonauta and IPEN/MB-01; the planned RR is the 30 MW Brazilian Multipurpose Reactor (RMB). The Brazilian National Commission for Nuclear Energy (CNEN) operates the existing four RRs and will also operate the planned RR.

The IEA-R1 reactor, located in the Nuclear and Energy Research Institute (IPEN) in São Paulo, reached criticality for the first time in September 1957. It is an MTR pool type reactor and is cooled and moderated using demineralized light water. The original fuel assemblies were made of plates containing highly enriched U–Al alloy and were Al-clad. In the 1980s, a programme was started to convert the core to LEU fuel. Since 1997, all fuel assemblies in the core are locally made with LEU, first using U_3O_8/Al dispersions, then, since 1999, using U_3Si_2/Al dispersions. Currently, the reactor is operating at 5 MW continuously for 64 h per week. This RR produces 8–10 SFAs a year and these are stored in the reactor pool. The spent fuel storage capacity is currently 108 SFAs; 60% of storage capacity has been used up and there are plans to double the storage capacity. There is a dry storage facility in the reactor building for 150 RRSNF assemblies, which requires major refurbishment prior to use.

The IPR-R1 is located at the Nuclear Technology Development Center in Belo Horizonte and is a Training Research Isotopes General Atomics (TRIGA) Mark I type reactor, and it is nominally operated at 250 kW. The original core consisted of 59 low enriched uranium–zirconium hydride rods clad in Al. The new fuel elements introduced in 2002 are clad in stainless steel. Since the new core has reached criticality, the integrated fuel burnup is approximately 200 MWd. Aside from the ageing concerns of the overall reactor, spent fuel is not a concern. The reactor pool has 12 positions for spent fuel, and an additional storage unit has space for 72 SFAs.

The Argonauta reactor is located in the Nuclear Engineering Institute in Rio de Janeiro and it reached first criticality in 1965. The designed power of this reactor is 5 kW but it was authorized to operate at 500 W continuously or at 1 kW for 1 h. The current fuel core configuration consists of eight Al-clad fuel assemblies containing LEU U_3O_8/Al dispersed in Al. Demineralized water is used as the moderator and coolant. Accumulated burnup since criticality in 1965 is 0.25 MWd. This is a lifetime core and the plan is to dispose of the fuel when the reactor is decommissioned.

The IPEN/MB-01 is also located at IPEN in São Paulo. It is a tank type critical facility with nominal power of 100 W. The reactor core consists of up to 680 stainless steel clad fuel pins with UO_2 pellets. Demineralized water is used as the moderator and coolant. This reactor went critical in 1998. There are 3500 fuel pin positions available in dry storage.

The expected future life of the IEA-R1 and IPEN/MB-01 reactors is 20 years. There is no set date for decommissioning the IPR-R1 and the Argonauta reactors.

I–3.1. Further information about spent fuel, spent fuel handling facilities and infrastructure

I–3.1.1. Existing radioactive waste management infrastructure in Brazil

The existing infrastructure for radioactive waste management can be summarized as follows:

- There are LLW and ILW repositories and these are in operation. There is no HLW repository, but there are plans to have one.
- The existing radioactive waste classification in Brazil is CNEN Norm NE 6.05 [I–3].
- There is no centralized wet or dry spent fuel storage. However, IPEN/MB-01 has fully operational dry storage only; IEA-R1 has interim wet storage that is operational; and IPR-R1 has interim storage in-reactor and also a wet auxiliary pool.

- In terms of previous experiences in managing RRSNF: (a) fuel from IEA-R1 was shipped to the United States of America under the FRRSNF acceptance programme; and (b) fuel repackaging was done for damaged fuel prior to shipment to the United States of America.
- Brazil does not have hot cells for fuel handling.

The IEA-R1 reactor has pool space available for underwater cask loading and cutting operations. These operations have been done in the pool of this reactor prior to shipping spent fuel from the United States of America.

Details of Brazil's spent fuel inventory (up to 2020) and other relevant information about back end options in Brazil can be found in Ref. [I–4].

I–3.1.2. Brazilian national long term strategy for RRSNF

The Brazilian national strategy for RRSNF is dry storage in casks after 10–15 years of wet storage. Brazil has no plans to reprocess RRSNF, in Brazil or elsewhere.

A dual purpose cask for transport and storage is being designed (Fig. I–11). A prototype cask, 1:2 size and made with small differences in the type of lid and fasteners used, is being designed and constructed jointly by Brazil and Argentina [I–5]. This development is part of an IAEA regional Technical Cooperation project for Latin America [I–6]. The cask failed the last drop test and the design parameters are being revised. No decisions have been taken regarding disposal of the spent fuel.

I–3.2. Other activities carried out related to this CRP

The objectives of Brazil in this CRP were (a) to provide information to help identify short and long term strategies for managing the back end of the RR nuclear fuel cycle; and (b) to contribute to the development of a standard approach to quantitatively assess and analyse individual RR back end options. In this context, even though Brazil's long term strategy is to indefinitely store its RRSNF in the spent fuel sections of the four RRs currently operating, as well as in the planned RMB, followed by transfer to dry

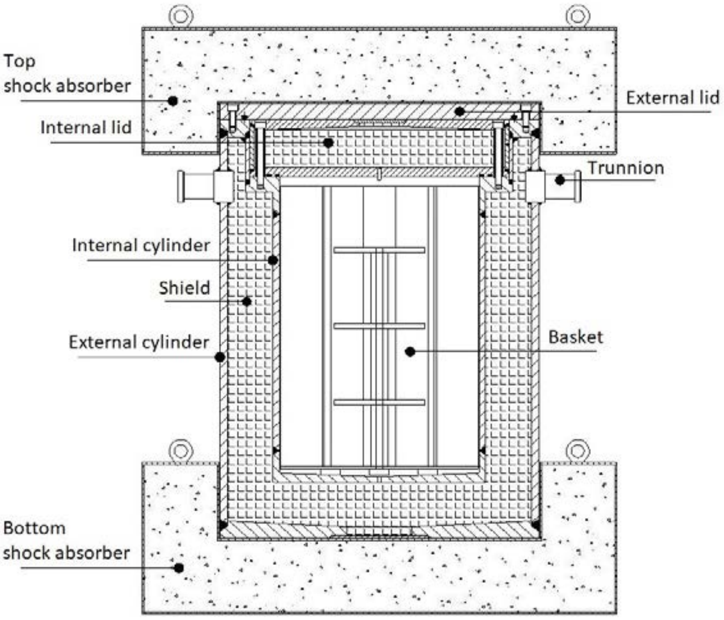

FIG. I–11. The dual purpose cask prototype under development (courtesy of Instituto de Pesquisas Energéticas e Nucleares/ Comissão Nacional de Energía Nuclear (IPEN/CNEN-S)) [I–5].

storage in dual purpose casks, the BRIDE tool was used to select three hypothetical scenarios. These were (a) near term direct disposal of spent fuel; (b) reprocessing abroad, followed by disposal of returned waste products; and (c) interim storage in a monitored facility followed by disposal. The FERREX tool was used to cost the current and the three hypothetical scenarios.

One of the research objectives of Brazil in this CRP was to develop and characterize coatings to protect Al-clad spent RR fuel during long term wet storage. The coatings included boehmite (γ-AlOOH), HTC, cerium incorporated boehmite and cerium incorporated HTC on Al alloy surfaces. HTC is lithium aluminium-nitrate-hydroxide hydrate and it forms on Al alloys immersed in an appropriate alkaline lithium salt solution.

A series of investigations were carried out in which Al alloy AA 6061 specimens (2 cm × 2 cm × 0.2 cm) used in laboratory tests and coupons (10 cm in diameter) as well as plates (62.4 cm × 7.0 cm) used in field tests had their surfaces prepared and coated with boehmite or HTC, with or without incorporation of cerium in the coating. Details about the procedures used to prepare the Al surface, to coat with boehmite or HTC and to incorporate cerium into the coating can be found in Ref. [I–7]. The results of preliminary laboratory corrosion tests and long term water immersion tests revealed that Al specimens and coupons coated with HTC were more corrosion resistant. Subsequent work was focused on further developing the HTC coating. The coating process was refined to prepare the Al surface, coat it with HTC and incorporate cerium into the coating, all at room temperature. Examination of the Al surfaces that were (a) coated with high temperature HTC (HT-HTC) at 98°C, without or with incorporation of Ce (referred to as HT-HTC + Ce); (b) coated with room temperature HTC (RT-HTC) and HTC + Ce; or (c) prepared to simulate spent RR fuel plate surfaces and then coated with HT-HTC + Ce and RT-HTC + Ce was undertaken prior to and after their exposure to the IEA-R1 reactor spent fuel section for a duration of up to three years [I–7, I–8].

This examination was undertaken with an optical microscope and/or a scanning electron microscope coupled to a field emission gun. Coating composition was determined using X ray diffraction analysis as well as electron spectroscopy [I–7, I–8]. The morphology of HTC, shown in Fig. I–12, revealed intersecting blades of HT-HTC crystallites all over the surface.

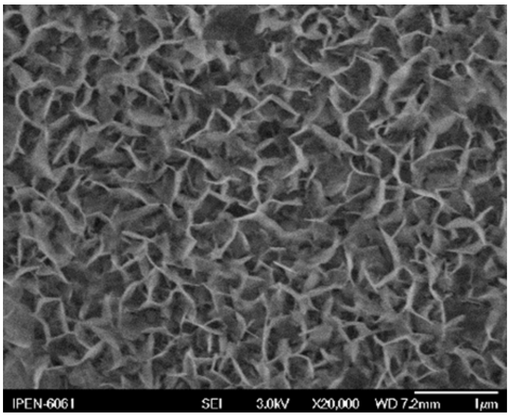

FIG. I–12. Scanning electron micrograph of HT-HTC showing intersecting blade-like morphology (reproduced courtesy of Materials Research[2]).

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The laboratory and field tests indicated a marked increase in the corrosion resistance of the Al alloy AA 6061 coated with HT-HTC. The corrosion resistance of this alloy was further enhanced by cerium incorporation in the coating. Cerium was chosen to enhance corrosion protection, as it is the only rare-earth element (besides europium) that can involve a change in oxidation state and form a water insoluble hydroxide/oxide on Al. To eventually protect highly radioactive spent Al-clad RR fuels during long term wet storage, fuel handling would be facilitated if the HTC coating could be done at room temperature. To this end, a new process was developed and consisted of Al surface preparation, HTC coating and cerium incorporation into the HTC coating, all at room temperature (23°C). Al alloy specimens, coupons and plates coated with RT-HTC using this procedure were also tested and the performance of the RT-HTC and RT-HTC + Ce was evaluated. Further, ‘dummy’ fuel assemblies were prepared containing HT-HTC, RT-HTC, HT-HTC + Ce and RT-HTC + Ce coated Al plates. These ‘dummy’ fuel assemblies were immersed in the IEA-R1 reactor spent fuel section and removed for evaluation after one, two and three years, respectively.

At present, the extent to which RT-HTC imparts protection is lower than that imparted by HT-HTC coating. Attempts are in progress to increase the RT-HTC layer thickness to increase its protection efficiency. Nonetheless, protecting spent fuel with cerium incorporated HTC coatings is the obvious choice. The HTC layer imparts pitting corrosion protection by acting as a physical barrier between the spent fuel basin water and the surface. The higher corrosion resistance of the Al surface with HT-HTC + Ce coating can also be attributed to coarsening of the HTC crystallites during cerium incorporation at 98°C. The mechanism by which the cerium in the HTC imparts protection is ‘active corrosion protection’, analogous to chromium coatings. According to this mechanism, the lower solubility of $CeO_2 \cdot 2H_2O$ allows the formation of $Ce(OH)_2^{2+}$ ions in solution, which then diffuse to defects in the coating that have exposed bare metal. When in contact with the bare metal, the tetravalent Ce in these ions reduces to Ce^{3+} and precipitates as cerium hydroxide, $Ce(OH)_3$, which seals the layer. This involves the release of Ce ions from the coating, the transport of Ce ions through the solution, and its action at defect sites to stifle corrosion. This is a form of self-healing of the exposed bare metal surface. The precipitated cerium hydroxide at the defect then stifles further corrosion. Another explanation that can be attributed to the increased protection given by the HT-HTC + Ce compared with that given by RT-HTC + Ce is the higher amount of Ce in the former, caused by treatment in a high temperature cerium solution, as opposed to treatment of a RT-HTC coated specimen in a room temperature cerium solution.

In conclusion, HTC coatings increased the pitting corrosion resistance of the Al alloy. Cerium incorporation into the HTC coating further increased the pitting corrosion resistance of the Al alloy. Full size plates coated with HTC and exposed to the IEA-R1 reactor spent fuel section for almost two years did not reveal any pits, indicating marked potential for the use of HTC as a protective coating on spent RR fuel during long term wet storage.

I–3.3. Brazilian legal framework for handling, transport, processing and acceptance of nuclear materials

There is no specific document outlining the legal framework for handling, transport, processing and acceptance of nuclear materials. However, the CNEN has norms and resolutions for specific activities [I–3]. Relevant parts of these extensive norms and resolutions could constitute the legal framework mentioned above. These norms were prepared based on IAEA guidelines.

The main norms or resolutions that can be used to extract information to form the legal framework are:

(a) CNEN Norm NN 6.09 and Resolution CNEN 012/02 (September 2002), Criteria for acceptance to store low and intermediate level radioactive wastes.
The main objective of this norm is to establish criteria for the acceptance of LLW and ILW for safe storage in a repository to assure and protect the staff, the general population and the environment from the harmful effects of ionizing radiation.

(b) CNEN Norm NE 5.01 and Resolution CNEN 013/88, Transport of radioactive materials. This norm establishes, with regard to transport of radioactive materials, requirements for radiological protection and safety to guarantee an adequate level of control of the eventual exposure of people, property and the environment to ionizing radiation, and includes (a) specifications about the radioactive materials to be transported, (b) selection of type of packaging, (c) specifications regarding design requisites and acceptance testing of the packaging, (d) guidance pertinent to transportation, and (e) responsibilities and administrative requirements.

(c) CNEN Norm NE 5.02 (October 1986, February 2003), Transport, acceptance, storage and handling of nuclear power plant fuels.

(d) CNEN Norm NE 5.03 (February 1989), Transport, acceptance, storage and handling of nuclear power plant items.

(e) CNEN Norm NE 6.06 and Resolution CNEN 014/89 (January 1990), Selection of sites to store radioactive wastes.

The transport of RR fuel, fresh or spent, has followed these norms and also those stipulated by the Brazilian Institute of the Environment and Renewable Natural Resources. This was done when 127 spent MTR type fuels from the IEA-R1 reactor were shipped to the Savannah River Site in the United States of America under the FRRSNF acceptance programme in 1999. Since 2000, the fuel used in the IEA-R1 reactor is manufactured within the premises of IPEN.

Further, since the long term Brazilian strategy for RRSNF is 10–15 years of at-reactor wet storage followed by at-reactor dry storage, there would be no need to transport RRSNF outside the premises of nuclear installations. However, should such transport become necessary in the future, CNEN Norm NE 5.03, related to the transport of NPP fuels, would be adapted for use.

I–4. CHILE

Chile has operated two RRs, RECH-1 and RECH-2, but only RECH-1 is currently in operation while RECH-2 is in extended shutdown. RECH-1 is a 5 MW thermal power reactor and it went critical in 1974. Table I–1 provides the main technical data about the RECH-1 RR.

In the RECH-1 reactor pool, 90 SFAs can be stored in racks, which were designed for storage of spent LEU and HEU fuel, in any combination, with natural convection for cooling. The RECH-2 reactor has a separate spent fuel storage pool to store 224 SFAs. This reactor also has three racks in the reactor pool to store 30 SFAs. When the fuel assemblies reach the end of their life under normal reactor operation conditions, they are removed and moved to wet storage for sufficient time prior to transfer to dry storage.

According to the Chilean Nuclear Energy Commission (CCHEN), it is estimated that RECH-1 will generate 91 SFAs. RECH-2 has generated 29 SFAs. Hence, with the separate storage pool at RECH-2, the spent fuel storage capacity in Chile is sufficient for at least 30–35 years (assuming that no corrosion-induced damage occurs because of lack of maintaining the pool water quality). Based on this data, a dry storage facility or the need to send SFAs for final disposal would be necessary only after 2030.

The Chilean SFAs will be maintained intact in wet storage and then moved to dry storage, but the schedule for this move has not been decided. Because of the need to maintain the integrity of the fuel cladding during wet storage, a water quality monitoring programme was implemented and a surveillance programme that includes corrosion tests, sipping tests and visual inspections was established. It is also important to have the capability to remove flawed fuels from the core of the reactor. The RECH-1 RR has so far generated 142 SFAs, two of which have presented signs of pitting corrosion. A device to isolate the failed fuel assemblies needs to be developed.

In 2004, a detailed design of a dry storage facility for SFAs was initiated and as of 2016, the basic engineering drawings were being completed. The minimum period for safe dry storage of SFAs, ensuring no risk to people, property and the environment, needs to be defined, as well as the necessary parameters to measure during storage. To maintain fuel cladding integrity, a device needs to be developed to adequately

TABLE I–1. RECH-1 GENERAL OVERVIEW

Parameter		
Purpose		Multipurpose research reactor
Reactor type		Pool
Thermal power		5 MW
Reflector		Beryllium
First criticality		13 October 1974
Operation cycle (full power)		24 h/week
Utilization (full power)		~48 d/year
Fuel use	U-235	300 g/year
	Fuel assemblies	~3.5 FA/year
Average extraction burnup		~40% (149 000 MWd/tU)
Fuel assemblies	Type	MTR type
	Number of plates	16 per fuel assembly
	Enrichment	19.75% U-235
	Meat composition	U_3Si_2/Al
	Meat loading	215 g U-235 per fuel assembly
Present core configuration		32 LEU fuel elements
Equilibrium core size		36 fuel assemblies
HEU to LEU conversion		Completed in May 2006
Thermal flux (max.)		$\sim 7.0 \times 10^{13}$ n · cm^{-2} · s^{-1}
Fast flux (max.)		$\sim 5.0 \times 10^{13}$ n · cm^{-2} · s^{-1}
Origin of fissile material		Russian Federation
Enrichment supplier		Russian Federation
LEU fuel element manufacturer		CCHEN
Operation standard		ISO 9001:2000

dry the fuel to ensure that there are no corrosion problems during dry storage. When this facility becomes available, the SFAs will be processed for transfer from the current storage in the pools. At that time, the SFAs will be stored based on the criterion of confinement and retrievability. Maintaining the SFAs intact provides the flexibility to take advantage of new technological solutions that may become available in the next decades and may be more favourable for the disposal of spent fuel.

I–5. FRANCE

In France, there are currently two operating RRs and 36 RRs that are in permanent shutdown, under decommissioning, or already decommissioned. One RR is under construction [I–9].

French RRSNF management relies on reprocessing in Orano's La Hague plant. RRSNF aluminium and silicide types coming from French RRs, such as Ulysse, Osiris, Orphée, Scarabée, Siloe (operated by the French Alternative Energies and Atomic Energy Commission (CEA)) and HFR (operated by the Laue-Langevin Institute), are transported from their sites to La Hague in TN MTR casks. After a storage period in La Hague pools, RRSNFs are processed and the resulting fission products are vitrified into vitrified waste universal canisters, following the same process scheme as for NPP spent fuels. These canisters are then stored in vault storage on the La Hague site awaiting deep geological disposal (in CIGÉO).

As of 2019, France is one of only two countries offering commercial reprocessing services for RRSNF, along with the Russian Federation. Some other countries (such as the United Kingdom and the United States of America) have been or are operating reprocessing facilities for RRSNF, but do not provide services to other countries. Details of this reprocessing services can be found in Section 2.3.1 of this publication and in NW-T-1.11 [I–10].

I–6. GHANA

Ghana has one operating RR, a low power (~30 kW) MNSR, which began operation in 1994 and is used primarily for neutron activation analysis, education and training. The MNSRs were initially designed to use HEU fuel and there was about 1 kg of HEU in each core. With a new fuel design, Ghana converted to LEU fuel and the reactor now operates at 34 kW; the original HEU core was shipped back to China in 2017.

In the supply agreement for the HEU fuel, it was stated that the fuel would be accepted by the country of origin when it had become spent or disused. This is not the case for LEU, hence Ghana will have spent fuel management responsibility if China does not commit to the acceptance of the spent LEU fuel. The Ghana Atomic Energy Commission will consult with experts to identify and define a comprehensive set of spent fuel management strategies. A costing model will be developed to enable Ghana to determine the most economical and viable means of RRSNF management. These strategies will focus on short and long term management, with ultimate disposal, and will include reprocessing and direct disposal. The evaluation of options will consider safety, security and safeguards requirements.

I–7. GREECE

The Greek Research Reactor (GRR-1) first went critical in July 1961 and ceased operation in July 2004. In 2005, all of the initial HEU core was shipped to the United States of America as part of the FRRSNF acceptance programme. Between 2004 and 2006, the reactor building was refurbished. Refurbishment work on the primary coolant system, however, was not completed and in 2016, it was decided that GRR-1 would be placed in extended shutdown. The GRR-1 fuel is MTR type, consisting of U_3Si_2. Only LEU fuel, fresh or irradiated with low burnup, is stored in the GRR-1 facility. No spent fuel (meeting lifetime expected burnup) is stored at GRR-1 and there are also no damaged fuel assemblies. The LEU fuel has been discharged since July 2004. In order to prepare for either safe fuel shipment for reprocessing or for a spent fuel return to the United States of America, the GRR-1 irradiated fuel inventory was characterized, comprising burnup and gamma heat load calculations.

The actions taken by the GRR-1 personnel involved in the CRP T33001 framework include: investigation of the legal framework related to RRSNF management; inter-institutional discussions to determine a common strategy; initiation of discussions with authorities on the GRR-1 reactor's future; submission of a proposal for GRR-1 restart funding in the framework of the Greek research infrastructure roadmap; contacts with the regulator to explore the regulator's understanding of the situation and assess targets; definition of the most appropriate RRSNF management scenarios; examination of the scenarios against BRIDE criteria; contacts with international partners experiencing similar issues in implementing RRSNF management solutions; contacts with the USDOE to determine the exact current conditions and terms of the fuel return programme status; and exchanges with providers of services related to RRSNF management solutions.

The Greek legal framework related to nuclear fuel includes three main decisions:

(1) It is forbidden to import nuclear waste;
(2) Every nuclear fuel import must be accompanied by a contract obliging the provider to take back the spent fuel;
(3) It is permitted to reimport radioactive waste produced within the country.

Based on discussions with the Greek Government and using the information gained during the CRP, it was decided that the spent fuel should be returned to the United States of America; the shipment was completed in March 2019. The unused fresh fuel has been allocated to be used in another RR.

I–8. JAMAICA

The Jamaican SLOWPOKE-2 RR (JM-1) is a 20 kW thermal pool type reactor, designed by Atomic Energy of Canada Ltd. The reactor is owned and operated by the University of the West Indies, Mona Campus, at the International Centre for Environmental and Nuclear Sciences, and was commissioned in March 1984 with 93% enriched HEU, U–Al fuel. JM-1 has been used primarily for neutron activation analysis in agriculture, health and mineral exploration studies. The conversion of JM-1's core from HEU fuel to LEU fuel was completed in October 2015 and resulted in 888 g of HEU being repatriated to the United States of America. The reactor now operates with 5.6 kg of 19.86% enriched zirconium-clad fuel.

For almost 30 years, the JM-1 facility has operated without a local regulatory authority and without any radiological protection legislation. However, in 2009, the Radiation Safety Authority was established with oversight responsibility for the HEU–LEU conversion of the reactor. In August 2015, the Nuclear Safety and Radiation Protection Act came into effect, requiring all operators of radiation facilities to have a facility decommissioning plan. Under this Act, the Hazardous Substances Regulatory Authority was established in September 2017, becoming the first nuclear regulatory body in Jamaica. It is in charge of implementing the Nuclear Safety and Radiation Protection Regulations of 2019.

As part of developing the decommissioning plan for JM-1, Jamaica opted to participate in this CRP to develop an RRSNF management plan for its LEU fuel. The objectives of the research project were:

- To estimate the LEU core life based on operating history;
- To determine the available spent fuel management and disposal strategies and technologies for RRSNF that are applicable to Jamaica.

I–9. MALAYSIA

Malaysia has one RR, TRIGA PUSPATI (RTP), a TRIGA Mark II type reactor with a power capacity of 1 MW, reaching first criticality in June 1982.

The reactor is fuelled with LEU (19.9% enriched ^{235}U) TRIGA fuel elements, which are made of a cylindrical uranium–zirconium hydride alloy embedded in three different types of uranium weight percentage (8.5wt%, 12.0wt% and 20.0wt%) and clad in stainless steel. Table I–2 summarizes the characteristics of the RTP TRIGA fuel.

I–9.1. Management of fuel

Currently, the inventory of nuclear fuel in Malaysia is small and contains only fuel from the RTP. When the contract was signed, it was agreed that the nuclear material would be used exclusively by, and remain at, the Tun Ismail Atomic Research Centre (now Malaysian Nuclear Agency), unless Malaysia and the United States of America otherwise agreed. It was further reinforced that, in the interest of safeguards, this condition would remain in effect even if such material, equipment or facility is no longer usable for any nuclear activity. No provision on fuel return or take back is mentioned in the purchasing agreement.

In 2004 and in 2014, the United States of America offered a repatriation programme for the spent nuclear fuel through the FRRSNF acceptance programme. This initiative was open to fuel from the

TABLE I–2. CHARACTERISTICS OF THE RTP TRIGA FUEL

Parameter		Nominal value
Thickness	Fuel element (meat and cladding)	3.73 cm
	Fuel meat (U–$ZrH_{1.6}$) and Zr rod	3.63 cm
	Cladding (SS304)	0.051 cm
Cross-section area	Water flow	5.38 m^2
Length	Entire fuel element	75.26 cm
	Active height (fuelled part)	38.1 cm
	Top graphite section	6.5 cm
	Bottom graphite section	9.45 cm
Nominal U content	8.5wt%	190 g
	12.0wt%	275 g
	20.0wt%	495 g
U-235 content	Enrichment	19.9%
	8.5wt%	40 g
	12.0wt%	55 g

United States of America, and participation in the programme is on a voluntary basis. However, with the intention of continuing the operation of the RTP beyond 2016, Malaysia could not participate in the programme and the nuclear fuel will continue to be in use in the RTP.

Based on the design fuel burnup limit of 40% for each fuel element, it is expected that the fuel will last until about 2032 at the current operational usage. The irradiated (spent) fuel elements are kept in the reactor pool, either at the core or within the temporary storage rack (Fig. I–13). The temporary storage rack is located 1 m above the central thimble, at the circumference wall of the reactor pool. The storage rack has the capacity to store 30 fuel elements. A custom-designed pneumatic fuel handler (Fig. I–14) is used to transfer the fuel from the core to the rack and vice versa.

In terms of the legal framework, there are no specific provisions in the Atomic Energy Licensing Act 1984 (Act 304) and its subsidiary regulations regarding spent fuel management. A policy statement is currently being drafted to emphasize the safety and safeguards aspects of the spent fuel management programme and strategy.

I–9.2. Long term back end management of the fuel

In 2016, Nuclear Malaysia initiated the construction on a new spent fuel storage pool to be operational in 2019. It is expected that the first batch of spent fuel from RTP operation will be generated in 2030. Following a cooling period of three years in the reactor pool, the spent fuel will be transferred into the new spent fuel storage pool. It is projected that the overall fuel inventory at the RTP will be declared as spent fuel by 2042.

FIG. I–13. View inside the reactor pool showing the storage rack (courtesy of Malaysian Nuclear Agency).

FIG. I–14. Watertight fuel handler used to remove fuel between storage rack and core (courtesy of Malaysian Nuclear Agency).

The technical requirements for spent fuel disposal are unique to the strategy selected for the spent fuel management. This includes all the administrative and operational activities that involve the handling, storage, treatment, transport and processing of spent fuel as well as the storage, transport and disposal of its derivatives. In addition, the technical requirements vary according to the inventory and the characteristics of the fuel. Hence, the importance of characterizing the spent fuel is an important management requirement. The general characteristics of spent fuel are widely documented and available. However, knowing the characteristics of the reactor-specific fuel is imperative to validate the spent fuel burnup calculation and determine the activity per element. An underwater test rig was designed and fabricated to facilitate characterization of fuel element; the rig is lowered down into the pool next to the fuel element that is intended to be analysed and inspected (Figs I–15 and I–16).

FIG. I–15. Researchers lowering the underwater test rig into the reactor pool (courtesy of Malaysian Nuclear Agency).

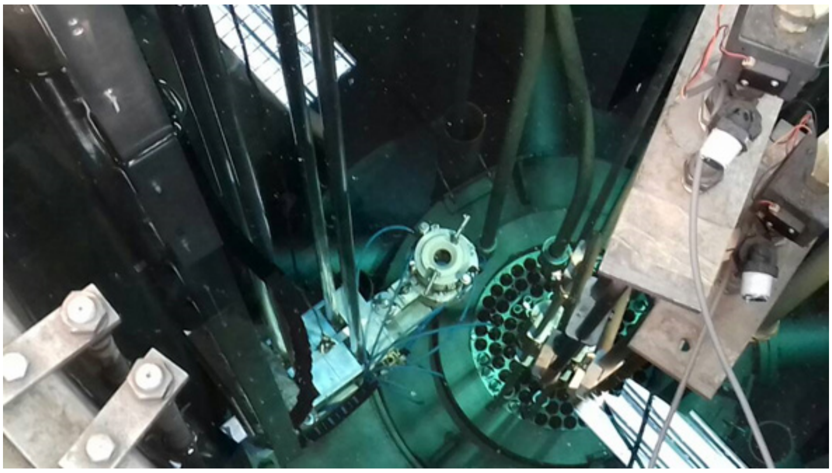


FIG. I–16. Newly developed underwater test rig designed for fuel inspection and characterization (courtesy of Malaysian Nuclear Agency).

With a new spent fuel storage pool soon to be available, it will be possible to carry out physical inspection and characterization in the future. For this purpose, a transfer cask is needed to transfer one element at a time from the reactor pool into the spent fuel pool. A transfer cask was developed and designed by Nuclear Malaysia and was fabricated locally.

In 2015, an initial decommissioning plan for the RTP was developed and presented to the regulator, the Atomic Energy Licensing Board. According to this plan, sustainable management of the spent fuel requires a disposal facility; however, no specific pathway or type of disposal facility for spent fuel is detailed in the plan. Instead, the decision remains open between disposal options within Malaysia or overseas. It is also noted that there is a direct linkage between the spent fuel management option and the resulting type of radioactive waste produced. As such, the strategies and policies of radioactive waste management and the back end management of the nuclear fuel cycle could be integrated. For example, if the fuel is repatriated, the type of radioactive waste to be handled is limited to LLW and ILW, mainly arising from the decommissioning of the reactor. Other than that, the fuel would inevitably be considered HLW.

I–10. NORWAY

I–10.1. Inventory of spent fuel in Norway

Stocks of RRSNF in Norway today have arisen from three heavy water RRs: the Joint European Experimental Pile (JEEP) I, which was operated at the Institute for Energy Technology (IFE) Kjeller site from 1951 to 1967; JEEP II, also located at Kjeller and in operation from 1966 until 2019; and the HBWR in Halden, which operated from 1959 until 2018. Another reactor, NORA, was operated at Kjeller from 1961 to 1968. The NORA fuel, which was identical to the JEEP I fuel, was returned to the United States of America.

Some spent fuel from JEEP I was used in a pilot reprocessing plant at the Kjeller site, which was in operation from 1961 to 1968 and later decommissioned. The second core loading of the HBWR was reprocessed in Belgium in 1969. The recovered uranium and plutonium were sold for civilian use and the waste was disposed of in Belgium. With these exceptions, all Norwegian spent fuel is currently stored at Kjeller and in Halden.

The JEEP I and the HBWR first charge fuels were metallic uranium clad in Al, while the JEEP II fuel is 3.5% enriched UO_2 clad in Al. With the exception of the first charge fuel, the majority of the HBWR fuel is UO_2 clad in Zircaloy and is thus similar to commercial light water reactor fuel.

The JEEP I fuel was all discharged by 1967, with typical burnups in the range from 200 to 400 MWd/tU.

On average, JEEP II fuel elements were irradiated for ten years, to a burnup of 15 000–16 000 MWd/tU. The JEEP II core contains about 220 kg of fuel and approximately 45 kg per year was discharged.

The HBWR first charge fuel was irradiated from 1959 to 1962, for 1000 h at low temperature and power, and the average rod burnup was approximately 12 MWd/tU. The core contained approximately 0.4 tonnes of uranium and up to its shutdown, the majority of the HBWR fuel was discharged after reaching a burnup of approximately 30 000–40 000 MWd/tU (approximately 80 kg per year).

Additionally, there is spent experimental fuel from the research programme conducted in the HBWR. Although the amount is small, this fuel will present challenges in its future management as there are several types of fuel, with varying dimensions.

In total, Norway has some 16 tonnes of spent fuel, of which 6 tonnes are stored at Kjeller and 10 tonnes in Halden. There are approximately 12 tonnes of Al-clad fuel, of which 10 tonnes is metallic uranium fuel and the remainder uranium dioxide (UO_2). Further details are given in Table I–3.

TABLE I–3. INVENTORY OF RRSNF IN NORWAY

Parameter	JEEP I	JEEP II	HBWR first charge	HBWR
Fuel material	Metallic U	UO_2	Metallic U	UO_2
Cladding	Al	Al	Al	Zircaloy
Enrichment (wt%)	Natural	3.5	Natural	6
Discharge burnup (MWd/tU)	1–1000	15 000	12	40 000
Irradiation period	1951–1967	1966–2019	1959–1962	1962–2018
Total mass U (tonnes)	3.1	2.0	6.7	3.5
Current storage	Dry, IFE Kjeller	Dry, IFE Kjeller	Dry, IFE Halden	Wet, IFE Halden

I–10.1.1. Organization and responsibilities

All four RRs in Norway, together with the associated spent fuel storage facilities, have been operated by the Institutt for Energiteknikk (Institute for Energy Technology, IFE), which is an independent foundation. Originally, at its establishment in 1948, the organization was State-owned and operated as the Institutt for Atomenergi (Institute for Atomic Energy).

The current policy is that existing RRSNF will be stored until final disposal is possible [I–11]. However, while there is capacity in the current storage facilities for spent fuel inventory, there is recognition that the current storage arrangements are not appropriate for long term storage and that they do not constitute an end point for the fuel. Thus, other facilities and practices will be required.

State funding for the Norwegian RRs is managed through the Nærings- og fiskeridepartementet (Ministry of Trade, Industry and Fisheries), previously the Nærings- og handelsdepartementet (Ministry of Trade and Industry). Thus, this organization also has responsibility for the long term management (i.e. intermediate storage and final disposal) of spent fuel in Norway. The Ministry has appointed committees comprising various stakeholders and technical experts to provide independent advice and make recommendations. A broad cross-section of stakeholders is represented in the committees, including local government, community representatives, NGOs, experts in geology, safety analyses and RRSNF management, and the Statsbygg (Directorate of Public Construction and Property). These recommendations, if accepted, will form the basis of government policy.

In 2016, the Norwegian Government recommended that funding should be provided for the future decommissioning of nuclear facilities and handling of spent fuel. Funding decisions are to be made as part of the regular annual budget process and approved by parliament.

In 2017, the Norwegian Government announced that it would establish a national radioactive waste management agency, Norsk nukleær dekommisjonering (Norwegian Nuclear Decommissioning, NND). NND will have responsibility for the management of all radioactive waste in Norway and decommissioning of nuclear facilities. NND was established in January 2018 and is expected to be fully operational by 2021. The division of responsibilities between NND and IFE, and their associated transfer, is currently being defined.

Also in 2017, IFE established a new sector, nuclear waste management, to provide support to the Norwegian authorities and other stakeholders in proposing final solutions for all radioactive waste streams, including spent fuels, vitrified waste received in return after reprocessing of spent fuels, and the various types of ILW that cannot be disposed of in the Kombinert Lager og Deponi for Lav- og Middelsaktivt Radioaktivt Avfall (Norwegian Combined Storage and Disposal Facility). A programme has been defined in which the subprogrammes correspond to the main recommendations made by the group that performed the KS1.

In parallel, IFE is continuing inspections of RRSNF and storage facilities, and is evaluating the different options for the long term management of RRSNF, as follows:

(1) Inspection of the condition of the Al-clad RRSNF;
(2) Inspection of the condition of the storage facilities in order to determine their fitness for purpose and estimate their remaining lifetimes;
(3) Investigation of alternative on-site storage arrangements;
(4) Feasibility studies on RRSNF reprocessing at Orano’s La Hague facility, including required infrastructure on the Kjeller and Halden sites;
(5) Feasibility studies on possible alternatives to reprocessing, including oxidation of metallic uranium fuel and decladding of JEEP II fuel with subsequent encapsulation in Zircaloy or stainless steel.

I–10.1.2. Current spent fuel storage arrangements

The Al-clad spent fuel from the three reactors is currently stored in separate dry storage facilities.

After discharge, JEEP I fuel was initially stored in aluminium baskets in a wet storage facility for periods of up to ten years. Transfer of the fuel to the JEEP I dry storage facility (Stavbrønn) started in 1961, and the final transfer took place in 2000. All fuel elements were inspected and repacked into stainless steel baskets in 1982. The JEEP I dry storage facility consists of top and bottom concrete slabs, with the top one at ground level and the bottom approximately 3 m underground. There are 97 vertical holes in each block, and in each hole is positioned a 2.7 m long stainless steel pipe (to hold the baskets), which is fixed into the 20 cm thick slab. The top of each tube is covered with a metal cap and an expansion gasket. The space around the tubes between the two slabs is filled mainly by sand. The storage block is covered by a free-standing building.

Spent fuel from JEEP II is stored in water-filled wells (with a purification system) for 6 to 12 months. The fuel elements are then packed into stainless steel cans before transfer to the dry storage facility (Brønnhuset). This consists of a concrete block with its top at ground level, located beneath a building specifically designed for loading and unloading of transports of radioactive material. The block houses 84 vertical steel tubes, of depth 3–3.5 m. After insertion of the stainless steel cans, the tubes are sealed with lead plugs.

The first charge HBWR fuel was placed in wet storage for approximately three years. In 1962, the rods were dried and loaded into aluminium storage capsules. Inspection showed that all the fuel rods were intact. These capsules were loaded into the dry storage facility (Bunkerbygning), which consists of a concrete shell with 2 m thick walls, with a 1 m thick front shield of reinforced concrete. There are 202 holes in the front, in which 7 m long steel tubes are fitted horizontally. The aluminium storage capsules are placed in the steel tubes. A metal frame to support the tubes is fitted inside the concrete shell. The steel tubes are cooled by natural circulation of air. This facility, together with wet storage ponds, is positioned inside a building fitted with a ventilation system.

The Zircaloy-clad UO_2 fuel from the HBWR is stored in one of two wet storage facilities at the reactor site, each of which consists of steel-lined pits. A forced circulation water loop maintains the required temperature and includes a purification system to maintain water quality.

With the permanent shutdown of the HBWR in 2018, there is sufficient storage capacity on the Halden site for all spent fuel.

I–10.2. Process towards defining a national RRSNF management strategy

In 2001, the Bergan committee submitted its recommendations for an overall policy on spent fuel management [I–12]. The two main recommendations were that the decision on a final disposal method should be delayed while awaiting technical developments in other countries, and that immediate work should be started on an intermediate storage facility, in which the RRSNF should be stored for 50–100 years pending the construction of a final disposal facility. The reprocessing option was not considered because it was “not in accordance with the official Norwegian positions” [I–12]. Export of spent fuel for storage abroad was not recommended, mainly due to both ethical considerations and a presumed low public acceptability.

In 2004, the ‘Foshaug committee’ was established to make recommendations on possible intermediate storage methods and to identify critical points regarding the choice of technical solution and location [I–13]. The committee recommended further investigation into dry storage in a concrete structure or transportable storage containers. It was suggested that a future committee should choose the final technical solution and location of the storage facility. The committee also identified the need for a technical review of metallic uranium fuel and Al-clad fuel safe storage because of the reactivity of metallic uranium and because there existed no current international method suitable for the storage of metallic fuel. Again, the use of reprocessing as an option for metallic uranium/Al-clad fuel was not investigated in depth.

The Stranden Committee, which comprises a wide range of stakeholders and technical experts, with the mandate to find the most suitable technical solution and localization for intermediate storage of spent nuclear fuel and long lived waste [I–14], reported its findings in 2011. Since approximately three quarters of the spent fuel consists of metallic uranium fuel and/or fuel with Al cladding, and with the recognition that this fuel presents significant challenges because of its chemical reactivity and physical instability, a ‘Technical Committee’ (consisting solely of technical experts) was appointed to recommend methods to condition such fuels to render them eligible for interim storage and final disposal [I–15]. The main recommendations of these two committees are summarized below.

Although the amount of RRSNF in Norway (16 tonnes) is very small in comparison with that in countries with commercial nuclear power generation, the majority of the fuel presents significant challenges because of its chemical reactivity and physical instability, and is therefore unsuitable in its current form for storage and disposal. Thus, the committees recommended that the fuel should be stabilized before being transferred to an interim storage facility and subsequently to a final repository. This stabilization should be done immediately, as it was considered that long term storage with a postponed decision on final treatment (often called ‘wait and see’) would be unethical as it would place an undue burden on future generations. This is in accordance with Paragraph 3.29 of IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [I–16], which states: “Radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations; that is, the generations that produce the waste have to seek and apply safe, practicable and environmentally acceptable solutions for its long term management.” The only proven and available stabilization process for the RRSNF in Norway was reprocessing. It was also acknowledged that it would be neither cost effective nor environmentally sound to construct a domestic reprocessing facility for the small amount of RRSNF, and thus a contract with a commercial supplier was required.

Dual purpose storage and transport casks were identified as the most suitable storage concept. The main reason behind this recommendation was that the fuel would be ready for transport to a repository at the end of the storage period. It was also considered an advantage that the casks are not dependent on external systems or structures to maintain safety, security and radiation protection. This would give a large degree of flexibility if it was found necessary to move the storage to another site in the future. There is wide experience in the use of such casks, both for indoor and outdoor storage. They are suitable for storage both of SFAs and the products of reprocessing, including uranium product, plutonium dioxide (PuO_2) and vitrified HLW.

Building a storage facility inside a mountain tunnel would give several advantages compared with an outside building, although both alternatives were considered acceptable solutions. A tunnel facility would give a high level of protection against external impacts, stable storage conditions, low energy costs and low maintenance costs. Investment costs for a tunnel facility were considered to be comparable to a standardized industrial building, and at least a factor of three lower than the costs of a building designed to withstand a high level of external impact.

Because the quantity of spent fuel is very limited, a new facility should be made to store both spent fuel and long lived radioactive waste (of which Norway has a minor quantity consisting of non-irradiated uranium and disused long lived radioactive sources), as well as the products arising from the proposed reprocessing of metallic uranium and Al-clad fuel.

The primary recommendation was to establish the new intermediate storage facility on the site of the Halden reactor. Alternative locations were a site approximately 1 km outside the HBWR reactor site, a site 10 km from the JEEP II reactor site, and a site 60 km from both sites.

All sites were selected based on having a geology and topology suitable for a mountain tunnel. Additional criteria were road standard, availability of infrastructure and potential conflict with other interests. All the proposed sites were considered to have a low value for alternative applications, including as recreation areas.

It was recommended that the organizational and financial framework for a storage facility should be defined as soon as possible by the government, including definition of the financial responsibility for legacy and future waste arising. A public sector organization, independent of the producer of the spent fuel, should be founded to manage the RRSNF, and this organization should also have responsibility for managing radioactive waste in Norway. Funding and operation of this organization should be based on the principle that the polluter pays.

In 2012, six metallic uranium fuel rods with Al cladding were inspected: five rods from the HBWR first charge and one rod from JEEP I. The five Halden rods were intact with no signs of significant degradation or corrosion. However, the one JEEP I rod, which was irradiated from 1951 to 1953 to a burnup of 0.13 MWd/tU, contained an internal blister of uranium hydride (UH_3), which covered almost 5% of the total uranium cross-section. The cladding was intact, and it is considered that the blister was formed as a result of water penetration during irradiation or initial wet storage. Detailed information on these investigations is given in Ref. [I–17].

The identification of this defect revealed the urgency of making a decision on the long term management of the fuel before further deterioration occurs, which may reduce the available options or make them more difficult. As a further result of this finding, a project is under way to investigate all JEEP I and HBWR first charge fuel to register its condition and evaluate the sufficiency of the current storage methods and facilities. This project is being conducted independently of the government-led evaluations detailed below, but its findings may influence the overall process depending on the state of the fuel and storage facilities.

All Norwegian Government projects with a budget of over 750 million Norwegian kroner must be evaluated in line with quality assurance requirements for major public investment projects. In 2013, the Ministry of Trade and Industry issued a call for tender for two ‘concept evaluation’ studies (Konseptvalgutredning, KVU) on the handling of spent fuel and on the future decommissioning of the Norwegian nuclear reactors. A concept evaluation study is an iterative process where the aim is to recommend one concept to meet a specified goal. The recommended concept is based on identified needs, goals and requirements, and includes identification and evaluation of possible concepts, together with uncertainty analyses of selected options and an assessment of the benefits to different stakeholders against the cost of the investment.

The specific questions to be addressed in the spent fuel study were:

(i) Which solutions provide the greatest socioeconomic benefit to society?
(ii) What is important to focus on in further planning to implement the chosen solutions?

The study was conducted by DNV GL AS, together with Studsvik Nuclear AB, Westinghouse Electric Sweden AB, Quintessa Ltd and Samfunns- og Næringslivsforskning — Centre for Applied Research at the NHH Norwegian School of Economics. The same group, with the exception of Quintessa Ltd, prepared the study on decommissioning, and the two studies were conducted in parallel with significant information exchange. The report was issued in January 2015 [I–18], and the main recommendations are summarized below.

Five alternative strategies for management of RRSNF were identified:

(i) Reference alternative (i.e. continued storage at Kjeller and Halden);
(ii) Storage of all RRSNF in one location in Norway;
(iii) A repository in Norway;
(iv) International cooperation on a repository;
(v) Reprocessing of all spent fuel.

All of the three latter strategies include reprocessing. It was also stated that the recommended strategy would depend on the duration of the operation of the reactors and whether reprocessing is acceptable to the Norwegian authorities.

From the results of the analyses and an evaluation of the time horizon, the group concluded that reprocessing all spent fuel is the recommended solution for managing spent fuel under the assumptions that both reactors are permanently shut down over the next few decades and that reprocessing is still a commercially available service.

A further recommendation was that spent fuel should be stored in as few locations as possible to minimize the costs of monitoring, operation and maintenance. Also noted was the need to establish a process for identifying municipalities willing to host a storage facility or repository, built on mutual trust and respect. The government should consider which incentives can stimulate voluntarism, and which can provide new value for a host municipality and the developer and owner of the new facility.

The next step in the official process is quality checking of the concept evaluation study, through the Kvalitetssikring 1 (quality assurance, stage 1, KS1) process, which undertakes socioeconomic analyses of the different identified options. The report, prepared by Atkins and Oslo Economics, was issued in April 2016 [I–19] and concluded that the following main activities should be given priority:

(i) Safe storage of the RRSNF should be ensured;
(ii) The possibilities for RRSNF return or export should be re-examined, at a political level;
(iii) The process to allow RRSNF reprocessing by Orano should be started;
(iv) The possibilities for reprocessing elsewhere should be investigated;
(v) The organizational responsibilities for management of the RRSNF should be clarified;
(vi) The 'polluter pays' principle for the handling and treatment of wastes should be introduced;
(vii) The possibilities for international cooperation on a deep geological repository should be investigated.

Following the recommendations made by the various committees and the previous investigations, many activities are under way as part of the effort to define the strategy for the long term management of Norwegian RRSNF.

I–11. PORTUGAL

Portugal has operated only one RR, the Portuguese Research Reactor (RPI), which reached criticality in 1961. The maximum thermal power of the RPI was 1 MW. From 1961 to 1987, the RPI fuel was MTR type LEU U–Al and 39 SFAs were generated. After major refurbishments, the RPI restarted in 1990 using HEU U–Al fuel. In September 2007, the conversion to LEU U_3Si_2 fuel was completed. The reactor ceased operation in May 2016 for refurbishment operations. The date chosen also enabled RPI to meet the conditions for an eventual return of the SNF within the US take back programme. In September 2017, Instituto Superior Técnico (IST) and the Minister for Science, Technology and Higher Education agreed to permanently shut down the RPI.

I–11.1. Legal framework of spent fuel management

European Union legislation (Directive 2011/70/EURATOM transposed into Portuguese legislation in 2013) obliges the Member States to develop a national programme for the implementation of their spent fuel and radioactive waste management policy. At this time, the only spent fuel management option foreseen was the return of the spent fuel to the United States of America. A new National Plan for Spent Nuclear Fuel and Radioactive Waste Management for the period 2015–2019 was developed by collaboration between the Portuguese regulatory body and IST from 2013 to 2015. This new plan allows the added option of foreign reprocessing of SNF and the storage of the resulting waste in Portugal under the condition that no HLW is produced. After conclusion of the obligatory environmental impact analysis, the plan was approved by the Portuguese Government in September 2017 [I–20].

I–11.2. Spent fuel management at the RPI

SFAs were stored in Al-6061 racks in the reactor pool. The two existing racks have a storage capacity of 20 fuel assemblies each. During the refurbishment of the reactor (1987–1990), the LEU assemblies were temporarily kept in a double-walled container, connected to the water demineralizing system.

The RPI demineralizer system runs permanently and processes about 100 m^3 of reactor pool water per day, which corresponds to about one quarter of the pool volume. For corrosion control, the pH and electrical conductivity are steadily maintained in the order of 6.0 and below 0.8 µS/cm, respectively, which is the recommendation for Al-clad fuels. A sensor immersed in the pool water monitors the pH and conductivity continuously. Additionally, weekly water samples are taken from the pool and analysed manually.

In 1999, Portugal expressed interest in participating in the FRRSNF acceptance programme and returning the HEU before May 2009. As a first step, in August 1999, 39 LEU U–Al fuel assemblies irradiated between 1961 and 1987 were sent to the United States of America (after up to 38 years of storage in the pool). In July 2008, all 31 HEU fuel assemblies (spent and fresh) were shipped to the United States of America.

As part of the CRP activities, the RPI team developed cost estimates using the FERREX and BASCET tools provided. Preliminary cost estimates for two spent fuel management options were developed. For scenario 1 (return of the SNF to the United States of America), the results relied on earlier experience and cost items already defined in the FRRSNF acceptance programme. For scenario 2 (foreign reprocessing and storage of the resulting waste in Portugal), the FERREX tool was used to obtain first rough estimates, which were refined by obtaining commercial offers. However, costs arising from the final waste disposal were not included, since it was unclear which future disposal options for the expected small amounts of waste would be available.

From the successful core conversion in September 2007 until May 2016, the reactor operated with LEU U_3Si_2 fuel. The SNF inventory consisted at that time of 14 fuel assemblies (12 used and 2 unused). After the decision to permanently shut down the RPI, all LEU U_3Si_2 fuel was shipped to the United States of America in March 2019. For efficiency and cost savings, this shipment was combined with the spent fuel shipment from Greece to the United States of America. There is no nuclear fuel in Portugal anymore.

I–12. RUSSIAN FEDERATION

As of July 2020, 18 RRs are operated in the Russian Federation. Besides that, 3 RRs were mothballed, 7 RRs are undergoing decommissioning, and 2 RRs are under construction [I–21]. For all of these reactors, the spent fuel management strategy is the same. After temporary storage in at-reactor facilities, the RRSNF is sent to the RT-1 plant at FSUE PA Mayak for reprocessing. SNF shipments to RT-1 for reprocessing have been considerably intensified due to government targeted financing. A total of 3754 RR SFAs were shipped to RT-1 for reprocessing in the period 2014–2016, and another 2051 RR SFAs in the period 2017–2019 [I–21].

I–12.1. Reprocessing capabilities in the Russian Federation

Capabilities and experience in reprocessing RRSNF at Russian facilities are described in Section 2.3.2 of this publication, as well as in NW-T-1.11 [I–10]. The Russian Federation is a Contracting Party to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. Thus, the spent fuel and radioactive waste both of Russian and foreign origin are managed in compliance with the provisions of the Joint Convention, which is demonstrated by the Russian Federation’s regular national reports describing fulfilment of the obligations of the Joint Convention [I–21].

The underlying principle of the SNF management policy in the Russian Federation is reprocessing to return the recovered nuclear materials into the nuclear fuel cycle and to ensure environmentally safe handling of the fission products. Currently, the national SNF management practice combines SNF controlled storage and reprocessing and ensures safety in handling the accumulated SNF, which is the top priority task.

I–12.2. Radioactive waste management in the Russian Federation

The current practice of radioactive waste management in the Russian Federation is characterized by the following important changes.

In the past, NPPs and large nuclear fuel cycle enterprises generally implemented collection, partial processing and further storage of radioactive waste at their sites. This practice is currently under revision — organizations are now responsible for radioactive waste conditioning (type and form fit for disposal) before the expiration of the temporary storage period regulated by the government agency in charge of radioactive waste management, and its further transfer to the FSUE National Operator for Radioactive Waste Management for disposal. At present, a transient regulatory requirement limits the storage of unconditioned radioactive waste to ten years for organizations operating highly hazardous nuclear and radiation facilities. For other organizations, this period is limited to five years, in accordance with law no. 190 on the Management of Radioactive Waste.

The radioactive waste management practice is being brought into line with the relevant requirements of the Unified State System for Radioactive Waste Management (USS RWM). USS RWM establishment is one of the priority tasks for the State Atomic Energy Corporation ROSATOM as the government agency in charge of radioactive waste management, and in 2018 the third stage of the USS RWM development was started, according to schedule.

The current status of the radioactive waste disposal facilities is as follows [I–21]:

- For Class I and II radioactive wastes:
  - At the deep geological repository for solid HLW and long lived ILW (Nizhnekansk massif in the Krasnoyarsk region), commissioning of the underground research laboratory is scheduled for 2026. The capacities for Class I and Class II radioactive waste disposal are 7500 m^3 and 155 000 m^3, respectively.
- For Class III and IV radioactive wastes:
  - A disposal facility with a total design capacity of 54 200 m^3 is located at the joint-stock company (JSC) Ural Electrochemical Combine (in operation). Commissioning of the Phase 2 facility (39 300 m^3) is scheduled for 2021. The radioactive waste capacity is 4500 m^3 per year, and the lifetime is 10–12 years.

- A disposal facility with a total design capacity of 225 000 m^3 is located at FSUE PA Mayak. Commissioning is scheduled for 2023 for startup facilities of 45 000 m^3 capacity. The radioactive waste capacity is 15 000 m^3 per year, and the lifetime is 15 years.
- A disposal facility with a total design capacity of 142 000 m^3 is located at the JSC Siberian Chemical Combine. Commissioning is scheduled for 2023 for startup facilities of 47 000 m^3 capacity. The radioactive waste capacity is up to 10 000 m^3 per year, and the lifetime is 15 years.

— For Class V radioactive wastes:
  - Three deep geological repositories for liquid radioactive waste are in operation: Seversk (Tomsk region), Zheleznogorsk (Krasnoyarsk region), and Dimitrovgrad (Ulyanovsk region).

FSUE RosRAO is in charge of the management of spent encapsulated radiation sources, LLW and ILW, including reprocessing, conditioning and interim storage, remediation of radioactively contaminated sites and transportation of radioactive materials within the Russian Federation. RosRAO is also implementing programmes on the dismantlement of nuclear submarines and nuclear maintenance ships, including the long term storage of reactor compartments resulting from nuclear submarine dismantlement.

To meet the primary objectives for radioactive waste management, the Federal Target Programmes ‘Nuclear and Radiation Safety’ and ‘Nuclear and Radiation Safety-2’ were developed and implemented to overcome accumulated radioactive waste management problems.

I–13. SOUTH AFRICA

SAFARI-1, located at the Pelindaba Research Center, is a tank-in-pool type RR, using MTR type fuel; it went into operation in 1965 and continues operation today. The reactor core was converted from HEU to LEU in 2009 and currently uses LEU silicide plate type fuel assemblies of conventional MTR design [I–22].

The SAFARI-1 core is loaded with 26 standard fuel assemblies and 6 control assemblies for each operating cycle. An operating cycle is 30 days followed by 5 shutdown days, so SAFARI-1 operates at 20 MW for approximately 300 days per year. In this operating environment, the spent fuel production rate is approximately 40 standard and 10 control assemblies per year. Table I–4 provides some details of the fuel material and the usage.

When in use, each fuel assembly has an end adaptor, machined in the shape of a round to rectangular transition piece welded to each end. However, the end adaptors are removed prior to shipment to the dry storage facility. It is estimated that approximately 1500 SFAs will remain at the end of life of the SAFARI-1 reactor, with approximately equal numbers of HEU and LEU assemblies.

I–13.1. Radioactive waste management policy and strategy in South Africa

In 2005, the South African Department of Minerals and Energy published a policy document titled Radioactive Waste Management Policy and Strategy for the Republic of South Africa [I–23] that outlines clear, well defined guidelines and options within the existing regulatory framework for the management of radioactive waste, including SNF [I–24]. The policy goes on to state that disposal is the ultimate end point for radioactive waste management, but a stepwise waste management process is acceptable. Therefore, in the interim, SNF is stored in authorized facilities at the reactor sites.

The policy also considers various options for the management of HLW and SNF, and dictates that investigations are conducted to support the choice of the most suitable option.

TABLE I–4. SAFARI-1 FUEL DESCRIPTION AND USAGE

Parameter			
Type	Flat plate type	Standard fuel assemblies	19 plates
		Control assemblies	15 plates
HEU	Fuel meat		U–Al alloy
	Cladding		Al
	Enrichment		90.00%
	Mass	Standard fuel assemblies	200 g and 300 g U-235
		Control assemblies	135 g and 202 g U-235
LEU	Fuel meat		U–Al–Si
	Cladding		Al
	Enrichment		19.75%
	Mass	Standard fuel assemblies	340 g U-235
		Control assemblies	229 g U-235
Dimensions		Fuel assemblies	63.0 cm × 8.015 cm × 7.59 cm
		Control assemblies	64.4 cm × 7.68 cm × 7.2 cm
Number of assemblies in reactor core		Total	32
		Standard fuel assemblies	26
		Control assemblies	6
Range of burnup for stored fuel		LEU	5–68%
		HEU	19–85%
Range of wet cooling times for stored fuel			2–10 years
Number of fuel assemblies in on-site dry storage			To be declared if needed
Type of dry storage			Vertical subterranean sealed pipes
Range of cooling times for stored fuel			1–31 years

The following options for investigation are prescribed by the policy:

(a) Long term above ground storage in an off-site facility licensed for this purpose. For SAFARI-1, the storage capacity of Thabana Pipe Store was increased in 2007, allowing enough capacity for the envisaged production of SNF during the lifetime of SAFARI-1.

(b) Reprocessing, conditioning and recycling:
  (i) Reprocessing in South Africa. Among the options investigated, the South African Nuclear Energy Corporation (Necsa) is undertaking preliminary investigations into the recovery of uranium from Al target plate residues.
  (ii) Reprocessing in a foreign country. There are available reprocessing facilities in some countries, and the option of sending South Africa's spent fuel for reprocessing will be investigated and compared to the other options.

(c) Deep geological disposal. The policy observes that disposal is the end point of radioactive waste and that disposal of SNF in a deep geological repository is the preferred option, in line with international consensus and recommendations. The policy emphasizes that, if chosen, the deep geological disposal should include an option for waste retrieval.

(d) Transmutation. There is no active transmutation research in South Africa as of October 2020; however, South Africa continues to monitor international developments in this regard [I–24].

It is a requirement that the choice of the most suitable option considers the policy principles and clearly demonstrates how the option satisfies the national policy objectives. All conclusions on investigations will be subject to public scrutiny.

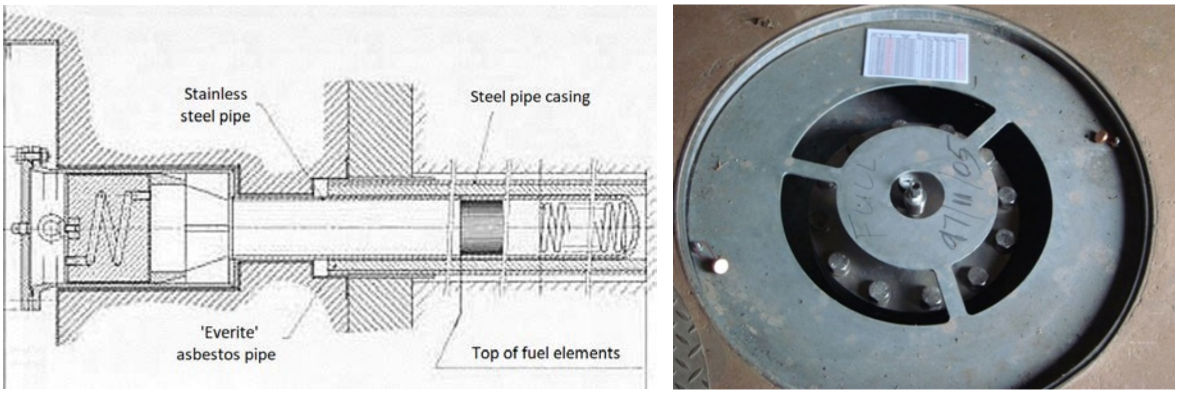
I–13.2. Management of RRSNF at SAFARI-1

At SAFARI-1, the used fuel assemblies, with an average burnup of 55%, are stored in the reactor storage pool for at least two years, but usually three to five years. After this, they are cropped and shipped to the on-site dry storage facility, Thabana Pipe Store (Figs I–17 and I–18), on the Pelindaba site.

As of December 2019, there were 245 spent fuel elements in the storage pool at SAFARI-1 and 1216 elements in the Thabana Pipe Store dry storage facility [I–24]. An ultimate disposal solution has not yet been determined.

(a) (b)

FIG. I–17. The Thabana Pipe Store dry storage facility: (a) exterior and (b) interior, showing an open pipe (courtesy of Necsa).



(a) (b)

FIG. I–18. (a) Diagram of the pipe storage and (b) open pipe (courtesy of Necsa).

I–14. UNITED STATES OF AMERICA

In the United States of America, there are currently 50 operating RRs and 257 that are in permanent shutdown, under decommissioning, or already decommissioned. RRSNF responsibility for these reactors resides with USDOE. Additionally, USDOE is responsible for the fuel returned to the United States of America from other countries via the FRRSNF acceptance programme. Currently, the RRSNF is managed using a combination of wet and dry storage. The United States of America maintains a policy of direct geologic disposal of spent fuel without reprocessing, although legacy reprocessing wastes exist from research and defence activities [I–25].

Most of the RRs have spent fuel storage capacity at their reactor facilities for a few years of operating fuel inventory before spent fuel must be shipped off-site to one of the USDOE laboratories. The Savannah River Site (SRS) in South Carolina stores Al-clad RRSNF. Idaho National Laboratory (INL) stores other types of spent fuel, for example, with stainless steel or Incoloy cladding, such as the TRIGA fuel. The RRSNF fuel stored at these sites includes both HEU and LEU fuel.

Domestic RRSNF is transported to SRS or INL by both rail and truck (Fig. I–19). Foreign RRSNF arrives via ship and is then transported to the appropriate laboratory via rail or truck. USDOE is responsible for preparing the fuel for eventual shipment to a federal repository for disposal, although the time frame for this is not known yet.

At SRS, MTR type spent fuel is being processed to produce down blended LEU; HEU and LEU spent fuel are processed together for efficiency. SRS is authorized to process MTR fuel until 2024; in order to continue processing MTR fuel past that date, they will need an additional authorization. Waste from the down-blending operations is also stored at SRS.

USDOE is conducting studies to look at long term options for SNF management, including continued reprocessing operations, dry storage, etc. The storage of Al-clad fuel poses unique challenges in dry storage because of the potential for small amounts of water to cause gas generation through radiolysis. Currently, sealed dry storage of Al-clad RRSNF is not being practised at any USDOE sites, although most of the stainless steel clad TRIGA fuel is in dry storage. SRS and INL are collaborating to conduct research in this area and establish a sealed dry storage demonstration to inform and guide USDOE decisions regarding a dry storage option for Al-clad RRSNF. A demonstration will be completed around 2027 to help guide USDOE decisions on dry storage implementation.

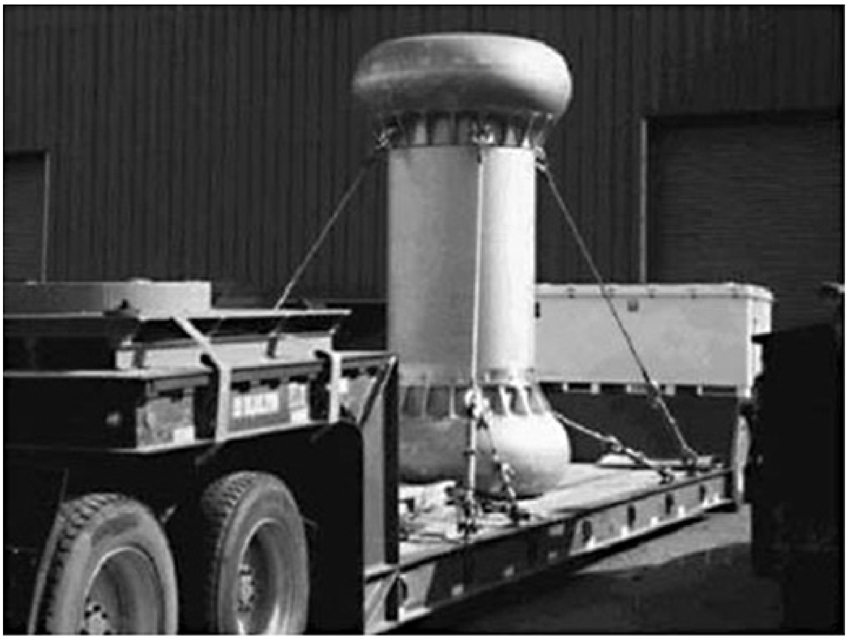


FIG. I–19. The GE Model 2000 package, which is used to transport RRSNF and other RR by-products, radioactive sources or special nuclear materials (courtesy of USDOE).

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Annex II

COUNTRY CASE STUDIES

During the course of the CRP, participants were asked to document the decision processes their countries used to determine the course of action they were taking with their spent fuel management. As noted in Annex I, some countries have not decided on a lifetime strategy for their RRSNF; however, several countries have a well developed, deliberately considered plan. In this annex, the decision processes and key decision points are elaborated. In some cases, the CRP participants used the BASCET and BRIDE tool to develop their plans.

II–1. AUSTRALIA

II–1.1. Cost

In 1998, the Australian Government undertook a review and decided that Australia would not develop local reprocessing of RR fuel. The supported strategy for the management of spent RR fuel was to send it overseas for reprocessing or treatment and receive back residues from the reprocessing operation. To support that decision, government funds were allocated to manage all of the HIFAR and Moata spent fuel.

Due to the design of the OPAL reactor and approximate ten year spent fuel capacity of the service pool, spent fuel shipments were envisaged every six to seven years of operation. Because OPAL operates on LEU silicide fuel, reprocessing options are limited. In the time since OPAL began operations, Orano has developed a process by which LEU silicide fuel can be treated.

Reprocessing and transport logistics costs were justified on the basis of:

- Significant savings over the life of the reactor due to one less shipment of wastes being required in comparison with a France/United States of America management solution (using the FRRSNF acceptance programme);
- Receipt of equivalent waste form to that received from HIFAR reprocessing;
- Proven success for the receipt of HIFAR waste.

II–1.2. Technical risk factors for existing infrastructure

The ageing infrastructure at ANSTO that was used during HIFAR’s lifetime for the management of spent fuel is no longer compliant with current standards. This infrastructure could not be used as a backup strategy for future spent fuel management without large expenditure to upgrade facilities.

An options analysis was completed to compare the benefits of cropping the fuel generated by OPAL to sending uncropped fuel for reprocessing. The cost involved in updating the infrastructure to crop the OPAL fuel was outweighed by the reprocessing savings over the lifetime of the reactor.

The existing spent fuel strategy for the OPAL reactor is that spent fuel is stored in racks in the storage/service pool for up to seven years prior to removal. The removal strategy is that spent fuel casks are introduced to the reactor during a shutdown, fuel is wet loaded into the spent fuel casks during operation and loaded casks are removed from the reactor during a scheduled maintenance shutdown. A 25 tonne nuclear rated crane is used for all movements of the cask within the reactor containment. The greatest technical risk is that the nuclear rated crane ceases operation during the loading phase.

II–1.3. Uncertainties associated with political situations (geography)

In Australia, bipartisan government approval was needed for the decision that reprocessing of spent fuel would occur overseas with the return of residues to Australia. This bipartisan approval occurred in the mid-1980s. This decision has not been revisited since it was taken but there has been general support from the government when new funding requests are submitted to it for spent fuel reprocessing activities. Initial funding to continue overseas reprocessing of OPAL's spent fuel was approved by the government in mid-2011. This initial funding has ensured ongoing operation of the OPAL reactor to about 2030, and further funding will be required from about 2025 to ensure long term commitments to schedule spent fuel to be shipped for reprocessing (to guarantee a reprocessing slot will be scheduled by the reprocessing facility).

A stable political environment within Australia means that external threat factors are relatively manageable during the spent fuel transport exercise.

The political environment of surrounding or transit countries must be considered with shipments of nuclear material. Shipment routes are developed to avoid areas of unrest or known piracy.

II–1.4. Public acceptance

Public acceptance is linked with familiarity with the activity and acceptance of the need for the activity. When spent fuel shipments first occurred in 1998, there was public outcry and protests from issue-motivated groups. With continued public outreach and a regular campaign of shipments over a period of ten years, public acceptance increased to the point where there was no public protest associated with the shipments.

The strategy for outreach was agreed with the ANSTO's governmental department and involved regular briefings to the government on the progress of the spent fuel shipment, scheduled updates to local residents and those along potential transport routes where a spent fuel shipment would necessitate transport along major roads, and public education on the safety of the casks used and the levels of radiation experienced.

II–1.5. Legal and regulatory framework

Australia is not a party to the Paris Convention on Nuclear Third Party Liability [II–1] and has its own government nuclear indemnity covering nuclear activities. It is necessary to define which legal framework is in force during the different phases of the spent fuel transport — loading, land transport in Australia, maritime transport to France and land transport within France. The handover points for nuclear and civil liabilities are explicitly specified in supporting contracts.

The maritime shipment's security and safety arrangements must be overseen by either the French or the Australian regulator, so that the whole transport operation is approved by one of the regulators.

In Australia, the transport of SNF is considered a 'Nuclear Action' under the Environment Protection and Biodiversity Conservation Act 1999. A referral must be made by ANSTO under the Act purporting that the transport and reprocessing of spent fuel to France is not a controlled action requiring an environmental impact assessment.

A number of regulatory bodies have oversight of the spent fuel shipments within Australia, as follows:

- ARPANSA will:
  - Validate the Certificate of Compliance of the Type B transport containers for use in Australia;
  - Provide a Shipment Approval Certificate (including approval of a Transport Safety Plan) permitting transport of the spent fuel along Australian roads;
  - Conduct inspections as required during loading and transport operations.

- The Australian Maritime Safety Authority will:
    - Validate the Certificate of Compliance of the Type B transport containers for use in Australian waters;
    - Provide a Shipment Approval Certificate (including approval of a Transport Safety Plan) permitting transport of the spent fuel in Australian waters;
    - Conduct inspections as required of the transport vessel.
- The Australian Safeguards and Non-proliferation Office (ASNO) will:
    - Approve the Security Plan for the spent fuel shipment for loading and transport operations;
    - Liaise with the Department of Industry, Uranium Industry Section on the export permit submission and conditions;
    - Liaise with United States of America authorities for US Government approval for retransfer of special nuclear material of US origin (note that LEU OPAL fuel has US obligations and permission must be obtained for reprocessing);
    - Liaise with French authorities on accepting receipt of the spent fuel;
    - Conduct inspections as required of the loading and transport operations.

The Department of Industry, Uranium Industry Section issues a customs export permit for the spent fuel, on advice from ASNO that export requirements have been fulfilled.

The Roads and Maritime Services issues a permit for the radioactive goods to transit NSW roads. Route approval is part of this permit.

II–1.6. Safety, security and safeguards requirements for each option

II–1.6.1. Australian safety considerations

Safety considerations must take into account both radiological and work health and safety requirements.

The loading operations must be planned with safety and risk assessments performed for each part of the operation (receipt of casks and equipment to ANSTO site, introduction of casks to reactor building, crane movements of casks on reactor floor, introduction of casks to service pool, loading of casks in service pool, removal of casks from service pool, draining of casks and preparation for transport, securing of casks in transport ISO containers). Both internal and regulatory approvals will be required in Australia before the cask loading can commence. Training and appropriate oversight of staff are essential to these approvals.

II–1.6.2. Australian security and safeguards considerations

Security and safeguards must be taken into account during both loading and transport operations. During loading the security measures in place for the reactor operation will extend to loading operations. Additional security measures may be needed once the loaded transport casks are removed from the reactor building and staged prior to transport.

The national threat level assessment will impact on the extent of the security measures in place during the transport of the spent fuel and the security operation around the port of departure. It is common for the route corridor and port of departure to be secured by NSW Police. Australian Federal Police is also required to secure the nuclear material.

II–1.7. Human resources

ANSTO has, over time, developed in-house or contracted expertise (to support its spent fuel programme) to best manage all activities in the following areas:

- Licensed crane operators;
- Accredited reactor utilization staff (spent fuel loading);
- Staff trained in the operation of spent fuel transport casks;
- Regulatory approvals;
- Transport logistics;
- Security experts;
- Work health and safety experts;
- Communications;
- Government liaison.

II–2. GREECE

Two scenarios for fuel management were examined as applicable to the Greek case: (a) activation of the ‘USA option’, returning the SNF to the United States of America for permanent storage before May 2019 (referred to in the following as ‘scenario A’) and (b) reprocessing abroad followed by disposal of returned products (referred to as ‘scenario B’). The other possible scenarios, such as (c) near term direct disposal of SNF, (d) stabilizing in a domestic facility followed by disposal of stabilized products, (e) storage of spent fuel in a monitored facility followed by disposal of spent fuel, and (f) reprocessing in a domestic facility followed by disposal of waste, are not applicable in the Greek case. This is because in Greece (i) there is no facility able to accept SNF for longer periods of time and (ii) there is no SNF reprocessing facility.

The above scenarios A and B were examined following the BRIDE process. The FERREX cost model is not applicable to the Greek case. In this context, a ‘go’ and ‘no go’ comparison of scenarios A and B indicated that both meet the criteria of safety, security, safeguards, legal and institutional (with a particular reading of the legislation for scenario B), industrial and technical (with technical assistance from the IAEA for scenario B), human resources (with complementary training of personnel for scenario B), environmental impact, legal and institutional (modification of the legislation needed for any new acquisition of fresh fuel in the frame of scenario B) and public acceptance (with some ‘public relations’ operation needed in case of scenario B). In terms of political support, scenario A is favoured.

Applying the BRIDE criteria to the two scenarios reveals that, for scenario A, the cost comprises transportation from the reactor to the port of Piraeus, maritime transport from Piraeus to the Savannah River Site and an acceptance fee, depending on the weight of the delivered SFAs; while for scenario B the cost comprises transportation of the SFAs from the reactor to the reprocessing facility, the reprocessing of the SFAs, the vitrification of minor actinides with proper dilution to reach the ILW characterization, and the transport of the vitrified ILW from the reprocessing facility to the reactor. The total cost of the application of scenario B is of the same order of magnitude as that for scenario A. To this cost one could add the construction of a new ILW storage facility if this proves necessary; alternatively, the acquisition of a transportation cask could solve the problem for a relatively long period, with the corresponding cost. Regarding time schedules, no deadline exists for scenario B and the reactor can operate until the existing fuel reaches limiting burnup. Further, after their extraction from the reactor core, the SFAs should remain in wet storage for cooling purposes before being sent for reprocessing abroad. The vitrified ILW is expected to be returned to Greece ten years after the arrival of the SFAs at the reprocessing facility. All of the above could provide a considerable time margin (at least 15 years) to decide on, and apply a solution for, permanent storage of the ILW.

Discussions were initiated at a senior management/political level on the question of available options should the USA option not be possible, or should there be a possible restart of the reactor in the future. The political decision regarding the current GRR-1 nuclear fuel was made for the activation of scenario A.

II–3. MALAYSIA

II–3.1. Formulating back end strategy

The spent fuel from the TRIGA PUSPATI (RTP) reactor is currently the sole source of future HLW in Malaysia. Unless the nuclear power programme is successful in Malaysia, RTP will remain the only source of SNF and requires specific back end management. Under the circumstance that the spent fuel is not repatriated to its country of origin, there are several possible pathways for managing it, based on either an open or closed nuclear fuel cycle. An example of a pathway is shown in Fig. II–1, which depicts a direct disposal strategy involving a storage phase, a treatment and conditioning phase, and ultimately permanent disposal. Between each phase of the spent fuel management, on-site and off-site transport of the spent fuel may be involved.

Storage is a mandatory step in spent fuel management to allow for cooling, which removes the heat produced by the decay of unstable fission products accumulated within the fuel element. In Malaysia, spent fuels are planned to be stored in the reactor pool for three years for cooling, after which the fuels will be transferred into the spent fuel pool for storage.

Therefore, assuming a scenario where spent fuels in Malaysia only come from the RTP, back end management is formulated based on the vulnerability of the environment and the availability of technologies. Four options for the back end strategy are identified, as follows.

II–3.1.1. Option 1: Long term direct disposal as HLW in Malaysia

This scenario assumes that the spent fuel can be disposed of directly into the ground in Malaysia. A small deep geological repository, for example a deep borehole facility, would be an appropriate means for isolating such wastes permanently from humans and the environment. The spent fuel would be packed into engineered waste packages, ready for direct disposal, with fuel quantities per package limited to satisfy criticality safety requirements for the repository.

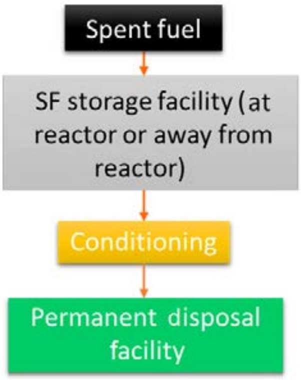


FIG. II–1. An example of a possible spent fuel management pathway.

II–3.1.2. Option 2: Reprocess abroad at a foreign facility with long term disposal as ILW in Malaysia

The reprocessing option is not excluded from the analysis, although the current terms of the purchasing agreement restrict spent fuel reprocessing. Assuming that all of the current fuel elements become spent fuel in 2030 at the earliest, this time horizon allows for advancement in spent fuel reprocessing technology to take place. Due consideration is given to the fact that this option might be practical in the future; however, no commercial reprocessing service is currently available for TRIGA fuel.

In this scenario, the spent fuel will be reprocessed abroad with a special request for the return waste package to be in the form of ILW packages. ILW that contains long lived radionuclides may require disposal at greater depths, of the order of tens of metres to a few hundred metres.

II–3.1.3. Option 3: Conditioning domestically and disposal as ILW

There are several different spent fuel conditioning technologies in different stages of development, such as can-in-canister, press and dilute, chop and dilute, melt and dilute, plasma arc treatment, and glass material oxidation and dissolution systems [II–2]. This scenario assumes that the conditioning of the fuel is carried out domestically in Malaysia, with international assistance, resulting in ILW packages. The waste packages will be permanently disposed of in Malaysia. No specific treatment and conditioning techniques are discussed in this option; rather, this phase is analysed collectively as one of the steps in the overall spent fuel management plan.

II–3.1.4. Option 4: Send and dispose abroad

The final option is to send the TRIGA spent fuel out of Malaysia for final disposal. A commercial service provider has indicated the potential of such a service being offered to foreign countries. This option is radical and subject to government-to-government agreements.

II–3.2. Ranking of the strategy options using AHP methodology

An elicitation process was carried out to rank the options for the back end management as determined above. The analytic hierarchy process (AHP), which is one of the multicriteria decision making models, has been chosen as the methodology to assist the elicitation process. Twenty respondents participated in the study, from the academic, waste operator and reactor operator communities.

In the AHP model, objective information, expert knowledge and subjective preferences are considered together. Figure II–2 illustrates the AHP model structure generated in this study. The main criteria that affect the decision are identified and listed in the figure. In this analysis, eight criteria similar to the BRIDE framework are used: industrial and technical, human resources, environmental impact, legal and institutional, public acceptance, political support, international partnerships and cost. A pairwise comparison matrix calculation is adopted to process the responses from the respondents in order to rank the various criteria. Figure II–3 shows an example of the pairwise comparison, where the numbers written in blue are the input data from the respondent (10 equates to the most important criterion in the ranking system).

The respondents viewed environmental impact as the most important issue pertaining to fuel management, as indicated in Table II–1. The environmental impact criterion was given the highest weightage (0.29), while the lowest weightage criterion was cost (0.07). The options are also treated using a pairwise comparison matrix, revealing the weight for each option. Next, the relative weight of each option to each of the criteria is determined. When the weight of an option with respect to all criteria has been obtained, the overall aggregate or overall weight is computed.

The overall weight vectors for the options with respect to all eight criteria are listed in Table II–2. For the ‘direct disposal’ function, the highest weight vector is 0.55 for the industrial and technical criterion, while the environmental impact and public acceptance criteria have the lowest weight (0.11), indicating

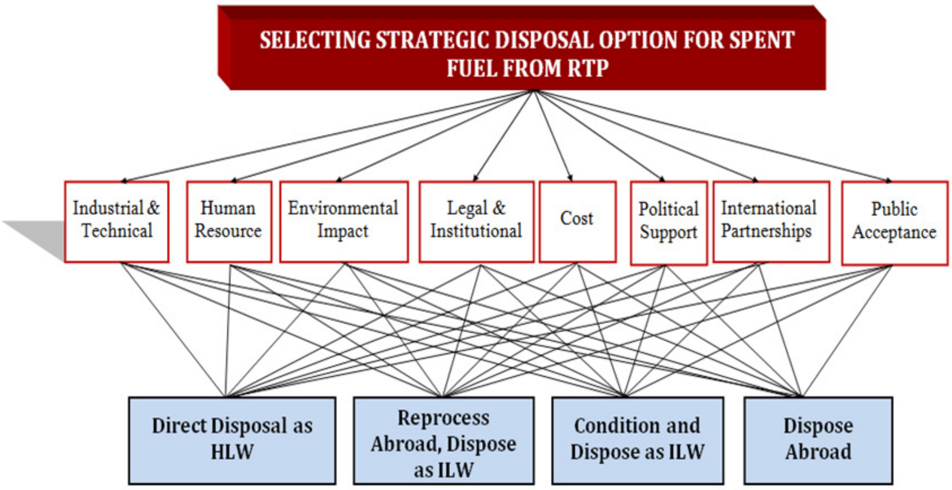
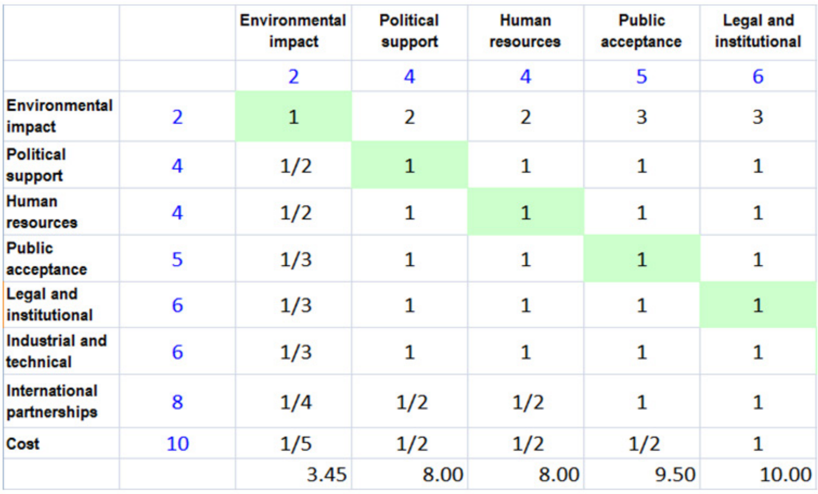


FIG. II–2. Hierarchy structure model for assessment of the back end strategy (courtesy of Malaysian Nuclear Agency).



		Environmental impact	Political support	Human resources	Public acceptance	Legal and institutional
		2	4	4	5	6
Environmental impact	2	1	2	2	3	3
Political support	4	1/2	1	1	1	1
Human resources	4	1/2	1	1	1	1
Public acceptance	5	1/3	1	1	1	1
Legal and institutional	6	1/3	1	1	1	1
Industrial and technical	6	1/3	1	1	1	1
International partnerships	8	1/4	1/2	1/2	1	1
Cost	10	1/5	1/2	1/2	1/2	1
		3.45	8.00	8.00	9.50	10.00

FIG. II–3. Example of pairwise matrix calculation for processing input data from a respondent.

TABLE II–1. NORMALIZED WEIGHT VECTOR FOR EACH CRITERION

Criterion	Weight vectors
Industrial and technical	0.10
Human resources	0.12
Environmental impact	0.29
Legal and institutional	0.10
Public acceptance	0.11
Political support	0.12
International partnerships	0.08
Cost	0.07

TABLE II–2. OVERALL WEIGHT VECTOR FOR THE ALTERNATIVES WITH RESPECT TO ALL CRITERIA

Criterion	Direct disposal as HLW	Reprocess abroad, dispose of as ILW	Dilute and Condition domestically, dispose of as ILW	Send and dispose of abroad
Industrial and technical	0.55	0.13	0.23	0.09
Human resources	0.31	0.16	0.40	0.13
Environmental impact	0.11	0.21	0.12	0.55
Legal and institutional	0.29	0.34	0.20	0.17
Public acceptance	0.11	0.56	0.18	0.14
Political support	0.34	0.29	0.20	0.17
International partnerships	0.29	0.29	0.29	0.14
Cost	0.24	0.52	0.12	0.12

that the most important issue in relation to the direct disposal option is technical capability and capacity. Meanwhile, for the ‘send and dispose abroad’ function the environmental impact criterion has the highest weight vector at 0.55, while the lowest weight is for the industrial and technical criterion (0.09), implying that this option is the most favourable from the environmental impact perspective.

The weight vectors of the criteria (Table II–1) are then multiplied by the weight vectors of the options (Table II–2) to obtain the score of each option and generate the priorities of the different options for SNF management. Table II–3 shows the priorities of the options calculated from the input data of one of the respondents.

Overall, the analysis shows that the ‘send and dispose abroad’ option is ranked as the first option, with 29% of respondents opting for it, while the least favourable option is ‘direct disposal as HLW’, which 22% of respondents opted for. The ‘send and dispose abroad’ option was viewed as superior in terms of having the lowest environmental risk. The ‘dilute and condition’ option is ranked as the second most favourable, with 25% support, while the ‘reprocess abroad with domestic disposal as ILW’ option received 24% and is ranked as the third most favourable option. The result also indicates that environmental impact and industrial and technical criteria are the dominant factors affecting the decision for these options. When the ‘send and dispose abroad’ function is taken out of the equation to eliminate bias between domestic and international disposal, the result shows that the options of ‘reprocess abroad, dispose of as ILW’ and ‘dilute and condition domestically as ILW’ are comparable, with 35% and 34% support, respectively. These two options are favoured over the ‘direct disposal as HLW’ option due to the final disposal being treated as ILW. ILW is perceived as more manageable than HLW with proper engineering design, while the disposal facility for HLW is regarded as technically challenging. If the cost criterion is not considered in the assessment, the ‘reprocess abroad, dispose of as ILW’ option ranks highest (39%). At the moment, the cost argument has a minimal contribution to the decision making process, probably due to the high subjectivity of the cost element, as very limited information is known at this point of analysis.

In conclusion, four options were identified and eight criteria comprising technical and non-technical elements were assessed in order to select and prioritize a disposal option. Each criterion was evaluated and converted into numerical values by AHP. The present study shows that the most favourable option

TABLE II–3. EXAMPLE OF COMPUTATION OF THE SCORES AND PRIORITIES OF THE OPTIONS

Alternative	Priority of direct disposal as HLW	Priority of reprocess abroad, dispose of as ILW	Priority of dilute and condition domestically, dispose of as ILW	Priority of send and dispose of abroad
Weight vectors multiplication (criterion × option)	0.10 × 0.55	0.10 × 0.13	0.10 × 0.23	0.10 × 0.09
	0.12 × 0.31	0.12 × 0.16	0.12 × 0.40	0.12 × 0.13
	0.29 × 0.11	0.29 × 0.21	0.29 × 0.12	0.29 × 0.55
	0.10 × 0.29	0.10 × 0.34	0.10 × 0.20	0.10 × 0.17
	0.11 × 0.11	0.11 × 0.56	0.11 × 0.18	0.11 × 0.14
	0.12 × 0.34	0.12 × 0.29	0.12 × 0.20	0.12 × 0.17
	0.08 × 0.29	0.08 × 0.29	0.08 × 0.29	0.08 × 0.14
	0.07 × 0.24	0.07 × 0.52	0.07 × 0.12	0.07 × 0.12
Score	0.25	0.29	0.20	0.26

is ‘send and dispose abroad’, although contrary to expectation, this option is not far ahead of the others. If this option is taken out of consideration, the ‘reprocess abroad, dispose of as ILW’ option is the most favourable for the back end management of spent fuel in Malaysia. It should be noted that this analysis is a form of exercise and the result of this study does not represent Malaysia’s decision on this matter.

II–3.3. Back end management analysis using BRIDE

The BRIDE tool developed in the project was tested to evaluate its capability as a decision making tool to help define a spent fuel back end strategy. The results of the test were also compared to the results from the AHP study described in Section II–3.2 of Annex II. Default scenarios in the BRIDE tool were tested. There are five default scenarios in the tool and for each scenario, the interpretation of the users is given. The scenarios are as follows:

- Scenario 1: Near term direct disposal.
  This scenario is perceived as being similar to the deep borehole disposal concept.
- Scenario 2: Reprocess abroad, followed by disposal of returned products.
  This scenario assumes that the spent fuels will be transported to a technology provider outside Malaysia for reprocessing, while the final products will be brought back to Malaysia for permanent disposal. No specific type of waste package product is specified, either HLW or ILW.
- Scenario 3: Stabilize in domestic facility followed by disposal of stabilized products.
  This scenario assumes that treatment and conditioning facilities will be developed and constructed in Malaysia to process the fuels into a stabilized form of product. It is assumed that international assistance is acquired to fulfil the technical capacity needed to develop such facilities.
- Scenario 4: Storage of RRSNF in a monitored facility, followed by disposal of RRSNF.
  This scenario refers to a status quo strategy whereby the spent fuels are stored in a storage facility for an undefined period, but with the intention of disposal in the future.

— Scenario 5: Reprocess domestically, followed by disposal of waste.
This scenario assumes that a reprocessing facility is developed and constructed in the country.

Three respondents took part in this test case and all of them had taken part in the previous AHP study. The backgrounds of the respondents are as follows:

— Respondent 1 is an officer in charge of policy and international relations;
— Respondent 2 is an academic staff member teaching nuclear engineering;
— Respondent 3 is an officer from a waste management unit.

II–3.3.1. Results of BRIDE test case

The results of the test case study showed that respondent 1 ruled out any option involving reprocessing from the scenario list and only selected two options for further consideration, which were scenario 1 and scenario 4. Respondent 2 and respondent 3 were willing to consider all the options. As for the weighting of the criteria, respondent 2 did not distinguish between the criteria, specifying a ‘10’ for all of them, while respondents 2 and 3 gave a weight of ‘5’ for the cost criterion, as compared to the non-cost criteria which were weighted ‘10’. The average weight score is summarized in Table II–4 below.

In the BRIDE simulation, the indicative costs in arbitrary units for each scenario are: 4.13 (scenario 1); 10.00 (scenario 2); 4.04 (scenario 3); 3.59 (scenario 4); and 1.56 (scenario 5). Each participant scored the scenarios individually. The total score for each scenario is calculated by summing up the generated non-economic factors score and the cost score. Figure II–4 depicts the overall score summary as tabulated in the ‘Master’ tab of the BRIDE tool.

II–3.3.2. Discussion

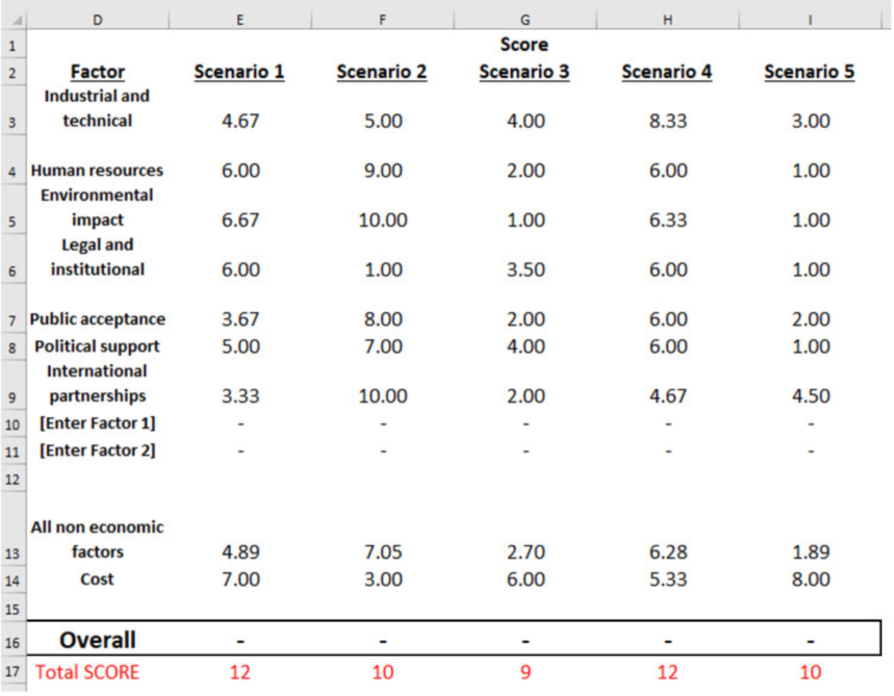
The result shows that the preferred option for managing spent fuel from the RTP RR is scenario 4, which is the long term storage of SNF in a monitored facility, with possible disposal in the future.

Comparing the outcome from the previous AHP analysis, in which the ‘send and dispose abroad’ option was preferred, one can conclude that a cheaper option with the lowest technical risk is in both cases the preferred option.

It is interesting to note that, in both types of assessment, only small difference in scores between the options are observed. This could stem from limited experience or exposure to the subject matter on the

TABLE II–4. AVERAGE WEIGHT SCORE IN THE BRIDE TEST CASE

Factor	Weight
Industrial and technical	9.67
Human resources	8.50
Environmental impact	10.0
Legal and institutional	10.0
Public acceptance	8.67
Political support	10.0
International partnerships	9.33



	D	E	F	G	H	I
1				Score		
2	Factor	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
3	Industrial and technical	4.67	5.00	4.00	8.33	3.00
4	Human resources	6.00	9.00	2.00	6.00	1.00
5	Environmental impact	6.67	10.00	1.00	6.33	1.00
6	Legal and institutional	6.00	1.00	3.50	6.00	1.00
7	Public acceptance	3.67	8.00	2.00	6.00	2.00
8	Political support	5.00	7.00	4.00	6.00	1.00
9	International partnerships	3.33	10.00	2.00	4.67	4.50
10	[Enter Factor 1]	-	-	-	-	-
11	[Enter Factor 2]	-	-	-	-	-
12						
13	All non economic factors	4.89	7.05	2.70	6.28	1.89
14	Cost	7.00	3.00	6.00	5.33	8.00
15						
16	**Overall**	-	-	-	-	-
17	Total SCORE	12	10	9	12	10

FIG. II–4. Summary of the total score for each scenario.

part of the respondents, making the respondents more reserved in their opinions. A valuable observation from this assessment is that the role of facilitator is crucial to encourage sufficient discussions for all participants to fully understand the scenarios and the impacts they have on each attribute of the evaluation. This would help the respondents to score more appropriately, and the result becomes more distinct between each option.

Nevertheless, the respondents should also be credited for their willingness to stay optimistic in their responses and consider options such as reprocessing that are beyond the current restrictions and limitations in technical capabilities, so that all five scenarios could be evaluated in this study.

II–4. NORWAY

As described in Section I–10 of Annex I, the Nærings- og Fiskeridepartementet (Ministry of Trade, Industry and Fisheries) has taken the lead in the definition of arrangements for the long term management (i.e. intermediate storage and final disposal) of spent fuel in Norway. The Ministry has appointed committees comprising various stakeholders and technical experts to provide independent advice and make recommendations. A broad cross-section of stakeholders have been represented in the committees, including local government, community representatives, NGOs, experts in geology, safety analyses and RRSNF management, and the Statsbygg (Directorate of Public Construction and Property). These recommendations, if accepted, then form the basis of government policy.

To support the Stranden Committee, a Technical Committee was appointed to recommend methods to condition such fuels to render them eligible for interim storage and final disposal [II–3]. The members of the Technical Committee were from the IFE, Studsvik Nuclear AB (Sweden) and the IAEA, and all were chosen by the management of their respective organizations. The Technical Committee’s report [II–4] was submitted to the Stranden Committee as input to the latter’s work.

In the sense that its main recommendation was accepted by subsequent committees, the Technical Committee's interpretation of its mandate can be considered to have set the terms of reference for follow on work. Specifically, the committee:

(1) Concluded that it should present opinions on all technically feasible options available, without excluding or failing to evaluate any option that might be impossible because of current national laws or known or perceived policy at the time of writing (the exception to this rule being technical options that entail the use of United Kingdom facilities on the Sellafield site, as these were specifically excluded in the mandate);
(2) Worked on the basis that any proposed conditioning process should render the fuel into a form eligible for both interim storage and final disposal;
(3) Assumed geological disposal as the final end point for the fuel.

In making recommendations for the management of these fuels, the committee identified possible treatment options and chose (based on other studies in, for example, Canada and the United Kingdom) a list of criteria against which to test the options. The criteria and options are listed below.

- Options:
  - Direct disposal;
  - Long term interim storage with postponed decision;
  - Exchange of fuel;
  - Return to the country of origin;
  - Commercial reprocessing;
  - Domestic conditioning;
  - Conditioning using developments of the Plutonium Uranium Redox Extraction (PUREX) process;
  - Electrometallurgical conditioning (pyroprocessing);
  - Calcination.
- Criteria:
  - IAEA and OECD/NEA recommendations, including ethical aspects;
  - Technical suitability;
  - Maturity and availability of the technology;
  - Decisions taken by other countries on similar fuel types;
  - Environmental impact;
  - Value for money;
  - Public acceptance (not considered, as can always find one stakeholder who would disagree).

The results of these analyses were presented in a decision table (Table II–5), which can be considered as a form of non-numerical BRIDE type analysis.

The committee's main recommendation, based on the decision table, was that "in practice, once recommendations were made against direct disposal and interim storage with postponed decision, one treatment option — overseas commercial processing — is clearly shown to be superior when compared against the chosen selection criteria."

This recommendation can be identified with the 'chosen scenario' arising from the BRIDE analyses.

Further, the committee recommended the following: "The next step should be a high level political decision on whether to pursue the overseas commercial processing option."

As discussed in more detail in Annex I, the Stranden Committee accepted this main recommendation and used it as a basis for its work. A 'concept evaluation' (Konseptvalgutredning, KVU) spent fuel study was conducted in 2014–2015 and the report stated that the recommended strategy would depend on whether reprocessing is acceptable to the Norwegian authorities [II–5].

TABLE II–5. COMPARISON OF OPTIONS FOR CONDITIONING OF METALLIC URANIUM AND AL-CLAD RRSNF

Method	IAEA and OECD/NEA recommendations/ethical aspects	Technical suitability	Technology maturity/ availability	International experience	Environmental impact	Value for money
Direct disposal	Not applicable	Low: possible formation of pyrophoric and gaseous reaction products with water	No experience with types of fuels under consideration. Concept accepted in, among others, Sweden and Finland for oxide fuel	None	Poor: possible formation of pyrophoric and gaseous reaction products with water. Possible release of radioactivity to the biosphere	Good
Storage and postponed decision	Ethical objections	Low: degradation of fuel may occur	Mature: current situation	Extensive	Poor: degradation of fuel will occur	Poor: is not a final solution
Exchange of fuel	Ethical objections	Unknown: no potential exchange identified	Unknown: no potential exchange identified	Cases exist	Unknown: no potential exchange identified	Unknown: no potential exchange identified
Return to the country of origin	Supported: for example US and Russian return programmes	Mature and well proven	Mature and well proven	Mature and well proven	Waste products stable in repository (fuel will be conditioned by PUREX)	Good
Commercial processing using PUREX	Supported: for example Serbian fuel, US and Russian return programmes	Mature and well proven	Mature and well proven	Mature and well proven	Waste products stable in repository (fuel will be conditioned)	Good: commercial services offered
Domestic conditioning using development of PUREX	Not applicable	PUREX is mature and well proven. Developments under way internationally	PUREX is mature and well proven. Developments under way internationally	PUREX is mature and well proven. No experience with developments	Waste products stable in repository (fuel will be conditioned). Additional radioactive waste from domestic facility	Very poor: domestic facility required

TABLE II–5. COMPARISON OF OPTIONS FOR CONDITIONING OF METALLIC URANIUM AND AL-CLAD RRSNF (cont.)

Method	IAEA and OECD/NEA recommendations/ethical aspects	Technical suitability	Technology maturity/ availability	International experience	Environmental impact	Value for money
Domestic conditioning using electrometallurgical conditioning	Not applicable	Medium: requires extra step for Al removal	Clad removal step unproven	Metallic U fuel with stainless steel cladding (EBR-II fuel)	Waste products probably stable in repository	Very poor: domestic facility required
Domestic conditioning using calcination	Not applicable	Low: requires decladding and extensive cutting of fuel rods, plus further conditioning to produce a stable waste form	Not proven	Tested on unirradiated material	Waste products would be stable in repository if suitable conditioning method identified	Very poor: domestic facility required

The next step in the official process is quality checking of the concept evaluation study. This is done in the so-called KS1 process, which undertakes socioeconomic analyses of the different identified options. The report, prepared by Atkins and Oslo Economics, was issued in April 2016 [II–6] and concluded that the process to allow reprocessing of the RRSNF by Orano should be started (although it also recommended further investigation of alternatives to reprocessing).

II–4.1. Conclusions

The recommendation to reprocess chemically unstable spent fuel was first made by a committee consisting solely of technical experts, and this recommendation has been accepted by subsequent committees which have comprised a majority of non-technical experts. As of June 2019, the feasibility of this option is still under investigation, although other stabilization methods are under investigation in parallel. The subsequent formal processes (KVU and KS1), after reviewing and accepting this main recommendation, have mainly considered the societal and financial aspects of the management route.

The Norwegian process shows some parallels with BRIDE, especially in the choice of options and criteria; the Technical Committee's decision making process can be considered as a non-numerical BRIDE process. However, one aspect of the Norwegian process shows a significant departure from BRIDE, which brings together a wide range of stakeholders at the beginning of the process to define the scenarios. It is unknown what would have been the Norwegian conclusion had the BRIDE process been followed from the beginning.

REFERENCES TO ANNEX II

[II–1] Paris Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, as amended by the Additional Protocol of 28 January 1964, by the Protocol of 16 November 1982 and by the Protocol of 12 February 2004, NEA/NLC/DOC(2017)5/FINAL, OECD/NEA, Paris (2020).

[II–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Cost Aspects of the Research Reactor Fuel Cycle, IAEA Nuclear Energy Series No. NG-T-4.3, IAEA, Vienna (2010).

[II–3] STRANDEN, E., et al., Mellomlagerløsning for brukt reaktorbrensel og langlivet mellomaktivt avfall, Rep. NOU 2011:2, Departementenes servicesenter Informasjonsforvaltning, Oslo (2011).

[II–4] BENNETT, P., OBERLÄNDER, B., ADELFANG, P., ERIKSSON, E., Recommendations for the Conditioning of Spent Metallic Uranium Fuel and Aluminium Clad Fuel for Interim Storage and Disposal, Nærings- og handelsdepartementet, Halden (2010).

[II–5] DNV GL, STUDSVIK NUCLEAR, WESTINGHOUSE ELECTRIC SWEDEN, QUINTESSA, Samfunns- og Næringslivsforskning, Konseptvalgutredning for oppbevaring av norsk radioaktivt avfall, Rep. 2014-1329, Rev. 1.0, Nærings- og fiskeridepartementet, Høvik (2015).

[II–6] ATKINS, OSLO ECONOMICS, Kvalitetssikring (KS1) Oppbevaring av radioaktivt avfall, Finansdepartementet and Nærings- og Fiskeridepartementet, Oslo (2016).

GLOSSARY

These terms have been used in the context of the CRP T33001, Options and Technologies for Managing the Back End of the Research Reactor Nuclear Fuel Cycle. While they are mostly drawn from current IAEA publications (reference provided), in some cases, they have been slightly modified to ensure their applicability to spent fuel versus radioactive waste or radioactive sources; these terms are identified as 'based on' the reference provided.

acceptance criteria. Specified bounds on the value of a functional indicator or condition indicator used to assess the ability of a structure, system or component to perform its design function. (IAEA Safety Glossary, 2018 Edition)

at-reactor SNF storage. A facility near the reactor (could be in the same building) in which the SNF is stored (usually) under water after discharge from the core, for cooling. This can also be called a 'cooling pond'. (Based on Management and Storage of Research Reactor Spent Nuclear Fuel, IAEA Proceedings of a Technical Meeting, Thurso, United Kingdom, 19–22 October 2009)

away-from-reactor SNF storage. A facility in which the SNF is stored until a final SNF disposal option is implemented. This is in another separate building from the reactor building. Away-from-reactor SNF storage may be wet (pool type, similar to the cooling pond) or dry (for example, in vaults or in casks). (Based on Management and Storage of Research Reactor Spent Nuclear Fuel, IAEA Proceedings of a Technical Meeting, Thurso, United Kingdom, 19–22 October 2009)

back end. That part of the nuclear fuel cycle that occurs from the point when the fuel is removed from the core for the final time (from the reactor to geological (ultimate) disposal). (IAEA Nuclear Energy Series No. NP-T-5.4, Optimization of Research Reactor Availability and Reliability: Recommended Practices, 2008)

borehole. A cylindrical excavation, made by a drilling device. (Based on IAEA Radioactive Waste Management Glossary, 2003 Edition)

cask. A vessel for the transport and/or storage of spent fuel and other radioactive materials. The cask serves several functions. It provides chemical, mechanical, thermal and radiological protection and dissipates decay heat during handling, transport and storage. (IAEA Radioactive Waste Management Glossary, 2003 Edition)

conditioning. Operations that produce a waste or spent fuel package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, enclosure of the waste in containers and, if necessary, provision of an overpack. (Based on IAEA Safety Glossary, 2018 Edition)

container, waste. The vessel into which the waste form is placed for handling, transport, storage, and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The waste container is a component of the waste package. For example, molten high level waste glass would be poured into a specially designed container (canister), where it would cool and solidify. (IAEA Safety Glossary, 2018 Edition)

containerization. To place spent fuel into a container followed by seal welding of the lid. (Based on IAEA-TECDOC-1644, Borehole Disposal of Disused Sealed Sources, 2011)

disposal. Emplacement of waste in an appropriate facility without the intention of retrieval. (IAEA Safety Glossary, 2018 Edition)

encapsulation. Emplacement of a solid waste form (e.g. spent fuel assemblies) in a container. (IAEA Radioactive Waste Management Glossary, 2003 Edition)

fuel assembly. A set of fuel elements and associated components which are loaded into and subsequently removed from a reactor core as a single unit. (IAEA Safety Glossary, 2018 Edition)

fuel element. A rod or plate of nuclear fuel, its cladding and any associated components necessary to form a structural entity. (IAEA Safety Glossary, 2018 Edition)

fuel handling. The movement, storage and control of fresh and irradiated fuel, whether manually or by means of automated systems, during reactor, shipping, storage, reprocessing and disposal operations. (Based on IAEA Safety Standards Series No. NS-G-4.3, Core Management and Fuel Handling for Research Reactors, 2008)

immobilization. Conversion of waste or spent fuel into a waste form by solidification, embedding or encapsulation. Immobilization reduces the potential for migration or dispersion of radionuclides during handling, transport, storage and/or disposal. (Based on IAEA Safety Glossary, 2018 Edition)

integrated approach. This term refers to a logical and preferably optimized strategy used in the planning and implementation of a radioactive waste management programme as a whole, from waste generation to disposal, such that the interactions between the various stages are taken into account so that decisions made at one stage do not foreclose certain alternatives at a subsequent stage. For example, the generation of waste is highly dependent on the design, planning and operation of a nuclear facility. (IAEA Radioactive Waste Management Glossary, 2003 Edition)

nuclear reactor core. The fuel assemblies and components essential to reactivity control, from the control rods to the reactor reflector or moderator/coolant housing. This includes equipment used to provide structural support of the core construction, the tools, devices or other items that are inserted into the reactor core for monitoring, flow control or other technological purposes. Core components include experimental devices that may be fixed in the core (e.g. flux trap and test loop components, cold and hot neutron sources and bulk samples for irradiation). (IAEA Safety Standards Series No. NS-G-4.3, Core Management and Fuel Handling for Research Reactors, 2008)

overpack. An enclosure which is used by a single responsible organization to facilitate as a handling unit a consignment of one or more packages for convenience of handling, stowage and carriage. (Based on IAEA Safety Glossary, 2018 Edition)

package. The complete product of the packing operation, consisting of the packaging and its contents prepared for transport. (IAEA Safety Glossary, 2018 Edition)

packaging. Preparation of radioactive waste for safe handling, transport, storage and/or disposal by means of enclosing it in a suitable container. (IAEA Safety Glossary, 2018 Edition)

package, spent fuel. Conditioned spent fuel in a form suitable for transport, storage and/or disposal. (IAEA Radioactive Waste Management Glossary, 2003 Edition)

package, waste. The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liners), prepared in accordance with the requirements for handling, transport, storage and/or disposal. (IAEA Radioactive Waste Management Glossary, 2003 Edition)

pretreatment. Any or all of the operations prior to waste treatment, such as collection, segregation, chemical adjustment and decontamination. (IAEA Safety Glossary, 2018 Edition)

processing. Any operation that changes the characteristics of waste, including pretreatment, treatment and conditioning. (IAEA Safety Glossary, 2018 Edition)

repository. An engineered facility where waste is emplaced for disposal. A disposal facility is the same as a repository. (IAEA Safety Glossary, 2018 Edition)

repository, geological. A facility for radioactive waste disposal located underground (usually several hundred metres or more below the surface) in a stable geological formation to provide long term isolation of radionuclides from the biosphere. (IAEA Safety Glossary, 2018 Edition)

repository, near surface. A facility for radioactive waste disposal located at or within a few tens of metres of the Earth's surface. (IAEA Safety Glossary, 2018 Edition)

reprocessing. A process or operation, the purpose of which is to extract radioactive isotopes from spent fuel for further use. (IAEA Safety Glossary, 2018 Edition)

site area. A geographical area that contains an authorized facility, authorized activity or source, and within which the management of the authorized facility or authorized activity may directly initiate emergency actions. This is typically the area within the security perimeter fence or other designated property marker. (IAEA Safety Glossary, 2018 Edition)

spent fuel. Nuclear fuel that has been irradiated in and permanently removed from a reactor core. (Based on IAEA Safety Glossary, 2018 Edition)

spent fuel management and disposal. All activities that relate to the handling or storage of spent fuel from removal from core to disposal. This includes all the predisposal activities performed on the spent fuel and activities pertaining to radioactive waste as a by-product of the aforementioned predisposal activities. (CRP expert opinion)

spent fuel management facility. Any facility or installation the primary purpose of which is spent fuel management. (IAEA Safety Glossary, 2018 Edition)

storage. The holding of radioactive sources, spent fuel or radioactive waste in a facility that provides for their/its containment, with the intention of retrieval. Storage is by definition an interim measure. As such, it is important to distinguish between disposal (without the intention of retrieval) and storage (with the intention of retrieval). (Based on IAEA Safety Glossary, 2018 Edition)

centralized SNF storage. A facility for SNF storage, built for the purpose of co-locating the spent nuclear fuel of several nuclear facilities at a single site. The centralized storage may also store different other types of radioactive waste, such the by-products of SNF or isotope processing. (Based on Management and Storage of Research Reactor Spent Nuclear Fuel, IAEA Proceedings of a Technical Meeting, Thurso, United Kingdom, 19–22 October 2009)

on-site SNF storage. Storage of the RR SNF in the same site area as the reactor facility. On-site SNF storage may be wet (in the reactor pool or in a separate facility with a different pool) or dry (for example, in vaults or in casks). (Based on Management and Storage of Research Reactor Spent Nuclear Fuel, IAEA Proceedings of a Technical Meeting, Thurso, United Kingdom, 19–22 October 2009)

waste characterization. Determination of the physical, mechanical, chemical, radiological and biological properties of radioactive waste to establish the need for further adjustment, treatment or conditioning, or its suitability for further handling, processing, storage or disposal. (IAEA Safety Glossary, 2018 Edition)

waste management, radioactive. All administrative and operational activities involved in the handling, pretreatment, treatment, conditioning, transport, storage and disposal of radioactive waste. (IAEA Safety Glossary, 2018 Edition)

INTRODUCTION TO THE SUPPLEMENTARY FILES

The on-line supplementary files for this publication, which can be found on the publication's individual web page at www.iaea.org/publications, contain BRIDE and FERREX tools, tutorials and handouts. The IAEA is not responsible for the content of the Member State reports, and all questions must be directed to the individual authors or organizations.

ABBREVIATIONS

AGE	Ezeiza Radioactive Waste Management Area
AHP	analytic hierarchy process
Andra	National Radioactive Waste Management Agency
ANSTO	Australian Nuclear Science and Technology Organization
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ASNO	Australian Safeguards and Non-proliferation Office
BASCET	Back end Analytical Scenario Cost Estimation Tool
BRIDE	Back end Research Reactor Integrated Decision making Evaluation
CCHEN	Chilean Nuclear Energy Commission
CEA	French Alternative Energies and Atomic Energy Commission
CERREX	Cost Estimation for Research Reactors in Excel
CIGÉO	Centre Industriel de Stockage Géologique
CNEA	National Atomic Energy Commission
CNEN	National Commission for Nuclear Energy
CRP	Coordinated Research Project
DCMFEI	Central Storage of Special Irradiated Fissionable Material
EXPER	Système d’Expédition des Résidus
FACIRI	Facility for Irradiated Fuel from Research Reactors
FERREX	Fuel Cycle Cost Estimation for Research Reactors in Excel
FRRSNF	Foreign Research Reactor Spent Nuclear Fuel
FSUE	Federal State Unitary Enterprise
HBWR	Halden Boiling Water Reactor
HEU	highly enriched uranium
HIFAR	High Flux Australian Reactor
HLW	high level waste
HTC	hydrotalcite
HT-HTC	high temperature HTC
IFE	Institute for Energy Technology
ILW	intermediate level waste
INL	Idaho National Laboratory
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IPEN	Nuclear and Energy Research Institute
ISDC	International Structure for Decommissioning Costing of Nuclear Installations
ISFC	International Structure for Spent Fuel Cycle Costing of Research Reactors
IST	Instituto Superior Técnico (Portugal — Higher Technical Institute)
JEEP	Joint European Experimental Pile
JSC	joint-stock company
KVU	Konseptvalgutredning (concept evaluation study)
KS1	Kvalitetssikring 1 (quality assurance, stage 1)
LEU	low enriched uranium
LLW	low level waste
MNSR	miniature neutron source reactor
MTR	materials testing reactor
Necsa	South African Nuclear Energy Corporation
NGO	non-governmental organization
NND	Norwegian Nuclear Decommissioning
NORA	Norwegian Zero-Power Reactor Assembly

NPP	nuclear power plant
NRWMF	National Radioactive Waste Management Facility
NSW	New South Wales
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	OECD Nuclear Energy Agency
OPAL reactor	Open Pool Australian Light Water Reactor
PIE	post-irradiation examination
PUREX	Plutonium Uranium Redox Extraction
RCM	research coordination meeting
RPI	Portuguese Research Reactor
RR	research reactor
RRRFR	Russian Research Reactor Fuel Return
RRSNF	research reactor spent nuclear fuel
RT-HTC	room temperature HTC
RTP	Reactor TRIGA PUSPATI
SFA	spent fuel assembly
SNF	spent nuclear fuel
SRS	Savannah River Site
TRIGA	Training Research Isotopes General Atomics
UAR	unité d’activité résiduelle
UMR	unité de masse résiduelle
USDOE	United States Department of Energy
USS RWM	Unified State System for Radioactive Waste Management
WIPP	Waste Isolation Pilot Project

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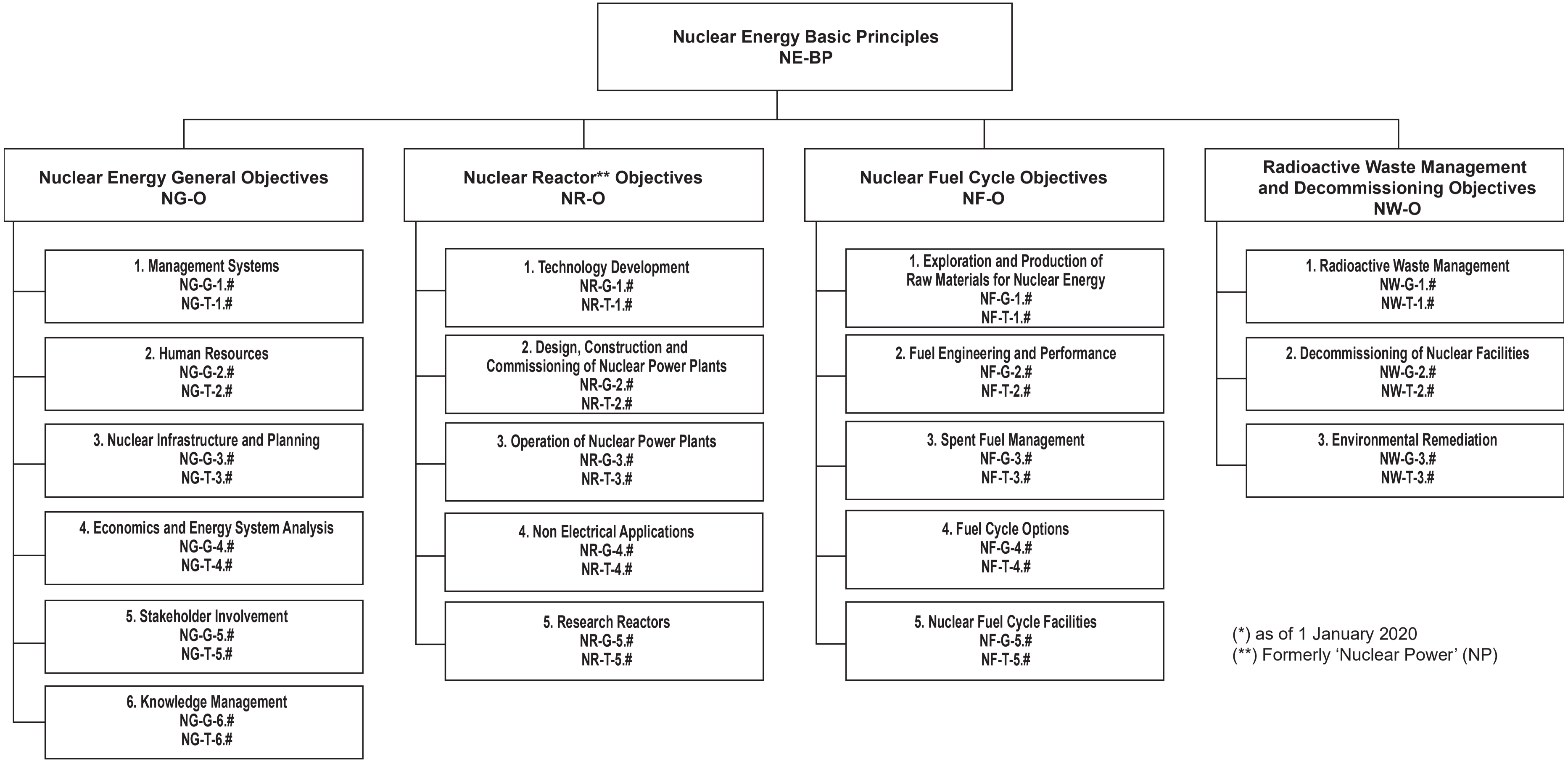

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Key

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