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Final Report of the DACCORD Collaborative Project

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DATA ANALYSIS AND COLLECTION FOR COSTING OF RESEARCH REACTOR DECOMMISSIONING

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IAEA NUCLEAR ENERGY SERIES No. NW-T-2.12

DATA ANALYSIS AND COLLECTION FOR COSTING OF RESEARCH REACTOR DECOMMISSIONING

FINAL REPORT OF THE DACCORD COLLABORATIVE PROJECT

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2021

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

Printed by the IAEA in Austria
September 2021
STI/PUB/1942

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Data analysis and collection for costing of research reactor decommissioning : final report of the DACCORD Collaborative Project / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2021. | Series: IAEA nuclear energy series, ISSN 1995–7807 ; no. NW-T-2.12 | Includes bibliographical references.
Identifiers: IAEAL 21-01417 | ISBN 978–92–0–108621–1 (paperback : alk. paper) | ISBN 978–92–0–108721–8 (pdf) | ISBN 978–92–0–108821–5 (epub)
Subjects: LCSH: Nuclear reactors — Decommissioning. | Cost. | International cooperation.
Classification: UDC 621.039.59 | STI/PUB/1942

FOREWORD

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

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

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

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

In 2007, the IAEA established the International Decommissioning Network (IDN) to enhance the sharing of knowledge and experience among Member States and to improve capabilities in the area of decommissioning, thereby facilitating safe and successful decommissioning activities. The importance of cost estimation for decommissioning was discussed at the IDN's 2011 annual meeting, which noted the lack of detailed published data on the cost of decommissioning research reactors and other small nuclear facilities. This led to the Data Analysis and Collection for Costing of Research Reactor Decommissioning (DACCORD) project, a collaborative endeavour focused on the collection and analysis of decommissioning costs for research reactors and on the development of information and methods to assist in the preparation of preliminary cost estimates.

The current project, DACCORD Phase 2, is an extension of the initial project. Even as DACCORD Phase 1 met its objectives, it became apparent that further input in the area of planning, characterization and estimation of uncertainty would be of great value in the preparation of preliminary cost estimates. It also became evident that the Cost Estimation for Research Reactors in Excel (CERREX) tool, the backbone of the cost estimating methodology promoted in the DACCORD project, would benefit from enhancements to improve user experience. It was therefore agreed to initiate DACCORD Phase 2 to improve the availability of information in these areas.

Three main working groups, comprising representatives of different IAEA Member States, undertook this work. They addressed the costing methodology and analysis of costing cases, the impact of characterization strategies on decommissioning costing, and sensitivity and probabilistic analysis. Overall project coordination was provided by a coordinating working group comprising G. Bacsko (Hungary), V. Daniska (Slovakia), P. Gengoux (France), E. Gouhier (France), P. Grossi (Brazil), P. Gui (Italy), A. Gyergyek (Slovenia), K. Krištofová (Slovakia), K. Moshonas Cole (Canada), G. Puskás (Lithuania) and A. Savidou (Greece).

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

EDITORIAL NOTE

The supplementary files for this publication can be found on the publication's individual web page at www.iaea.org/publications

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Phase 2 of the Data Analysis and Collection for Costing of Research Reactor Decommissioning (DACCORD) project was launched in 2016 at the end of the original project, which was initiated in 2012 to support Member States in the development of preliminary cost estimates for research reactor decommissioning. Phase 1 of the project [1] addressed this challenge by identifying benchmarking data, developing reference cases using the Cost Estimation for Research Reactors in Excel (CERREX) cost estimating tool developed by the IAEA, increasing the experience in cost estimation and sharing of knowledge among members of the coordinating working group.

Well founded preliminary cost estimates are critical for organizations that need to plan for future decommissioning and establish future financing, and for governmental authorities that review them. Furthermore, due to large variations in the design and operational history of research reactors, it is difficult to establish ‘typical’ estimates for specific reactor types or sizes as the costing cases can be very different for individual facilities and may be specific to national legal and institutional frameworks. The challenge is to develop methods to accommodate different types of research reactors, different planned end states, operating histories including normal and abnormal events, limited decommissioning background and experience, and differing options concerning waste and spent fuel management. For some facilities, the fuel has been removed from the site, but in others, removal of the spent fuel is included in the decommissioning project.

In Phase 1 of DACCORD, the approach to this challenge was to collect and organize information and data sets that would simplify the use of CERREX, which is based on the International Structure for Decommissioning Costing (ISDC) [2] and presents cost estimates according to the ISDC structure. CERREX determines costs according to defined activity segments, which together represent the entire project. The costing method is based on unit factors (UFs) that are defined as a normalized quantity of resource related to a project activity (e.g. the number of person-hours per unit of activity).

In the process of collecting information and developing CERREX improvements, participating Member States were supported in enhancing their skills and developing defendable preliminary estimates. These estimates were assembled and analysed as a group. By the end of Phase I, it became clear that — to improve the research reactor community’s ability to perform cost estimates — a second phase of DACCORD would help focus on enhancements to CERREX to facilitate its use; better awareness of the impact of decommissioning planning and the impact of characterization on cost estimating; and an improved understanding of contingency and uncertainty related to the cost estimates.

DACCORD Phase 2 builds on the work of Phase 1 and benefits from the activities, tools and knowledge that have been developed by the IAEA and its partners. In addition to referencing studies and publications addressing cost estimation, risks and uncertainties, Phase 2 utilizes the following:

— The ISDC [2];
— The cost estimating tool CERREX [3], which has been enhanced and further developed as CERREX-D2 to meet the needs of the DACCORD project and to improve its usability for future users.

Phase 2 was completed in three years. The work was undertaken by three working groups (WGs). Project guidance and consistency were provided by the project’s coordinating working group, comprising a project chair, experts, WG chairs and co-chairs, technical experts and the IAEA officers responsible for the project. The responsibilities of the WGs were as follows:

— WG1: Costing methodology, CERREX usability factors, including improved inventory inputs and UF development, and analysis of costing cases;
— WG2: Impact of planning and characterization strategies on decommissioning costing;
— WG3: Probabilistic analysis for in scope and out of scope uncertainties and risks.

Regular discussions in the coordinating working group ensured that the approaches being followed by the WGs were aligned, with the WGs working in close collaboration over the course of the project. There was a cross-over of expertise and experience between the team members and experts; the teams benefited from numerous interactions over the course of the project.

New participants joined throughout the three year period, working closely with WG1 to develop initial preliminary cost estimates for their research reactors. Once they were sufficiently developed, these estimates were included in the overall analysis and development of the project work.

WG2 and WG3 developed various methods and defined assessments based on experience and research and applied the methods to cases prepared by WG1. Specific approaches employed and results obtained by each of the WGs are provided in the relevant sections and appendices of this publication.

1.2. OBJECTIVE

This publication reports on the DACCORD project, which supported Member States, particularly those with little or no decommissioning experience, in preparing preliminary cost estimates for the decommissioning of their research reactors. It describes DACCORD Phase 2, in particular, which sought to improve the ability of research reactor operators to prepare preliminary cost estimates for decommissioning; enhance the available tools, specifically the CERREX software; collect information from completed decommissioning cases, available decommissioning plans and cost estimates and use these to understand the impact of planning decisions and characterization; and develop a more comprehensive understanding of uncertainty and contingency in estimating costs.

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

1.3. SCOPE

This publication focuses on cost estimations for decommissioning of research reactors, which can be very broad in scope with many possible inputs, influencers and impact of decisions. It covers use of the CERREX-D2 code by non-experts; increasing information on UFs for research reactor decommissioning; providing a basis for estimating uncertainties and contingencies; assessing the impact of decommissioning planning and characterization activities; and supporting participating Member States in developing plans and cost estimates using the CERREX-D2 code.

1.4. STRUCTURE

Section 2 describes the activity of cost estimation and provides definitions of concepts related to this activity. It provides the user with information on cost estimating and provides an overview of the types of decisions that are important. Section 2 also includes information on the use of CERREX-D2, on developing inventory inputs and selecting UFs. Section 3 describes illustrative cost cases for different types of TRIGA reactors. Section 4 provides an analysis of the available costing cases developed in

Phase 2 of DACCORD. Section 5 provides information on estimating contingencies and estimating uncertainty both in scope and out of scope. It provides a description of these elements, a defined method for addressing them, and information to assist the user in understanding the results. Additionally, an analysis of out of scope uncertainty based on an available cost case is provided. Section 6 describes the results of the collection of planning and characterization information and the analysis of the impacts of this knowledge and the decisions on the costs of decommissioning. Section 7 is a summary of the conclusions drawn from the work described in the preceding sections and identifies recommendations flowing from these conclusions.

Seven appendices are provided with detailed information to support the contents of this report, as well as several annexes that supplement the information in the text and that may be accessed as part of the on-line version of this publication[1].

2. COST ESTIMATION FOR DECOMMISSIONING

2.1. BASICS OF ESTIMATING THE COST OF DECOMMISSIONING

To estimate the cost of decommissioning a research reactor facility, the following basic inputs are required regardless of the methodology being utilized: a well developed decommissioning plan, a detailed material analysis, a description of the required working steps and a proposed time schedule. Use of the ISDC [2] ensures that all typical decommissioning activities are considered when preparing preliminary cost estimates, prior to the preparation of a detailed decommissioning plan. The costing methodology used in this project follows guidance developed by the IAEA and the OECD Nuclear Energy Agency (OECD/NEA) [3–5].

2.1.1. Quality

The quality of a decommissioning cost estimate is linked to the level of detail and veracity of the input information used to develop the estimate, including information that enables uncertainties to be quantified [3]. This, in turn, is related to the diligence applied to ensure that the information collected is soundly based. Addressing uncertainties represents a major challenge for all decommissioning projects. These are typically addressed in cost estimates by including provisions for in scope uncertainty (contingency) and making allowance for project risks. Whereas the contingency estimates are provided to account for costs that are expected to occur but are not well defined (also typical in cost estimating of construction work), project uncertainties also include the risk of outcomes which are foreseeable but are not normally expected to occur. Both types of uncertainty are addressed in Section 5 of this publication.

The following sections provide guidance for a facility owner to prepare an order of magnitude estimate as used in the DACCORD project. Specifically, information on process elements to be followed and information about the CERREX-D2 tool are presented.

2.1.2. Methodologies

Decommissioning costing methodologies have been developed based on experience derived from completed decommissioning projects. The developed UFs are then used for similar facilities after adjustment of UFs and other elements of cost methodologies for the differences in facility size and inventory, and for country specific factors. This approach is generally referred to as the unit factor approach. In addition to the use of UFs, work difficulty factors (WDFs) are used to reflect local working

[1] Available on the publication’s individual web page at www.iaea.org/publications

constraints relevant to individual costing cases. By illustration, taking as an example the activity of dismantling piping of a defined size category, a UF would be used to calculate the staff effort needed per unit mass of the piping under defined working conditions. Typically, the UF is based on ideal working conditions without constraints on activity implementation. If the conditions are not ideal, an appropriate WDF is applied.

In general, using a facility specific approach results in better quality cost estimates. Here, the main activities occurring in a decommissioning project are disaggregated into subactivities, following a hierarchical approach, and costs are estimated at subactivity level using locally adapted, calculation specific data. This approach is consistent with the 'bottom-up' costing principle, which is generally considered to be the most accurate costing approach in decommissioning costing, since it considers decommissioning activities which are specific to each costing case. In decommissioning projects, cost elements related to decommissioning activities are classified into four basic cost types, as generally described in Refs [4, 5]:

— Activity dependent costs (hands-on activities or inventory dependent activities) are directly related to the extent of hands-on work involved in decommissioning (activities related to inventory, performed manually or remotely controlled). They include activities such as decontamination, removal of components, packaging, shipping and disposal of waste. Costs arise from labour, materials, energy, equipment and services. In the CERREX-D2 software, the inventory dependent activities and waste management activities are referred to as INV and WM, respectively.
— Period dependent costs are proportional to the duration of individual activities, phases of the decommissioning project or of the entire project. They arise from project management, administration, routine maintenance, radiological, environmental and industrial safety and security activities. These costs may be independent of hands-on activities being undertaken concurrently. Especially in cases of small facilities such as research reactors, the ratios between the amount of inventory dependent and period dependent activities may vary significantly.
— Collateral costs are costs for special items that cannot be assigned either to a certain work activity or to a period dependent activity. For example, if equipment is needed to support activities, the purchase or the rental of this equipment may belong to this category. Taxes, insurances, specific services, consultancies and other specific payments are other examples.
— Contingency is a cost element added to address the estimation of uncertainty, i.e. to ensure that all costs which are expected to occur are included based on previous experience from similar activities, even when there is uncertainty about their precise nature or timing. In the CERREX-D2 software, contingency is calculated at the level of each elementary calculation item. The level of contingency is defined by the user for the individual calculation item as a percentage of the activity estimate. Tentative values of contingency are included in CERREX-D2 templates based on data presented in Ref. [6].

2.2. USE OF CERREX-D2 FOR DECOMMISSIONING COST ESTIMATION

This section describes the general process for using CERREX-D2 to perform cost estimations; more specific information is provided in the User Manual (Annex I) which provides detailed procedures for use of the code. As mentioned earlier, CERREX is a Microsoft Excel based software code based directly on the ISDC cost calculation structure [2]. The software has been substantially enhanced — as CERREX-D2 — following completion of the first phase of the DACCORD project.

2.2.1. Cost assessment methodology using CERREX-D2

The main principles for implementing the ISDC methodology in the CERREX-D2 code are the following:

— Inventory and waste related data are counted in accordance with pre-defined or user defined decommissioning categories (e.g. dismantling of pipework) or waste management categories (e.g. management of very low level waste (VLLW)). Decommissioning categories represent typical components in terms of their construction, size and the material used. Waste management categories are based on the IAEA's waste classification as established in IAEA Safety Standards Series No. GSG-1, Classification of Radioactive Waste [7].
— Accounting of UF information for the inventory dependent and waste management activities is coupled with WDFs to reflect any constraints due to anticipated local working conditions. Three complementary UFs are used — workforce unit factor[2], investment cost unit factor and expenses cost unit factor, to reflect the ISDC cost categories. The typical WDFs are used as presented in Ref. [6].
— Identification of the cost elements (calculation items) includes inventory or waste management activities, period dependent activities and any collateral costs (e.g. tax payments) or assets (e.g. from the sale of non-contaminated metals). Contingency (as defined in Ref. [2]) is added at the level of elementary calculation items.

Implementing these principles to prepare a cost estimate with CERREX-D2 requires the following sequence of activities [1] to assemble the required input information.

2.2.2. Definition and selection of decommissioning options

Decommissioning options (i.e. the full sequence of activities envisaged to be undertaken to decommission the facility) are based on existing or planned decommissioning infrastructure and the selected decommissioning strategy. The associated cost calculation needs to cover all relevant possibilities being considered: immediate or deferred decommissioning strategies and the envisaged end states, combined with various scenarios for waste treatment. Individual costing cases (options) are defined by the selection of relevant ISDC items at Level 1, Level 2 (most relevant) and, in specific cases, also at Level 3. Costs are calculated based on the decommissioning inventory database and the extent of decommissioning activities anticipated for each selected option.

2.2.3. Development of an inventory database

CERREX-D2 includes the possibility of undertaking cost calculations based on the assumed radiological inventory for the facility. The inventory database has three main components: (i) inventory of systems; (ii) inventory of structures; and (iii) radiological parameters. The inventories of systems and structures typically identify the location of the inventory item in the building: floor, room and equipment structure and provide parameters such as mass, surface areas, volumes, different classes of systems and structures (e.g. pipework), and materials. The radiological parameters refer to contamination of inner and outer surfaces, activation of construction materials and dose rates (differentiated by radionuclide content). In simplified cases, the radiological parameters are substituted by manual partitioning of individual inventory items to waste classes by users based on their knowledge of systems and components.

[2] For example, the typical number of staff hours taken to implement an activity per unit of mass handled.

2.2.4. Selection of a database of unit factors

The cost estimating process converts the inventory into costs by applying workforce UFs for the performance of individual inventory dependent decommissioning activities. The UFs and WDFs convert the inventories of items into workforce hours and subsequently, by applying hourly labour rates for involved professions, the ISDC cost category labour cost is calculated. By applying investment and expenses cost unit factors (e.g. electricity, gas, water) to inventories, ISDC cost categories investment cost and expenses are calculated.

Regarding the waste management categories, the first step is to identify the waste streams, including the quantities for each waste stream. In simple cases, the waste streams are developed by partitioning individual inventory items to waste classes; in advanced cases, the radiological data in the inventory database are used. Results in both cases represent quantities for individual waste streams, to which the workforce and cost UFs are applied as was done for inventory dependent activities. The generation of secondary waste is considered in the waste streams.

CERREX-D2 incorporates a set of representative decommissioning and waste management categories, relating to typical decommissioning and waste management activities, and associated inventory items typical of research reactors. The code also includes default workforce and UFs associated with these decommissioning and waste management categories. A detailed analysis of the unit factors used in the costing cases presented in this publication is provided in Appendix I.

The default UFs incorporate all relevant preparatory and finishing activities associated with each activity. Users are encouraged to be deliberate in deciding whether to rely on the default UFs provided or to modify them according to their specific situation. It should be noted that UFs are often specific to country, reactor type and even facility. It is typically necessary to modify the default UFs in the code to achieve a reasonable level of accuracy in the cost calculation.

2.2.5. Definition of input data for period dependent activities, collateral cost and for contingency

Individual costing cases are completed by setting input data for individual period dependent activities such as defining personnel numbers and categories, activity durations and, where relevant, period dependent cost UFs or fixed (one-off) costs. The level of contingency is defined for individual decommissioning activities of costing cases.

2.3. COST ESTIMATE ASSUMPTIONS AND BOUNDARY CONDITIONS

The scope of a decommissioning cost estimate is defined by the major assumptions being made and by boundary conditions related to the external conditions. These define the assumed scenario in which decommissioning takes place. Significant sources of boundary conditions and assumptions are the decommissioning strategy, the selected end state, and the available knowledge of the facility. Use of ISDC facilitates the application of assumptions and boundary conditions.

2.3.1. Decommissioning strategy

The selected decommissioning strategy — whether immediate or deferred dismantling — is central to the definition of the scenario on which the cost estimate is based. The assumed duration of major decommissioning activities has a significant impact on the cost estimate. With unexpected situations arising, the duration might differ significantly from what is considered in the planning schedule. In cases where activities on the project critical path are affected, there will also be an implication for the entire duration of the project and hence the cost. For the purposes of the estimate, however, a baseline strategy needs to be determined and assumptions made concerning the associated schedule and duration of activities.

2.3.2. Selected end state

Experience from the decommissioning of all types of nuclear facilities suggests that the selection of an end state with no restrictions being placed on future use of the facility will result in significantly higher costs compared with projects with end states for which there are restrictions on future uses (e.g. prohibition on use for agricultural or residential purposes). The development of a decommissioning plan requires assumptions to be made concerning the end state and potential future use of the facility. Changes to the assumed end state will generally have a significant impact on the project plan and the associated cost estimate.

2.3.3. Level of knowledge of the facility

As the inventory and radiological characteristics of the facility are required inputs for preparing a cost estimate, assumptions will be required where there is incomplete knowledge of physical and radiological condition. The assumptions can be based on knowledge of other similar facilities adjusted for known conditions or available historical information. Incomplete facility information is an important source of uncertainty in the cost estimate. Typical situations that diminish the quality of facility knowledge include the following:

— The physical configuration of the facility may not correspond to that described in the facility drawings and related information sources.
— Leakages or other incidents may have taken place which are inadequately described in plant records, and in some cases such events are not described at all.
— Levels of radioactive contamination or activation may differ from expected levels.

2.4. INVENTORY

An inventory database provides reliable information on the physical, chemical and radiological status of the nuclear facility. This database is populated with information derived from facility knowledge and from a facility characterization process. The facility inventory provides the basis for decommissioning activity planning (i.e. costs, staffing needs, personnel doses, waste streams, safety assessment).

Poor inventory data (e.g. based on incomplete historical information, limited or lack of radiological data on activation and contamination) strongly impact the implementation and success of the decommissioning project. With insufficient or incorrect information, time and resource needs, costs and waste volumes may be underestimated and inappropriate decisions on decommissioning strategy and/or waste management may be taken.

It is generally accepted that the level of accuracy of decommissioning cost estimates is strongly linked to the extent of prior characterization of the facility. Accordingly, it was decided to enhance the CERREX-D2 software with modules in which the results of radiological characterization may be introduced at the level of individual inventory items, and the radiological data lead directly to the classification of the resulting waste streams.

2.4.1. Approach to inventory development

Five new spreadsheets were developed as part of the advanced inventory database. The original manual partitioning of inventory items by the user was replaced by partitioning based on radiological parameters of inventory items according to the decay of individual radionuclides referenced to the user defined start date of the decommissioning project. The option of manual partitioning of individual inventory items may still be used where radiological data are not available to a sufficient extent.

CERREX-D2 incorporates the following features of a robust and effective advanced inventory database:

— Hierarchical inventory structure, comprising lists of buildings, floors, rooms, equipment (BLD sheet);
— Inventory data comprising identification, physical, hazardous material, radiological parameters and dynamic (time related) calculation of radioactivity and waste quantities (ADIN sheet (ADvanced INventory Database));
— Systems and material parameters including hazardous waste (SMHW sheet);
— Radionuclide composition of activation and contamination (i.e. the radionuclide vectors and radioactive waste limits (RND sheet));
— Possibility to perform sensitivity analysis focused on inventory data (INV SA sheet).

The concept of an advanced inventory database is implemented by the ADIN sheet in which the radiological data are used for dynamic (i.e. time related) derivation of partitioning coefficients, to allocate waste according to different waste classes, while also allowing the use of expert estimated partitioning coefficients for inventory items where radiological data are not available. The inventory items introduced in the ADIN sheet are automatically linked to the already existing INV spreadsheet to calculate workforce quantities. Workforce UFs are defined for individual decommissioning categories and WDFs defined by users for individual inventory items are used to calculate individual workforce parameters.

In addition to the required functionality (i.e. time related modification of radiological parameters), the system of linked sheets listed above promotes better understanding of the role of decommissioning inventory databases. To assist the user, examples of typical inventory items and their parameters are prefilled in the ADIN sheet, such as activated item, externally contaminated item, internally contaminated item and non-contaminated item (see Fig. 1).

The basic approach to the development of radiological inventory data in the ADIN sheet is to complete the following set of parameters:

— Contamination/activation values and corresponding surface/mass data;
— Radionuclide vector (selected value from the drop-down menu);
— Reference dates for the activity value and the vector definition.

The ADIN sheet allows the user to introduce radiological parameters, to set the calculation date (i.e. date relevant to the classification of material as radioactive waste), and to calculate automatically the resulting waste quantities for individual inventory items according to radioactive waste limits (waste acceptance criteria for VLLW and LLW repositories and clearance criteria) in an RND spreadsheet. The option in the ADIN spreadsheet to set partitioning coefficients manually allows the user to introduce the inventory database items with or without radiological data, as is usual for a facility database. For a rapid inventory database assessment, the spreadsheet INV SA was developed with in-built predefined sensitivity analysis on waste quantities of radioactive waste types, i.e. intermediate level waste (ILW),

Building	Floor	Room No.	Equipment ID	Equipment Name	ISDC No.	Tech System	Mass (t)	Inner surface (m2)	Outer surface (m2)	Bulk volume (m3)	Inner volume (m3)	CERREX category	Dominant material
Total							2.60E+01						
RB		RB001	R001	Example 1 - Activated item	04.0501	RCM	1.00					INV9	GRAP
RB		RB002	R002	Example 2 - Externally contaminated item	04.0601	HEQ	10.00		50.0			INV3	LEAD
RB		RB003	R003	Example 3 - Internally contaminated item	04.0503	PCC	5.00	100.0				INV21	STST
RB		RB002	S001	Example 4 - Non-contaminated item	04.0601	SCC	10.00					INV2	CAST

1: User defined input parameter in green; 2: selected parameter from drop-down menu; 3: calculated parameter.

FIG. 1. Prefilled parameters for typical inventory items in an ADIN sheet.

low level waste (LLW), very low level waste (VLLW) and exempt waste (EW). The spreadsheet displays the following:

- Quantities of waste types versus modification of activity levels by factors of 0.01, 0.1, 10, 100;
- Quantities of waste in different waste classes versus deferring the start of dismantling for 5, 10, 30 and 50 years in comparison with the immediate dismantling scenario.

A detailed step by step procedure for advanced inventory database development using ADIN is provided in the User Manual for CERREX-D2 (Annex I), and also in summary form directly in the CERREX-D2 'GENERAL' sheet.

When sufficient radiological data for items within the controlled area are available, it is recommended to develop the inventory in the advanced inventory database. Additional inventory data (surfaces for decontamination and monitoring) are then introduced directly into the INV sheet where the partitioning to waste types is done manually. Alternatively, when the radiological data are not available for any item within the controlled area, the INV spreadsheet can be used together with manual waste partitioning as in previous versions of the CERREX code.

2.5. UNIT FACTORS

The cost of each decommissioning related activity is determined as shown in (1):

$$\text{Decommissioning cost} = \text{labour cost} + \text{investment cost} + \text{expenses} + \text{contingency} \quad (1)$$

where

- Labour cost = workforce UF × selected WDF × inventory quantity × hourly labour rate for inventory dependent activities. For waste management activities, WDFs are not applicable. For period dependent activities the labour cost is determined from the activity duration and the hourly labour rates of different professions.
- Investment cost (for inventory dependent and waste management activities) = investment unit factor × inventory (waste) quantity.
- Investment cost (for period dependent activities) = specific investment cost unit factor × duration, or by introducing single cost items.
- Expenses (for inventory dependent and waste management activities) = expenses unit factor × inventory (waste) quantity.
- Expenses (for period dependent activities specific expenses) = expenses unit factor × duration, or by introducing single cost items.
- Contingency = (labour cost + investment cost + expenses) × contingency factor (%).

The aim of the UF analysis undertaken in this project is to provide information on UFs used in different countries for decommissioning cost estimation of a range of facilities. Defining appropriate UFs is a complex and time consuming task and, in some cases, relevant information is only available from ongoing projects or through direct contact with the technology providers. Such data may be subject to confidentiality provisions. The default UF data provided in the CERREX software code were derived primarily from data obtained from the decommissioning of nuclear power plants, modified to reflect the specific conditions reported by participants in the DACCORD project and/or relevant data provided by them. Use of the default data enables users to proceed with development of specific costing cases. Nonetheless, for each costing case, the default UF data should be reviewed and adapted to the specific situation being analysed.

The methodology and results of the average values of the involved workforce, investment, expenses and total cost UFs are presented in Appendix I and shown graphically in Annex II. Having this information does not deter users from carrying out a UF analysis of their data. An illustration of this approach was developed using MS Excel and is presented in Appendix II, based on data provided in Annex III.

3. CERREX-D2 COSTING CASES

Illustrative costing cases provide CERREX-D2 users with completed examples of decommissioning cost estimates, together with a reference list of main inventory items relevant to specific research reactor types, which together serve as guidance for developing specific costing cases. Two illustrative costing cases were developed for TRIGA reactors, one for TRIGA Mark I/Mark II and a second case specifically for TRIGA Mark III. Due to the variety of research reactor types, style of construction, engineering designs and technical assemblies and facilities, it was judged that the benefit in attempting to develop generic costing cases for other reactor types would be modest.

Assessment of available TRIGA research reactor costing cases combined with expert judgement resulted in the development of a list of main inventory items representative of TRIGA reactors (including ISDC numbers, inventory numbers and waste partitioning coefficients). To create the illustrative costing cases, the lists of inventory items for existing costing estimations were converted into the representative/reference list of main inventory items for TRIGA reactors, presented in Table 1.

The following steps were followed in developing the illustrative costing cases:

- Establishment of the main inventory items reference list (reactor type specific, Table 1 in the case of TRIGA reactors);
- Conversion of the existing costing cases, inventory items into the reference main inventory items;
- Evaluation of illustrative values based on the mean values of converted inventory items for the existing costing cases;
- Inputting of the illustrative quantities in CERREX-D2 for ISDC inventory dependent activities (using ADIN);
- Evaluation of the expected workforce, duration, investment and expenses for the period of dependent activities;
- Adoption of the default UFs for decommissioning and waste management categories;
- Adoption of a reference labour rate, US $50/h;[3]
- Adoption of the radionuclide vectors (when available and applicable);
- Use of ADIN to include the equipment with physical and radiological parameters, calculation of radiological inventory for user defined calculation date (when available and applicable).

In line with the above methodology, two illustrative costing cases for TRIGA research reactors were developed:

- Illustrative costing case for TRIGA Mark I and Mark II;
- Illustrative costing case for TRIGA Mark III.

The CERREX-D2 files for these cases are provided in separate files as Annex IV and Annex V.

[3] No particular significance should be ascribed to the adopted reference labour rate, given that average employment costs vary widely between different programmes.

Section 5 presents the uncertainty analysis and the influence of input parameters on the total cost and total workforce for the TRIGA illustrative costing cases. It also includes the sensitivity analysis and a comparison of deterministic and probabilistic estimates.

TABLE 1. REFERENCE LIST OF MAIN INVENTORY ITEMS FOR TRIGA REACTORS

Inventory item	Unit	ISDC No.	CERREX INV No.	Waste partitioning (%)			
				ILW	LLW	VLLW	EW
Demineralizer resin	t	02.0500	INV14	0	0	10	90
Tanks	t	04.0503	INV22	0	0	10	90
Piping and valves	t	04.0503	INV21	0	0	10	90
Heat exchanger	t	04.0503	INV22	0	0	10	90
Structural equipment (stairs, core bridge, covers)	t	04.0600	INV38	0	0	10	90
Neutron beam tubes and port	t	04.0502	INV6	50	50	0	0
Ventilation (duct, fan, motor, stack, filter)	t	04.0600	INV24	0	0	10	90
Core assemblies (control rods, grid plate)	t	04.0501	INV6	50	50	0	0
Rotating specimen rack (RSR)	t	04.0501	INV7	50	50	0	0
Graphite elements and graphite reflectors	t	04.0502	INV9	50	50	0	0
Cables and cable trays	t	04.0600	INV26	0	0	10	90
Liquid water and sludge	m^3	02.0500	INV15	0	0	0	0
Pool liner, reactor liner	t	04.0502	INV23	0	20	20	60
Decontamination of building surface	m^2	04.0700	INV16	0	0	0	0
Monitoring of building surface	m^2	04.0900	INV18	0	0	0	0
Masonry	t	07.0300	INV40	0	0	0	0
Bioshield concrete	t	04.0506	INV8	10	10	0	80

4. ANALYSIS OF COSTING CASES

This project focused on the collection and analysis of data relevant to the decommissioning of 20 participating research reactors, comprising actual reported costs and calculated estimates (e.g. in cases where the reactors are not yet in decommissioning). The cost cases from DACCORD Phase 1 were recalculated based on newly available information and using the updated CERREX-D2 software. In addition, a second group of new cases was developed comprising research reactors not included in Phase 1.

For consistency, the costs were calculated first in the relevant local currency, converted to US dollars for the year of estimation and then adjusted for inflation to the reference year of the project (i.e. 2018). Table 2 provides a list of the research reactors included in the project. The costing cases analysed are not of uniform scope, although the majority include only the research reactor and materials directly related to its operation. Costing cases with exceptional features include the following:

- DR 2 (Denmark) reflects only dismantling in the radiation controlled area (i.e. rather than complete dismantling); this case is suitable for benchmarking ISDC 04 activities. Similarly, GRR-1 reflects a limited scope of activities to dismantle select systems.
- Siloëtte (France) is linked with other on-site facilities. Thus, the decommissioning project shares site related activities.
- Apsara (India) includes very limited waste management activities, the waste being put into drums. This is the end state of the case; some asset recovery occurs.
- Some costing cases (e.g. ASTRA (Austria)), are completed projects where actual data were available; these data were transferred into the costing case to simulate the case in ISDC format. Radioactive waste was stored and a fund for future processing was created.
- The Tammuz-2 reactor in Iraq is a special case, as the decommissioning project is concerned only with the remains of buildings and systems following the destruction of the facility during the Gulf Wars.

A comparison of actual or estimated costs, inventories and workforce for the reactors involved in the project is presented in the following sections. When comparing values, it is important to bear in mind that the information and data have been collected from programmes with significant differences in the relative cost of labour and other resources. The following should also be considered:

- Decommissioning cost estimates developed during the project have not been normalized to a common interpretation of project scope.
- Information and data are subject to local specific conditions and regulations.
- The basic setting of costing cases is specific for each country and reflects the decommissioning background in the given country and the level of experience in decommissioning planning and costing. Some parameters which have been identified as outliers were corrected; otherwise, the setting as defined by the country of origin was kept.

It is challenging to establish clear correlations among different parameters such as reactor power rating, inventory quantities, total decommissioning cost, workforce and productivity. Bearing this in mind, the following analysis aims to identify possible correlations based on observations made during the project. Caution should nonetheless be exercised when using the following data to prepare new estimates or benchmarks. Detailed understanding of applicable project scope, assumptions and boundary conditions is important in preparing a soundly based cost estimate. Detailed data on costing cases are reported in Appendix IV.

TABLE 2. LIST OF REACTORS FOR DACCORD PHASE 2

No.	Facility name	Country	Reactor type	Power (kW(th))	Dismantling in controlled area	Extent of waste management system in ISDC 05	Demolition in ISDC 07	End state in ISDC 07	Completed case
1	IPR-R1	Brazil	TRIGA Mark I	100	Complete	All stages	Partial	Nuclear reuse	No
2	Vienna	Austria	TRIGA Mark II	250	Reactor only	All stages	None	Nuclear reuse	No
3	Puspati	Malaysia	TRIGA Mark II	1 000	Complete	All stages	Partial	Industrial reuse	No
4	KRR-2	Korea, Rep. of	TRIGA Mark III	2 000	Complete	All stages	None	Nuclear reuse	Yes
5	Bandung	Indonesia	TRIGA Mark II	2 000	Complete	All stages	Partial	Nuclear reuse	No
6	PRR-1	Philippines	Converted TRIGA	3 000	Complete	All stages	None	Industrial reuse	No
7	JSI	Slovenia	TRIGA Mark II	250	Reactor only	All stages	None	Nuclear reuse	No
8	Kartini	Indonesia	TRIGA Mark II	100	Complete	All stages	Partial	Industrial reuse	No
9	WWR-M	Ukraine	Pool in tank	10 000	Complete	Limited	Partial	Industrial reuse	No
10	WWR-SM10	Hungary	Pool in tank	10 000	Complete	Limited[a]	None	Industrial reuse	No
11	HIFAR	Australia	Dido	10 000	Complete	Limited	None	Industrial reuse	No
12	L-54M	Italy	Homogeneous	50	Complete	Limited	Full	Public access	No
13	Siloëtte	France	Open pool	100	Complete	All stages	None	Nuclear reuse	Yes
14	Tammuz-2	Iraq	Open pool	500	Reactor only	Limited	Limited	Nuclear reuse	No
15	Apsara	India	Open pool	1 000	Complete	None	None	Nuclear reuse	No

TABLE 2. LIST OF REACTORS FOR DACCORD PHASE 2 (cont.)

No.	Facility name	Country	Reactor type	Power (kW(th))	Dismantling in controlled area	Extent of waste management system in ISDC 05	Demolition in ISDC 07	End state in ISDC 07	Completed case
16	JEN-1	Spain	Open pool	3 000	Complete	All stages	Partial	Industrial reuse	Yes
17	GRR-1	Greece	Open pool	5 000	Reactor only	Limited	None	Nuclear reuse	No
18	DR 2	Denmark	Open pool	5 000	Reactor only	None	None	Nuclear reuse	No
19	ASTRA	Austria	Open pool	10 000	Reactor only	All stages	None	Nuclear reuse	Yes
20	Phébus	France	Open pool	38 000	Complete	All stages	None	Nuclear reuse	No

[a] Not all waste management steps are included (e.g. only activities leading to waste storage are addressed but not final disposal).

4.1. ANALYSIS OF RESULTS AT LEVEL 0

Figures 2 and 3 show total cost and total workforce data (ISDC Level 0) for the 20 research reactors involved in the project as a function of reactor power. (Figures 4 and 5 reproduce the data for those reactors with thermal power ratings up to 10 MW.)

Figures 2 and 3 show that the costing cases considered include a large variation in reactor power (50 kW–40 MW) and commensurate total costs (US $1.1 million–124 million). Almost all the reactors analysed have thermal reactor power ratings in the range of 0–10 MW, with only one reactor, Phébus (France), having a power rating of 40 MW; this reactor also has the highest decommissioning cost (US $124 million). The values for the Phébus reactor are important as they are indicative of the relationship between decommissioning cost and higher reactor power rating; nonetheless, this reactor is an outlier in comparison to the other facilities analysed.

Figures 4 and 5 show the total cost and total workforce as a function of reactor power within the range 0.05–10 MW(th) (i.e. excluding Phébus).

Figure 4 presents the total cost versus reactor power for the research reactors in the project rated up to 10 MW(th). The cost was estimated based on the decommissioning plans and approach to waste management of the specific facility and jurisdiction. National labour rates were used in developing the estimates. It is evident that the costs are greatly impacted by the differences in labour rates. For example, for the reactors in Indonesia (Kartini, Bandung) and Philippines, where the labour rates are lower than in other countries, the total estimated decommissioning costs are lower.

The graph in Fig. 5, presenting total workforce effort versus power, is less ‘country dependent’. Although variations are still observed, the analysis suggests that the total workforce effort is broadly aligned with reactor power levels and the variations observed result from differences in the scope of the decommissioning projects, inventories and waste management systems.

It should be noted that the figures are based on outturn cost (for completed projects) or calculated estimates (for facilities not yet under decommissioning). Given that no data normalization has been performed, differences in scope and assumptions will impact the cost calculation. For example, some costing cases may exclude disposal costs or might be calculated considering a different facility end state scenario (e.g. preservation of some buildings versus full building demolition).

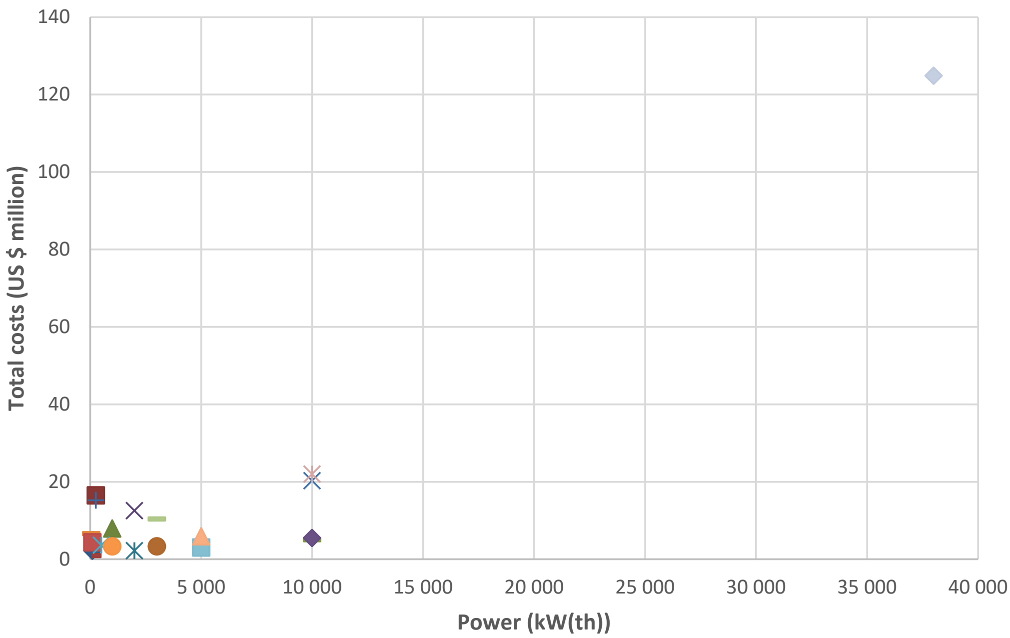


FIG. 2. Relationship of total decommissioning cost (Level 0) to reactor power.

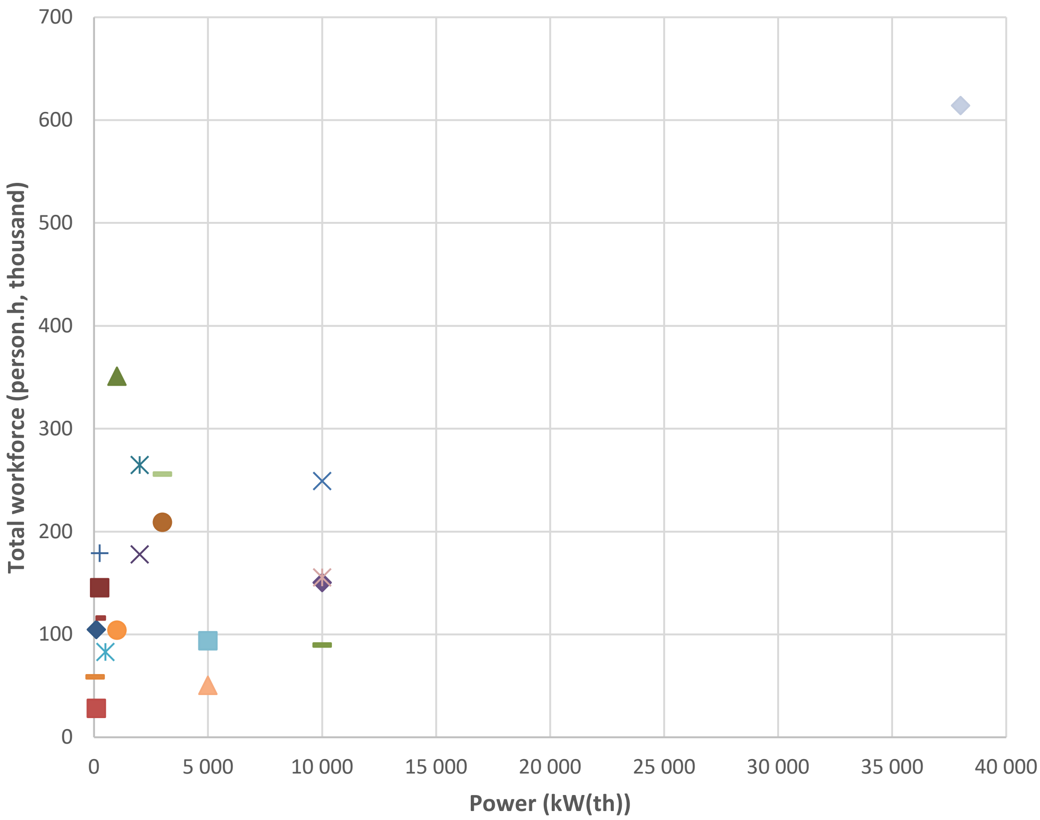


FIG. 3. Relationship of total workforce hours (Level 0) to reactor power.

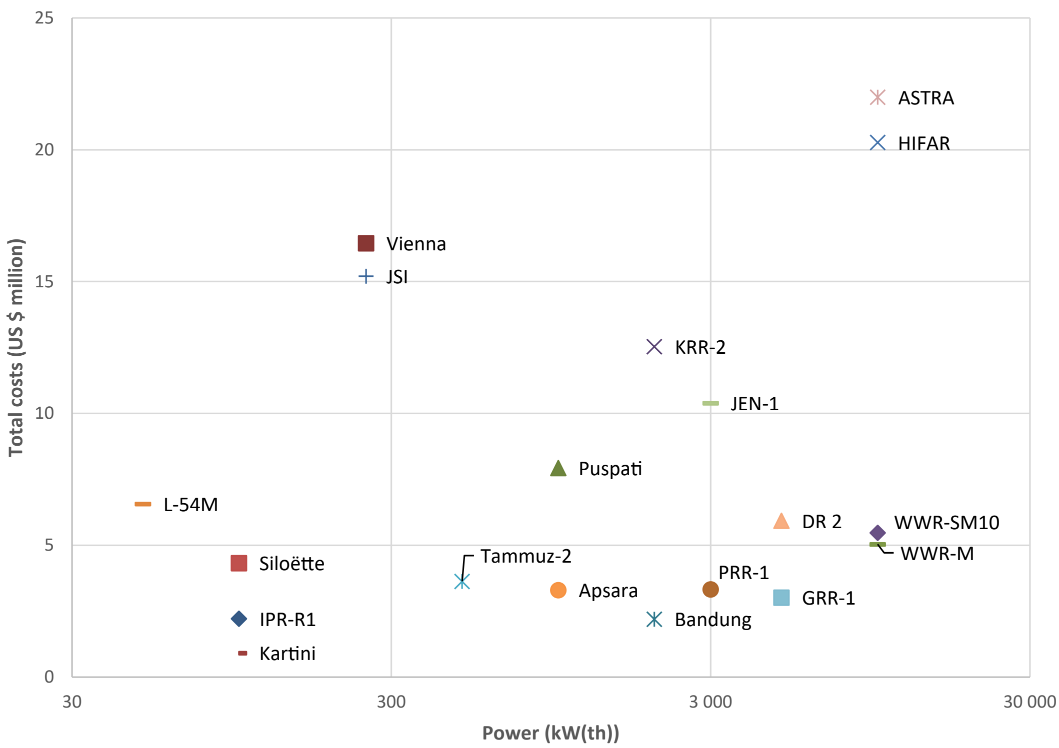


FIG. 4. Relationship of total decommissioning cost (Level 0) to reactor power (up to 10 MW(th)).

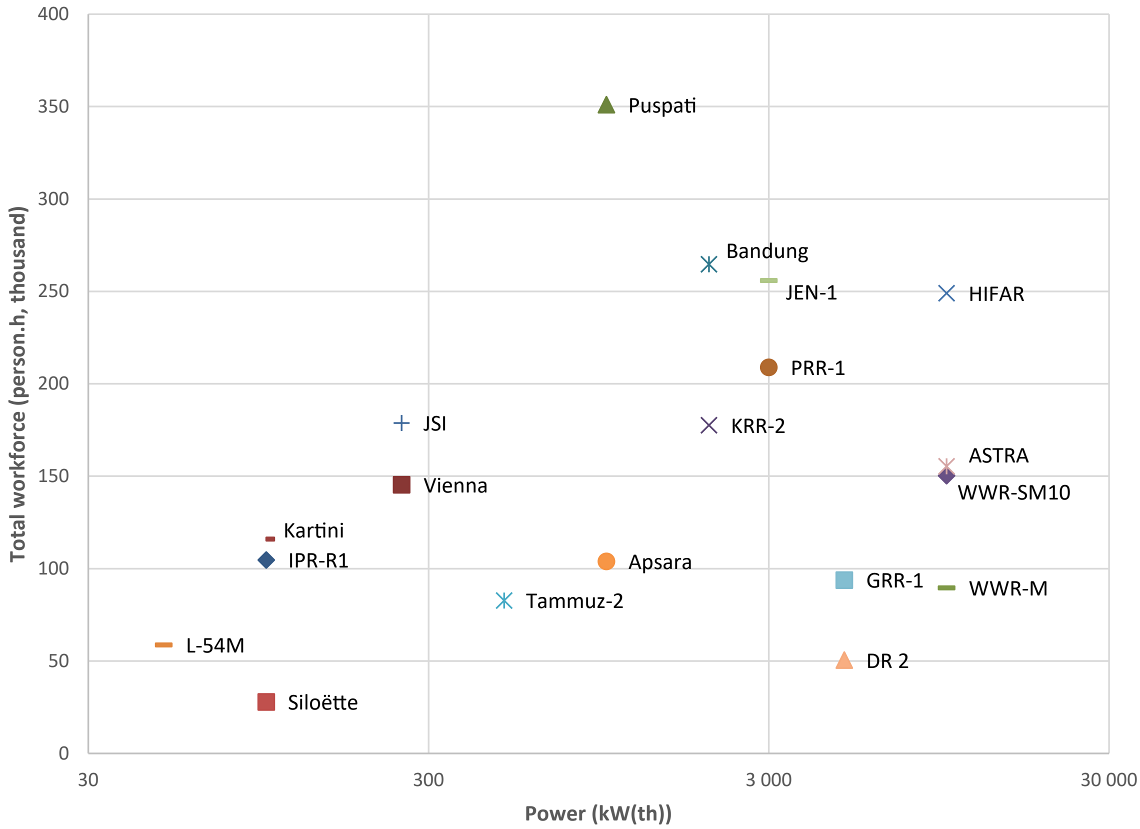


FIG. 5. Relationship of total workforce hours (Level 0) to reactor power (up to 10 MW(th)).

It should be noted that Bandung and Puspati both assume high levels of labour time due to a high level of workforce participation in ISDC 01, 02, 06 and 08, all of which are relatively inventory independent activities.

It is significant that the cases with lower workforce in the power range over 3 000 kW(th) are related to the limited scope of the costing case. Examples include DR 2, which represents only the dismantling activities in the controlled area (ISDC 04), or the GRR-1 case, which also includes a limited scope. It is observed that WWR-M also has lower workforce values.

As noted in DACCORD Phase 1 [1], total cost values confirm that there is a general tendency for cost to increase with increasing thermal power and that decommissioning costs at any given power level can vary widely. At the lower power range (tens of kW), there is likely to be a minimum decommissioning cost level, not dependent on power output, as was also concluded from Phase 1 of the project.

The variation in total decommissioning costs for reactors with similar thermal power may have several causes such as reactor type, project scope, operational history, labour rates, workforce productivity and regulation.

The workforce results also indicate a general tendency to increase with thermal power, although there is notable data variability and significant differences in the basis of the cost estimates. In the light of this, the costs of each case have been split into the four ISDC cost categories as follows:

— Labour costs: Payments to employees, social security and health insurance according to national legislation and overheads;
— Investments: Capital/equipment/material costs;
— Expenses: Consumables, spare parts, taxes, etc;
— Contingencies: Specific provision for unforeseeable elements of costs within the defined project scope.

The percentage of cost resulting from the various cost categories is illustrated in Fig. 6, together with the average values. Labour cost is the most significant category with a percentage average of 54%, followed by expenses (23%), investment (12%) and contingency (11%).

The analysis confirms that decommissioning is a labour intensive process and total costs are dominated by labour costs. Considering the 20 costing cases collected during the project and the differences among reactor type, project scope, country, etc., the labour cost is typically the largest cost contributor, although in some cases large investments can represent a significant part of the total cost. In the Philippines case, the largest cost element is the investment cost, with a high level of investment being made for dismantling, waste management and spent fuel management (ISDC 04, 05, 10).

As labour cost is generally the largest cost element, evaluating workforce hours and labour rates are key activities in the cost estimation process (see below). Attention must be given to estimating workforce hours and to establishing labour rates as these are likely to significantly impact the total decommissioning cost estimate.

Figure 7 shows the impact of changing local labour rates (blue bars) to a normalized rate of US $50/h (red bars) in 19 costing cases (Phébus excluded). The ratio of total costs calculated according to the two assumptions is shown as a solid green line. The results show clearly that the labour rate significantly impacts the overall cost estimate. In some cases, the estimate changes by over 500%, rendering the result of limited value as such an increase would undoubtedly impact the overall decommissioning strategy.

The results point to the importance, when undertaking a decommissioning cost estimation, of benchmarking against other available information to consider differences in country specific parameters (e.g. hourly wage rates), in addition to technical differences among facilities. Country specific parameters are likely to have a higher impact on total cost than technical differences between facilities.

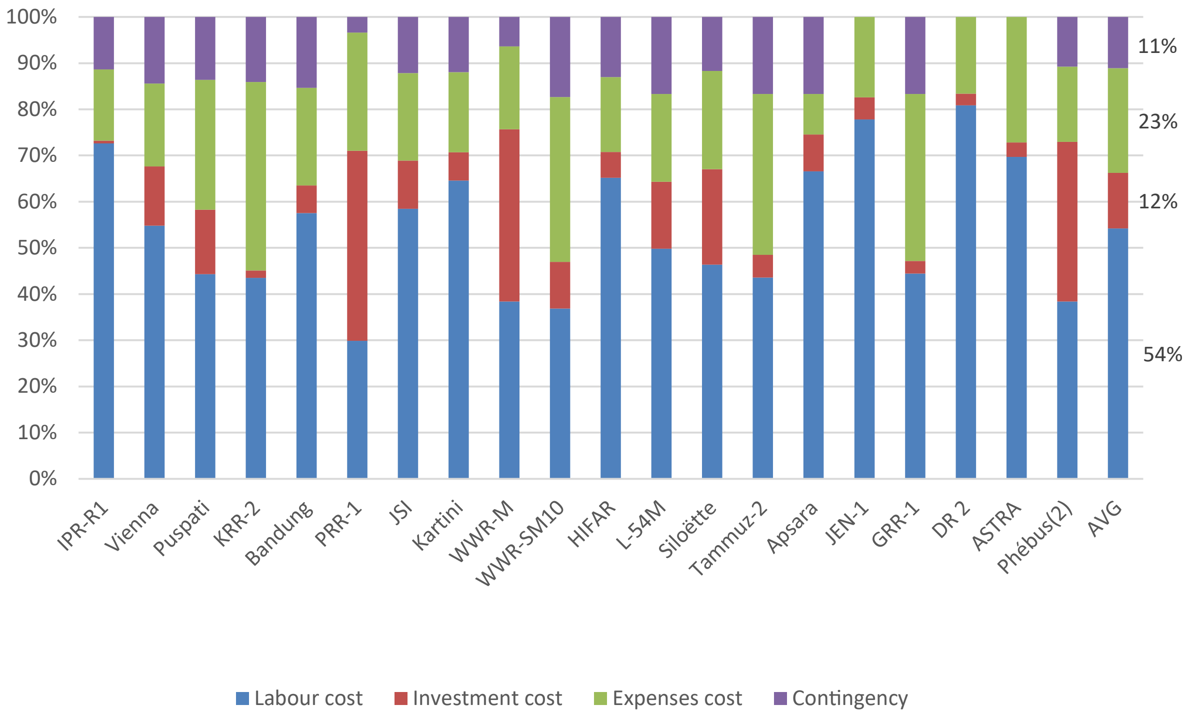


FIG. 6. Comparison of contributions from ISDC cost categories as a percentage of total.

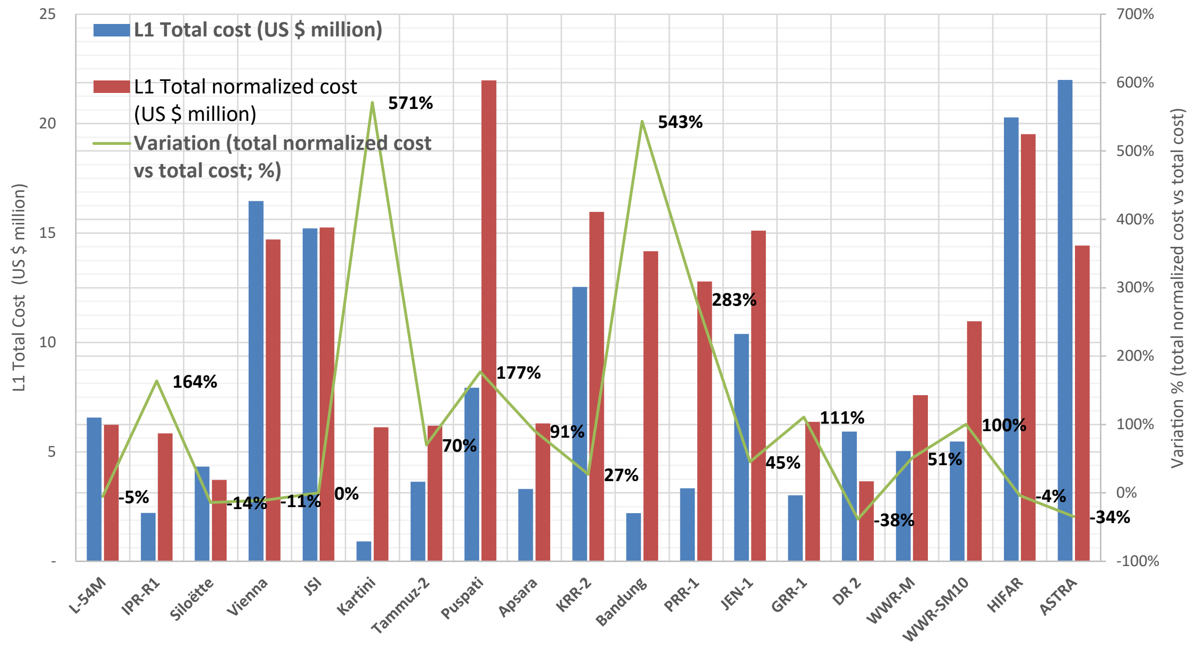


FIG. 7. Comparison of total decommissioning cost using local labour rates versus the default labour rate of US $50/h.

4.2. ANALYSIS BY ISDC LEVEL 1 ACTIVITIES

In order to identify the activities that have the greatest effect on the total cost, the estimates have been split into ISDC Level 1 (L1) Principal Activity categories [2]:

— 01: Pre-decommissioning actions;
— 02: Facility shutdown activities;
— 03: Additional activities for safe enclosure or entombment;
— 04: Dismantling activities within the controlled area;
— 05: Waste processing, storage and disposal;
— 06: Site infrastructure and operation;
— 07: Conventional dismantling and demolition and site restoration;
— 08: Project management, engineering and support;
— 09: Research and development;
— 10: Fuel and nuclear material;
— 11: Miscellaneous expenditures.

Figures 8 and 9 show total decommissioning costs and staff effort for each facility, split according to ISDC L1 Principal Activity percentages.[4]

The results are strongly related to the defined scope of the costing cases, with differences in scope having a significant impact on the differences between individual cases. It should be noted that the Apsara reactor case assumes some income generation (ISDC 11) from disposal of materials, which are of value.

Table 3 presents the percentage contributions to total cost of each ISDC L1 Principal Activity. The last column shows the average percentage for each Principal Activity averaged among the 18 cases (the Tammuz-2 and DR 2 costing cases are not included in the table due to their limited scope).

[4] Some asset recovery is anticipated in the case of the Apsara reactor; thus the ISDC L1 Principal Activity percentages do not total 100%.

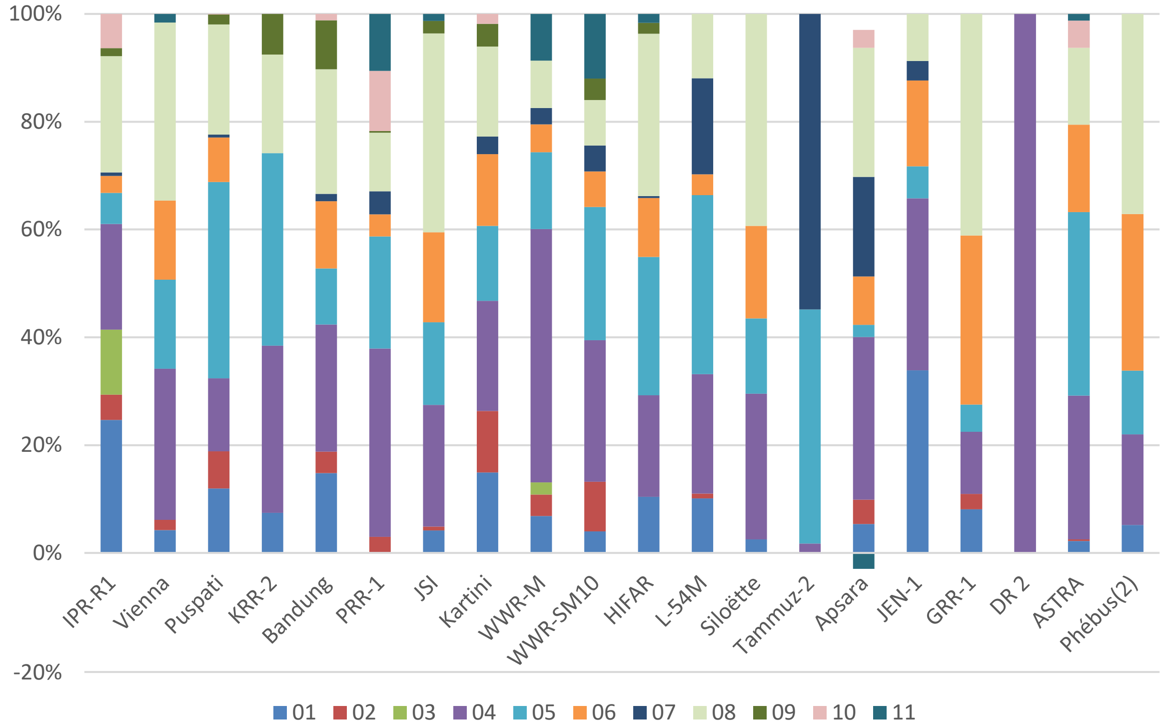


FIG. 8. Decommissioning cost breakdown by ISDC L1 Principal Activity as a percentage of total.

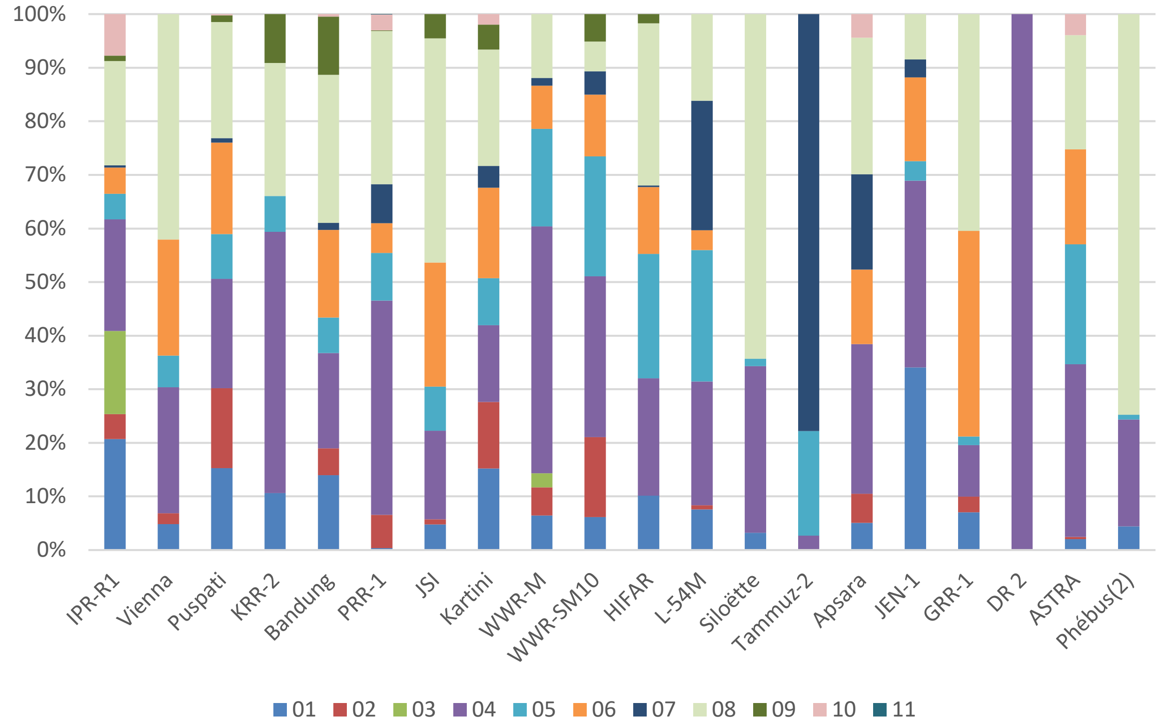


FIG. 9. Workforce breakdown by ISDC L1 Principal Activity as a percentage of total.

TABLE 3. PERCENTAGE OF TOTAL COST BY ISDC L1 PRINCIPAL ACTIVITY

ISDC No.	IPR-R1	Vienna	Puspati	KRR-2	Bandung	PRR-1	JSI	Kartini	WWR-M	WWR-SM10	HIFAR	L-54M	Siloëtte	Apsara	JEN-1	GRR-1	ASTRA	Phébus (2)	Average
01	25	4	12	7	15	0	4	15	7	4	10	10	3	6	34	8	2	5	10
02	5	2	7	0	4	3	1	11	4	9	0	1	0	5	0	3	0	0	3
03	12	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1
04	20	28	14	31	24	35	23	20	47	26	19	22	27	32	32	12	27	17	25
05	6	16	36	36	10	21	15	14	14	25	26	3	14	2	6	5	34	12	18
06	3	15	8	0	12	4	17	13	5	7	11	4	17	10	16	31	16	29	12
07	1	0	1	0	1	4	0	3	3	5	0	18	0	20	4	0	0	0	3
08	22	33	20	18	23	11	37	17	9	8	30	12	39	25	9	41	14	37	23
09	1	0	2	8	9	0	2	4	0	4	2	0	0	0	0	0	0	0	2
10	6	0	0	0	1	11	0	2	0	0	0	0	0	4	0	0	5	0	2
11	0	2	0	0	0	11	1	0	9	12	2	0	0	-3	0	0	1	0	2

Table 3 shows that the dominant contributors to total costs are (in decreasing order of magnitude) the following ISDC L1 Principal Activities:

— ISDC 04: Dismantling activities within the controlled area;
— ISDC 08: Project management, engineering and support;
— ISDC 05: Waste processing, storage and disposal;
— ISDC 06: Site infrastructure and operation;
— ISDC 01: Pre-decommissioning actions.

These results confirm the outcomes of DACCORD Phase 1 [1], in which ISDC 04, 08, 05, 06 and 01 were identified as the most significant contributors to total cost.

Table 4 shows the aggregation of cost by four category groups (ISDC 04+07; 05; 06+08; others) to facilitate easier comparison with published cost studies not presented according to the ISDC L1 Principal Activities. This grouping was also used to facilitate cost comparisons in a recent international study of NPP decommissioning costs [8] (see also Section 4.3).

Figures 10 and 11 present total cost and total workforce values for ISDC 04, 05 and 07 in correlation with reactor power.

The analysis suggests a good correlation between ISDC 04, 05 and 07 cost and workforce and reactor power. Significant variances are observed among similar power rated reactors connected to the different project scopes reflected in the estimates. It should be noted that the GRR-1 reactor is an outlier because it has a limited scope.

Figure 12 presents an analysis of the collected data, focusing on ISDC 04 and 07 and their correlation with inventory data (masses). Some costing cases have been excluded from the analysis because of significant differences in inventory data (i.e. dismantling of the reactor building or other surrounding facilities, or no available details (L-54M, JEN-1, Tammuz, Apsara, Phébus)).

The analysis suggests a broad inverse correlation between ISDC 04 and 07 unit cost per tonne (US $/t) and power rating (i.e. an increased power rating typically leads to a reduction in the unit cost per tonne of inventory for ISDC 04 and 07 activities). It is evident that the cost cases with low labour rates also have lower costs per tonne of inventory; this trend is more likely to be related to the increased inventory rather than the power rating per se. The KRR-2 reactor has a large inventory with corresponding low UFs, mainly due to shield elements made of masonry and plain concrete.

Research reactors have small inventories compared with nuclear power plant decommissioning projects. In small projects preparatory and finishing activities are relatively independent of the size of

TABLE 4. PERCENTAGE OF TOTAL COST FOR THE MOST SIGNIFICANT COST GROUPS

ISDC No.	IPR-R1	Vienna	Puspati	KRR-2	Bandung	PRR-1	JSI	Kartini	WWR-M	WWR-SM10	HIFAR	L-54M	Siloëtte	Apsara	JEN-1	GRR-1	ASTRA	Phébus (2)	Average
04+07	20	28	14	31	25	39	23	24	50	31	19	40	27	52	36	12	27	17	29
05	6	16	36	36	10	21	15	14	14	25	26	33	14	2	6	5	34	12	18
06+08	25	48	29	18	36	15	54	30	14	15	41	16	56	35	25	72	30	66	35
Others	49	8	21	15	29	25	8	32	22	29	14	11	3	11	34	11	9	5	19

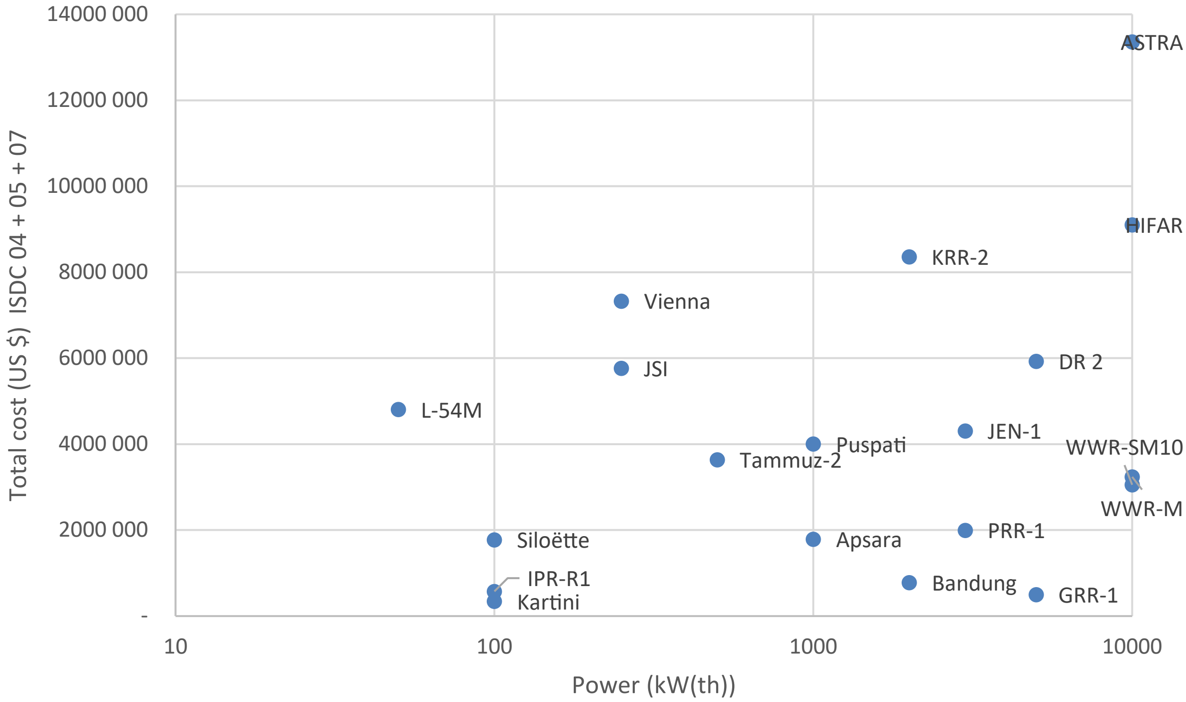


FIG. 10. Total costs for ISDC 04, 05 and 07.

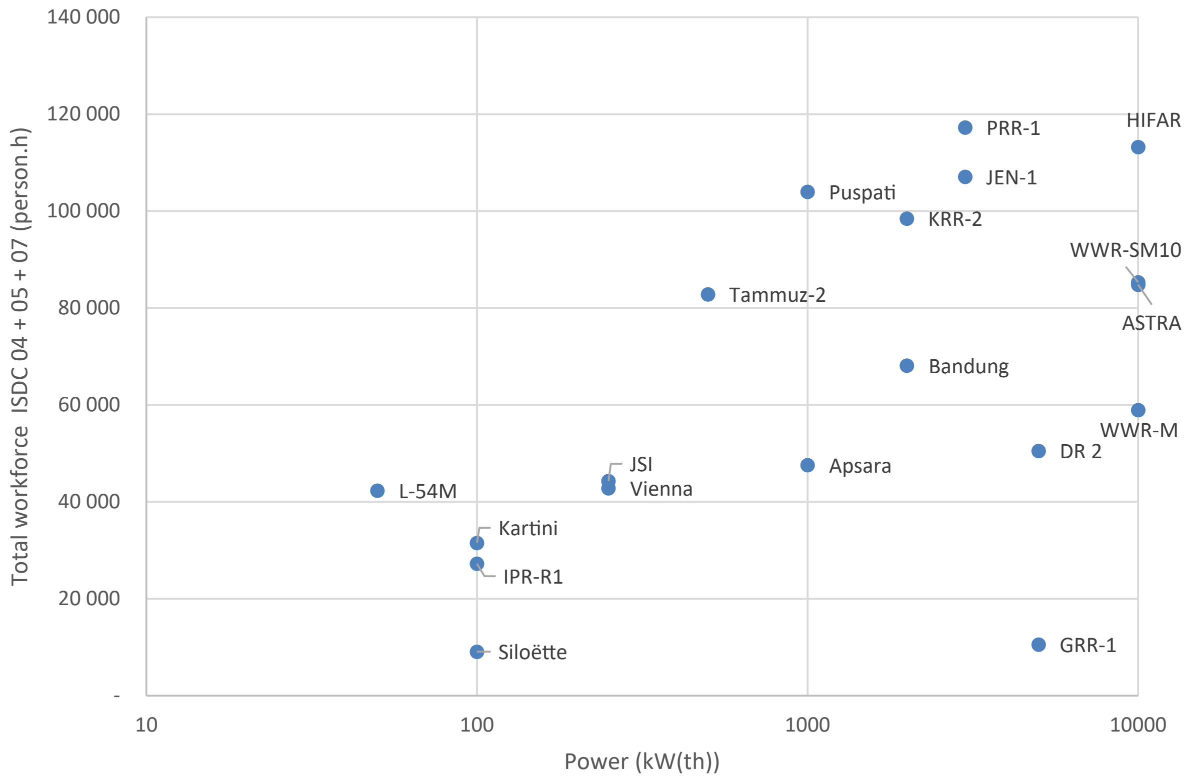


FIG. 11. Total workforce hours for ISDC 04, 05 and 07.

the inventory. Nuclear power reactors generally have significantly larger inventories, resulting in a lower relative cost per tonne and increased productivity levels.

Figure 13 shows the relationship between dismantling/demolition yields for ISDC 04 and 07, in terms of kg/person-hour and reactor power rating.

The data collected generally show a broad tendency towards higher yield levels — in terms of the quantity of inventory processed per unit of labour input — at higher power ratings, with increased variance of yield levels at higher power rating. As noted earlier, research reactor decommissioning projects involve significantly smaller inventories than nuclear power plant decommissioning projects. In small projects, the effort involved in undertaking preparatory and finishing activities is largely independent of the quantities of inventories, whereas higher power reactors have larger inventories, resulting in lower relative cost and increased productivity in terms of tonnes of inventory per workforce time.

Figure 14 shows the relation between ISDC 05 (waste processing, storage and disposal) and rated thermal power. The data indicate a general tendency for the ISDC 05 cost to increase with thermal power, although the results are significantly influenced by scope. Those projects which include waste management and disposal within the defined scope for the purposes of the cost estimate will typically have significantly higher waste management costs, whereas those with fewer waste management activities in the assumed scope (e.g. because long term activities are excluded) have lower costs. It is evident that the four cases at 10 MW(th) show a variation in ISDC 05 cost largely associated with the variation in the waste management scope. The ASTRA reactor has the most complete waste management scope, while the other cases are more limited.

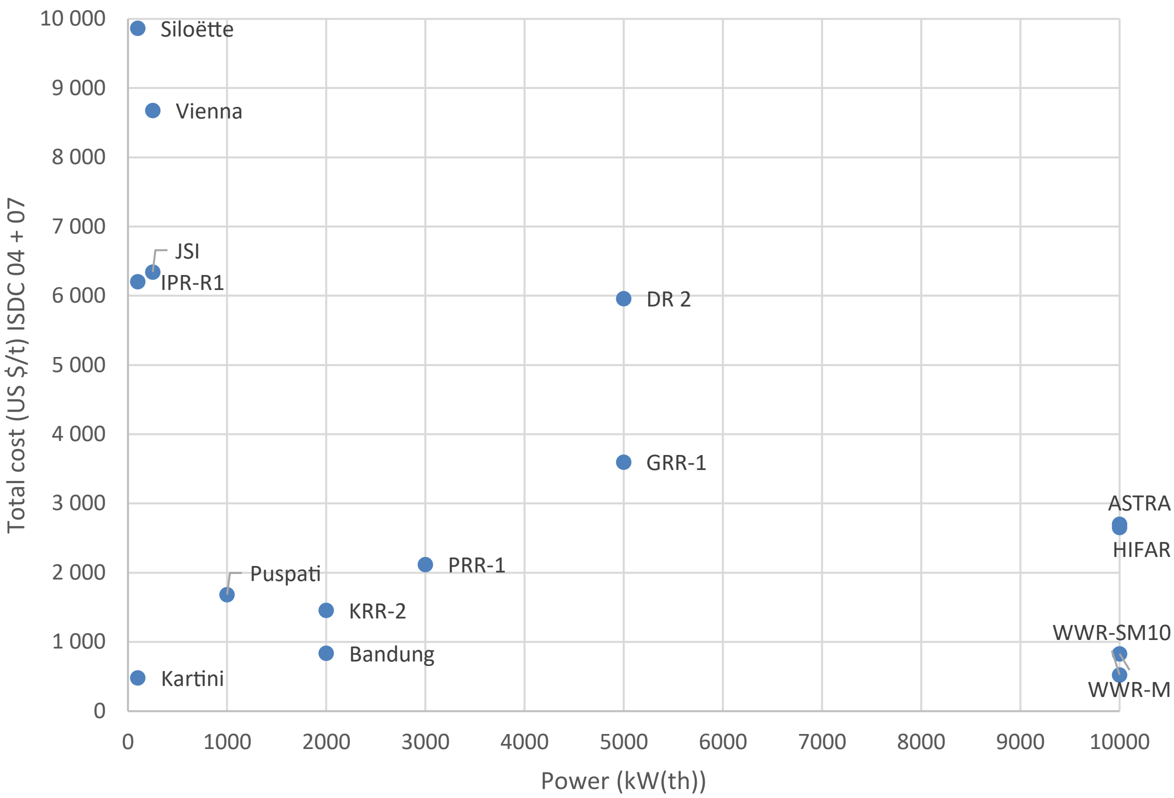


FIG. 12. Cost per tonne for ISDC 04 and 07 as a function of thermal power.

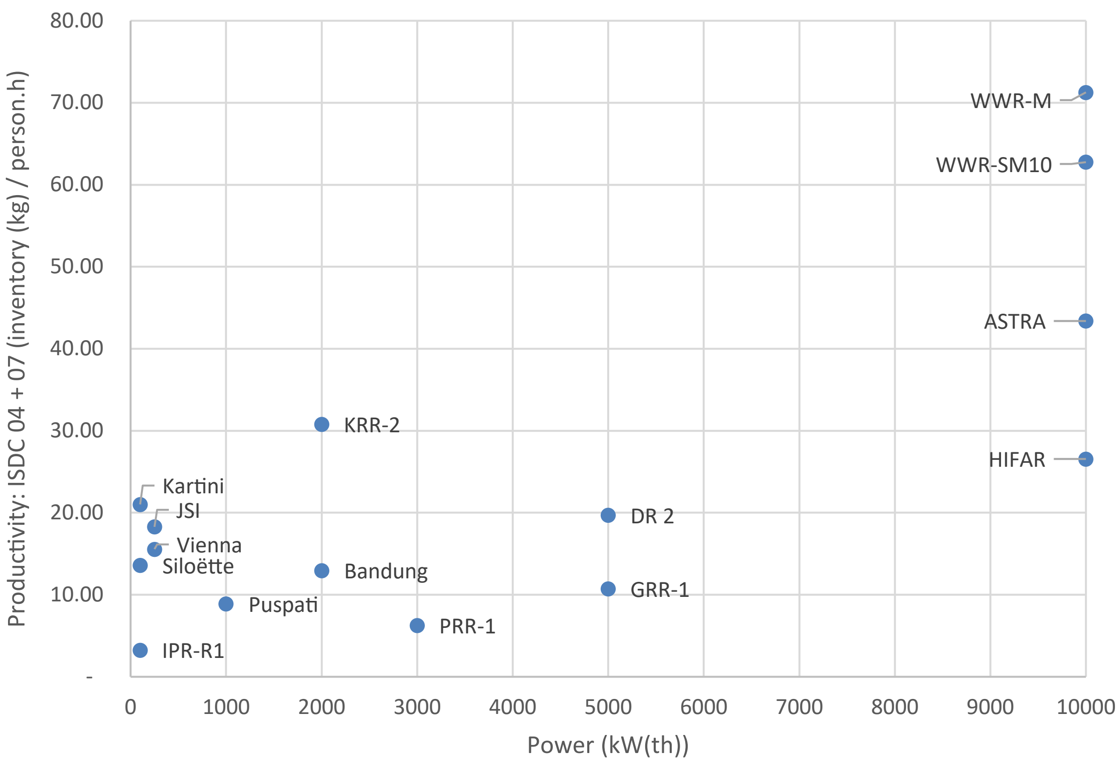


FIG. 13. Relationship between dismantling/demolition yield for ISDC 04 and 07 and thermal power.

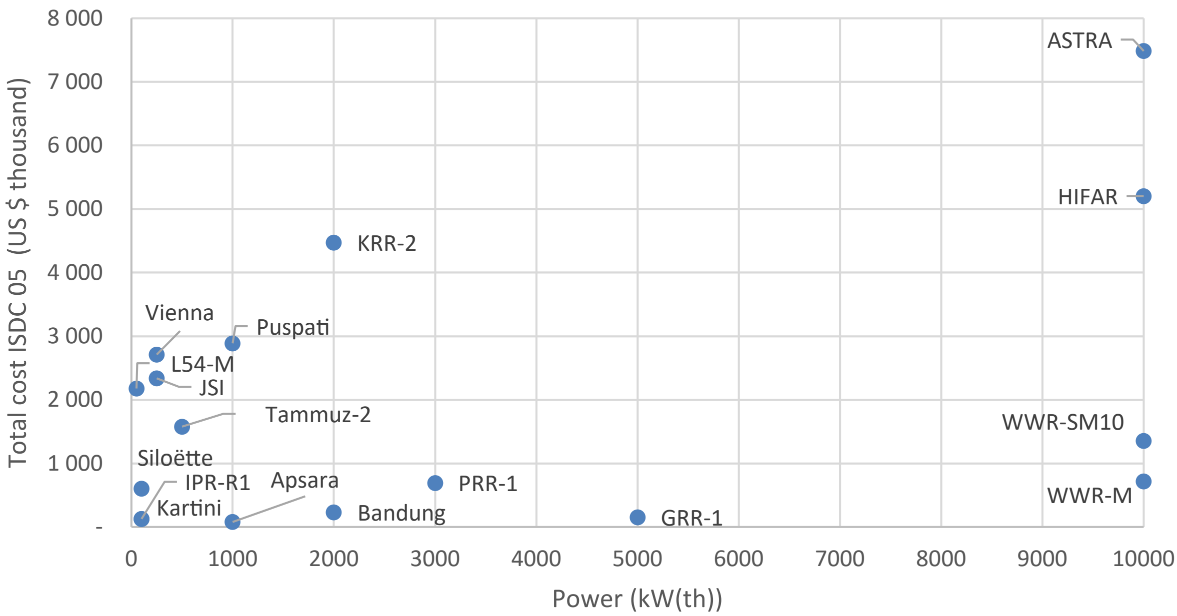


FIG. 14. Waste costs for ISDC 05 as a function of thermal power.

4.3. COMPARISON WITH NUCLEAR POWER PLANT DECOMMISSIONING COSTS

To enable easier comparison with cost estimates presented in different formats to the ISDC, an approach involving aggregation of ISDC items into groups — 04+07, 05, 06+08 and others — has been used in other studies. For example, in Ref. [8], the decommissioning cost for selected decommissioning projects for nuclear power plants in Europe (projects in various lifecycle stages) and in the United States of America (USA) (completed projects) were analysed. Cost data from Europe were delivered in ISDC format; cost data from the USA were transformed from US decommissioning cost formats to the ISDC format. Data are presented in Table 5, which generally shows good correlation between the data for research reactors and nuclear power plants.

TABLE 5. DECOMMISSIONING COSTS BY ISDC ACTIVITY GROUPS AS A PERCENTAGE OF TOTAL COST

USA NPP decommissioning projects [8]	La Salle Unit 1	La Salle Unit 2	Comanche Peak Unit 1	Comanche Peak Unit 2	Duane Arnold	Kewaunee	Haddam Neck Plant	Haddam Neck Plant-R	Main Yankee	Trojan NPP	Rancho Secco	Average USA
04 + 07	25	28	19	24	19	18	40	36	37	57	23	30
05	22	21	26	22	21	18	12	11	22	21	15	19
06 + 08	44	45	45	48	45	46	37	34	32	22	55	41
Others	10	6	10	6	15	18	11	18	9	1	8	10

TABLE 5. DECOMMISSIONING COSTS BY ISDC ACTIVITY GROUPS AS A PERCENTAGE OF TOTAL COST (cont.)

Europe NPP decommissioning projects [8]	José Cabrera ES-P1	Generic – ESP ES-P2	Generic – CH CH-P1	Generic – FR FR-P1	S.M. Garona ES-B1	Generic – ESB ES-B2	Loviisa FI-V1	Bohunice SK-V1	Average Europe	Average USA	Average USA+Europe	Average DACCORD 2
04 + 07	22	43	12	50	29	43	44	29	34	30	32	29
05	4	5	10	19	6	8	8	29	11	19	15	18
06 + 08	46	44	33	14	55	41	5	29	33	41	37	35
Others	28	7	46	17	11	7	42	13	22	10	16	19

Regarding the variation in the percentages for ISDC 05, there are projects in Europe in which the percentage is significantly below 10%; the context of the extent of waste management should be considered carefully, as some of the cases analysed have taken the end state of waste management (for decommissioning costing purposes) as the point at which it enters the storage facility. Full waste management is implemented only in some of the European decommissioning projects; in these projects the percentage is far greater than 10%. Conversely, the waste management costs provided for the US plants typically include all management stages through to final disposal, with waste often being transported directly from the facility site to the disposal without an interim storage step.

In the group ISDC 06+08, ISDC 06 shows good consistency. However, for ISDC 08 the costs are much greater for US projects. There are likely to be several reasons for this, such as structure of the decommissioning organization, and the effect of fleet and multi-unit approaches, with project management and support costs being spread across projects.

There is less consistency in the ‘Others’ group, which includes ISDC 01, 02, 09, 10 and 11. For the aggregate of these, the European reactors indicate a much larger share of the overall cost, at 22% average as compared with 10% for US reactors. This is largely due to ISDC 01 and 02, which are doubled in the European projects. ISDC 10 is a separate item in US projects; ISDC 11 is closely comparable [8].

Overall, the average values for the nuclear power plant decommissioning projects in both Europe and the USA are similar to the DACCORD Phase 2 costing cases. This is interesting as the DACCORD set of cases includes decommissioning projects from all continents except North America.

4.4. OBSERVATIONS

It is evident that among the 20 decommissioning cases analysed in this project, there are many differences related to the following:

- Reactor types and designs;
- Reactor power;
- Facility location, local country regulations, labour rates;
- Facility operational history (standard operation, accidents, legacy waste);
- Decommissioning project scope and end state;
- Isolated decommissioning project versus multi-facility sites;
- Waste management system considered in the costing case.

This project analysed 20 different research reactor facilities in 18 countries at different stages in their life cycle (i.e. some already decommissioned, some in a permanent shutdown phase, and some still in operation). The analysis suggests that even if the decommissioning costs strongly depend on the factors listed above, there are some correlations or tendencies that must be taken into account when estimating decommissioning cost, including the following:

- Correlation between total decommissioning cost and workforce versus reactor power. Increasing the reactor power is linked to a general increase in total decommissioning costs and workforce involved. The increase can be considered as broadly proportional, though there is a cost threshold at very low power ratings or zero power installations.
- Labour cost is the most significant category, with an average percentage of around 50% of total cost. Varying the labour rates can have a large impact on the total estimated decommissioning cost. This should be taken into account when determining the labour rates to use in the estimate. Including workforce data when comparing the cost may help understand the differences in cost.
- The analysis confirms the conclusion of DACCORD Phase 1, where ISDC 04, 08, 05, 06 and 01 are identified as the most significant contributors to the total cost.
- Analysis of dismantling/demolition activity unit cost (ISDC 04, 07 — US $/t) shows a general tendency of relative cost reduction with increasing reactor power rating, with high unit cost figures being more applicable to low reactor power costing cases. There are two basic components, one being broadly proportional to inventory levels (e.g. cutting (dismantling) itself). A second component, such as preparatory and finishing activities, is less directly related to inventory levels; this component increases unit cost for small reactors.
- Analysis of dismantling activity productivity (ISDC 04, 07 — t/h) shows a general tendency towards productivity increases at larger reactor power levels.
- At the lower power range (tens of kW), there is likely to be a minimum decommissioning cost level, not dependent on power output, as was also concluded from Phase 1 of the project. The threshold cost is likely to be closely related to the national labour rate, while the workforce threshold is less ‘national specific’.
- Non-inventory dependent activities (ISDC 06, 08, 01, 02) represent a significant component of the decommissioning cost and workforce. As such, accurate definition of staffing requirements and duration is important.
- Waste management assumptions may differ significantly, from a minimalist approach involving putting the waste into storage, to full consideration of long term management activities, including treatment, conditioning and final disposal of waste streams.
- Comparison of ratios for cost groups ISDC 04 + 07, ISDC 05, ISDC 06 + 08 and others (ISDC 01, 02, 09, 10, 11), as proposed and developed in the OECD/NEA project [8], shows very good consistency in the relative importance of the different cost groups for both nuclear power plant decommissioning and research reactor decommissioning (this project).
- Comparison of the average cost ratio (US $/kW(th)) between lower power reactors (≤250 kW) and higher power reactors (e.g. tens of MW) developed in this project shows a difference of values by up to a factor of 10.
- Experience from this project attests to the utility of ISDC as a structured format for collecting consistent data sets to be entered into CERREX-D2 to provide cost estimations, and effectively for presenting the data for comparing costs for decommissioning research reactors.

5. UNCERTAINTY ANALYSIS

Information obtained during the implementation of decommissioning projects over recent decades shows that outturn costs may diverge significantly from estimates undertaken prior to project implementation. This occurs sometimes because costing estimates developed using solely deterministic approaches do not always anticipate the broad range of uncertainties and unknowns associated with the decommissioning project and its associated cost estimate. This section identifies various types of uncertainties and presents methods to quantify them. Section 5.1 focuses on the uncertainty of input parameters used in costing cases, Section 5.2 focuses on in scope uncertainty associated with ISDC contingency (alternative probabilistic estimation of contingency), while Section 5.3 focuses on out of scope uncertainty in costing estimate assumptions (impact of external risks) which is not related to ISDC contingency (i.e. related to project scope uncertainty).

Cost estimates developed using CERREX-D2 are based on an anticipated set of activities which represent an assumed baseline scenario. The methodology used by the software accounts for in scope uncertainties; the impact of out of scope uncertainties may only be addressed by making revisions to the baseline scenario to reflect the cost impacts of external risks to costing cases and then repeating the calculation to determine the resulting impact [9]. Having determined the cost implications of the out of scope uncertainties, a decision needs to be taken as to the extent to which these are funded, which in turn depends on the chosen 'risk appetite' of the funding organization.

Figure 15, adapted from Ref. [9], describes the different elements of a comprehensive cost estimate, including risk. The approach incorporates the following important concepts:

— Basis of estimate (BoE): This describes the scope of the project (boundary conditions, assumptions, decommissioning strategy, etc.); allowances are a regular part of the BoE.
— The baseline estimate: This provides the cost of the project according to the activity scope described in the BoE, including 'in scope' uncertainties ('estimating uncertainty' or 'contingency'). The baseline estimate may in some cases also include out of scope mitigation. The baseline estimates for identified external risks are calculated in CERREX-D2 by establishing modified decommissioning scenarios which reflect the identified risks.

5.1. PROBABILISTIC ANALYSIS OF INPUT PARAMETERS

5.1.1. One factor at a time (OFAT) analysis

A simplified approach to evaluating the uncertainty of a calculation is to perform 'one factor at a time' (OFAT) calculations attributing such limiting values to the input parameters at which the result value is maximal and minimal. This type of analysis was demonstrated during DACCORD Phase 1 and is documented in the project report [1]. The methodology used in Phase 1 was to change one input parameter at a time. Key input parameters were identified and were changed twice; once by –30% and then by +30% of the base value, recalculating total costs using CERREX. Other input parameters were retained at their baseline (nominal) values; the parameter being modified was returned to its nominal value and the same procedure was repeated for each of the other input parameters. Five input parameters were chosen for analysis: labour rate, total inventory, duration of ISDC 06 and 08 activities, WM UFs and decommissioning UFs.

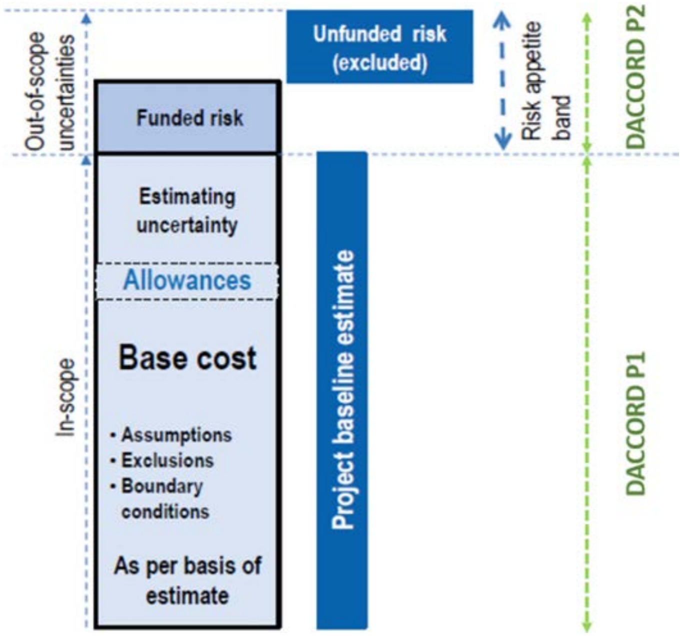


FIG. 15. Elements of a cost estimate. (Adapted with permission from Ref. [9].)

This simple but effective approach was also used in Phase 2, being applied to labour rate, quantities of inventories, UFs for decommissioning categories, UFs for WM categories, WM options (user defined, minimum WM, full WM including disposal), duration of ISDC 06, 08 and relevant ISDC 11 activities. The sensitivity analysis was extended to –50% to +50% in five steps and graphical interpretation was included. Results are included in the individual costing cases.

The results were analysed for all the reactors in the study, including TRIGA (IPR-R1, Puspati, KRR-2, Bandung, Philippines RR), pool in tank or WWR reactor type (WWR-M, WWR-SM) and open pool reactors (Siloëtte, Tammuz-2, Apsara, JEN-1, GRR-1, DR 2, ASTRA). The following general conclusions were made based on this analysis:

— In most cases changes in labour rate had the largest impact on total cost uncertainty;
— Total inventory and duration of period dependent activities generally were the second most important input parameters;
— The variation of other assessed parameters showed lower levels of impact.

A weakness of the above approach is that the limiting values of input parameters do not always determine the limiting values of results for a complex task or a complex system under analysis (e.g. decommissioning costing case estimate), as these values may be influenced by a combination of input parameter values. Therefore, in such cases, it is best to perform the uncertainty analysis using the probabilistic method. This method of analysis allows evaluation of uncertainty for all parameters at the same time.

5.1.2. Methodology for probabilistic uncertainty and sensitivity analysis

In order to overcome the shortcomings of OFAT analysis, probabilistic uncertainty analysis methodology was used, based on the Monte Carlo (MC) random sampling method. This method assumes that the input parameters are random values and the values are described by a normal probability distribution function (Table 6).

TABLE 6. PROPERTIES OF THE INPUT PARAMETERS

Name	Description	Location in CERREX	Nominal value (best estimate)	Min value	Max value	PDF
AVW LR	Factor for changing labour rate	ISDC M2	1	0.7	1.3	Normal
Mass	Factor for changing quantities of inventories	ISDC N2	1	0.7	1.3	Normal
Duration	Factor for changing period dependent activities (ISDC 06, 08, 11.0200, 11.0300)	ISDC O3	1	0.7	1.3	Normal
UF D&D	Factor for changing UFs for D&D categories	ISDC O2	1	0.7	1.3	Normal
UF WM	Factor for changing UFs for WM categories	ISDC M3	1	0.7	1.3	Normal

To simulate the OFAT analysis done during Phase 1 of DACCORD to the same extent, a total of 91 input parameters are needed. Using such a high number of input parameters would lead to extremely large iteration counts of the MC method. To optimize the iteration counts, the CERREX-D2 code incorporates multiplication factors[5], enabling all values for specific input parameter groups to be changed simultaneously. As shown in Table 6, five input parameters (factors) were used for probabilistic uncertainty analysis. These factors modify labour rate, quantities of all inventories, duration of ISDC 06, 08, 11.0200, 11.0300 items, UFs for decommissioning categories and UFs for WM categories. The nominal value for all input parameters was set to 1 and they were randomly sampled according to a standard continuous normal (Gaussian) probability distribution in the 0.7 to 1.3 range.

The analysis of result uncertainty is not limited to the evaluation of the possible boundaries of the result or the probability at which the result will or will not exceed the set value. In order to optimize the system, time and cost, it is advisable to evaluate which parameters have the greatest influence on the results. The main objective of the sensitivity analysis is to determine which input parameter has the biggest influence on the model result and evaluate (rank) the importance of primary parameters. The Pearson correlation coefficient (CC)[6] was used as a measure of the strength of a linear association between two variables since non-linear dependencies are not used in CERREX-D2 software.

To implement this methodology the CERREX-D2 software was coupled with additional software, which utilizes an additional MS Excel file to generate random values for input parameters that are then inserted into the CERREX costing case. For each iteration, the cost estimate was recalculated and the calculation results were stored for later processing and analysis.

[5] Multiplication factors are found in the ISDC sheet in the M2:O3 cell range.

[6] The Pearson correlation coefficient (PCC or CC) is a statistic that measures the linear correlation between two variables.

5.1.3. Analysis of results

A probabilistic approach was used to evaluate the uncertainty of total cost and total workforce based on the uncertainty of important input parameters. Two illustrative costing cases, representing TRIGA Mark I and Mark II and TRIGA Mark III type reactors (see Section 3), were analysed. Probability density functions (PDF) and cumulative distribution functions (CDF) illustrate the probability (frequency) of the total cost falling within a range of values. For this analysis the values of all input parameters were maintained within ±30% of their initial values.

As can be seen in Fig. 16, the total decommissioning cost calculation for the TRIGA Mark I and Mark II illustrative costing case is in the range of US $6.5 million–28.6 million. The minimum and maximum values have very low probability, and the most probable values are in the interquartile range (IQR), which is between US $14.8 million and US $18.2 million, i.e. values from the first quartile (Q^1) to third quartile (Q^3), respectively, or middle 50% values (IQR = Q^3–Q^1). As regards the TRIGA Mark III costing case, the minimum and maximum values are in the range of US $7.5 million–31.9 million, while the IQR is between US $17.5 million and US $21.2 million (Fig. 17).

A similar analysis was done for total workforce. For the TRIGA Mark I and Mark II costing case, the minimum and maximum values are between 164 000 and 298 000 person-h, though with very low probability, while the IQR is between 223 000 and 244 000 person-h (Fig. 18). As for the TRIGA Mark III costing case, the minimum and maximum values are between 152 000 and 283 000 person-h, while the IQR is between 197 000 and 215 000 person-h (Fig. 19).

A comparison of the deterministic and probabilistic estimates for the TRIGA Mark I–Mark III costing cases is provided in Table 7. The deterministic and the probabilistic estimates at the P50 confidence level for total cost and total workforce are similar for both costing cases, although this result depends strongly on the assumed uncertainty ranges of the input parameters. At higher confidence levels, the probabilistic estimates of contingency are higher than the deterministic value, providing an illustration of the relationship between assumed contingency levels and the likelihood that project budgets may be exceeded (e.g. in this illustration the deterministic estimate should be increased by 20% to be equal to the 90% confidence level). As regards the total workforce, the results show that this parameter is not as sensitive as total cost.

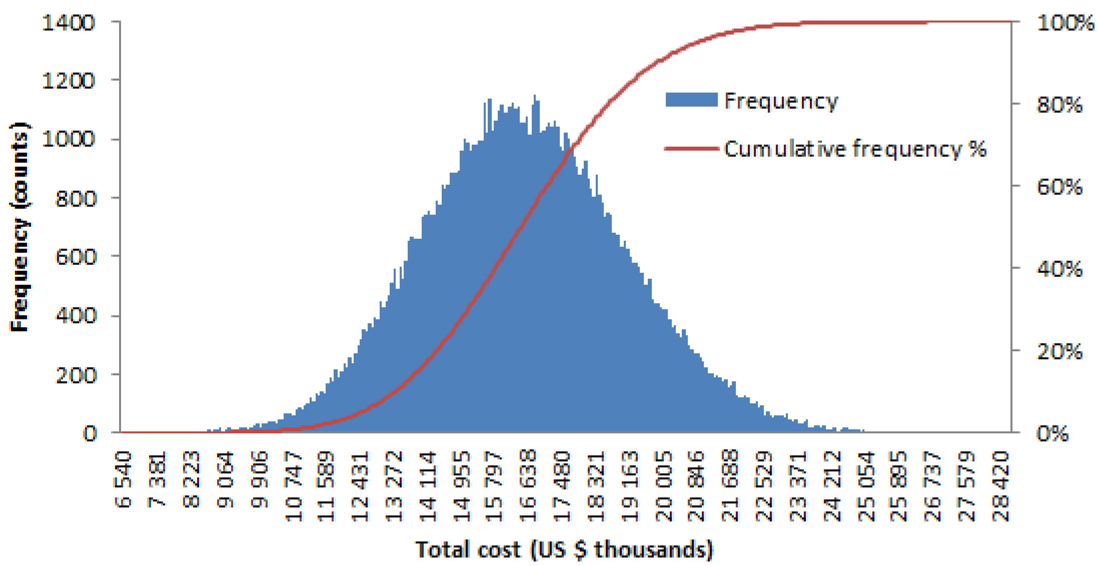


FIG. 16. Total cost PDF and CDF for the illustrative TRIGA Mark I and Mark II costing case.

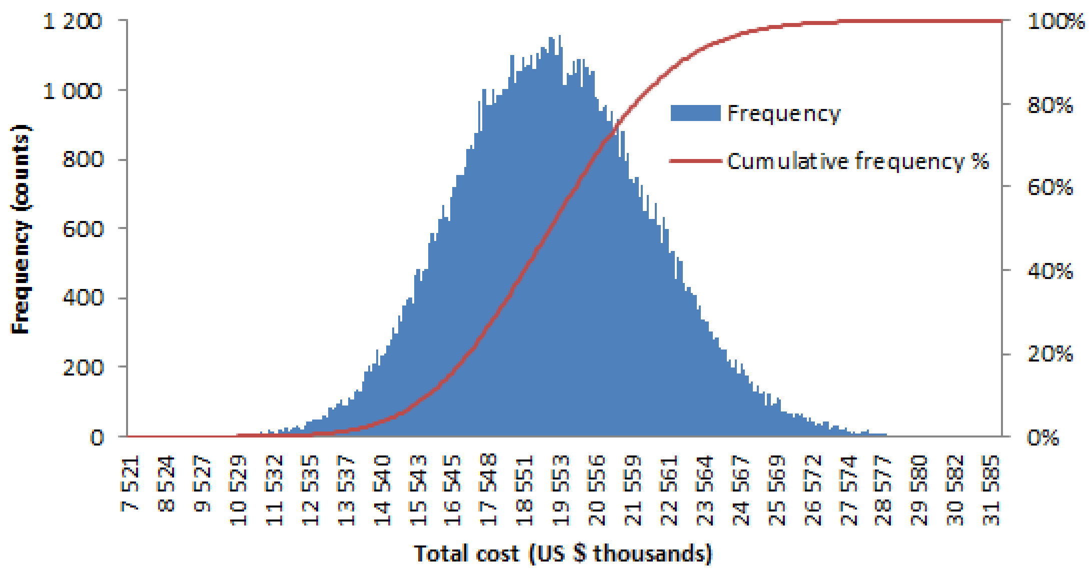


FIG. 17. Total cost PDF and CDF for the illustrative TRIGA Mark III costing case.

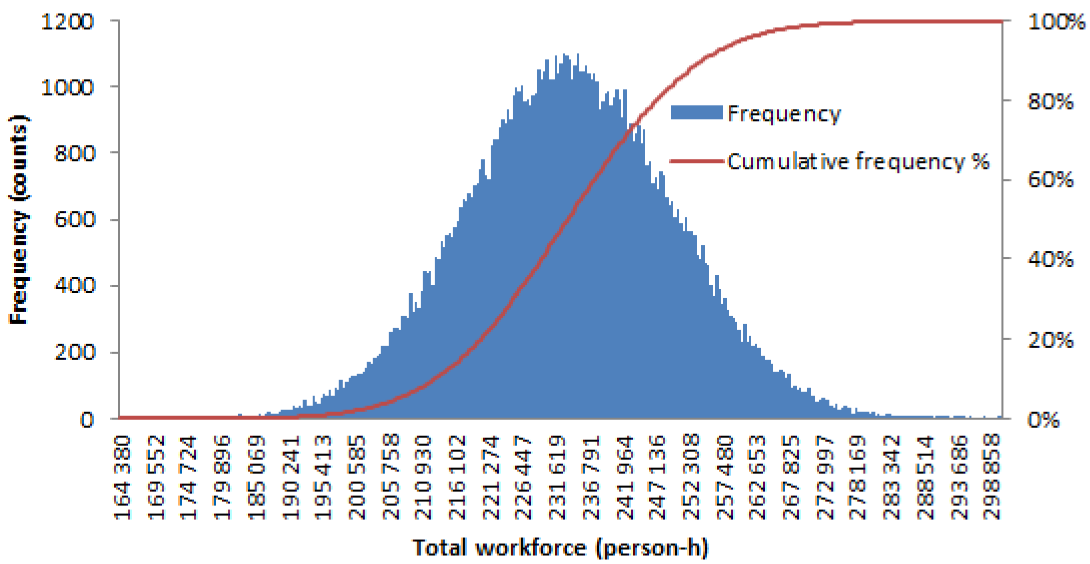


FIG. 18. Total workforce PDF and CDF for the illustrative TRIGA Mark I and Mark II costing case.

It is important to distinguish between sensitivity analysis, as discussed above, and estimation of contingency due to the uncertainty of the input parameters. The purpose of sensitivity analysis is to identify impacts of variations of selected input parameters (in the above case ±30%), while the probabilistic estimation of contingency in Section 5.2 addresses overall uncertainty in the overall estimate as a result of potential variation of selected input parameters.

The results of the sensitivity analysis for total cost are presented in Fig. 20, which shows the calculated correlation coefficient for each of the analysed input parameters — for both the TRIGA Mark I–Mark II and TRIGA Mark III costing cases. The results for both cases are similar. The greatest influence on the total cost estimation is the average worker labour rate (AVW LR), while the uncertainty of other input parameters has a much lower impact on total cost estimate.

In contrast to the above, the sensitivity analysis results for total workforce, presented in Fig. 21, are different for the TRIGA Mark I–Mark II and TRIGA Mark III costing cases. For the TRIGA Mark I–Mark II costing case, the greatest influence on the total workforce estimation is the uncertainty of duration (ISDC 06, 08, 11.0200, 11.0300 items), while other input parameters have a much lower impact. As for the TRIGA Mark III costing case, the greatest influence on the total workforce estimation is the quantity of inventories (mass), UFs for decommissioning categories (UF D&D) and duration (ISDC 06, 08, 11.0200, 11.0300 items). Also, there is a modest impact from UFs for waste management categories (UF WM).

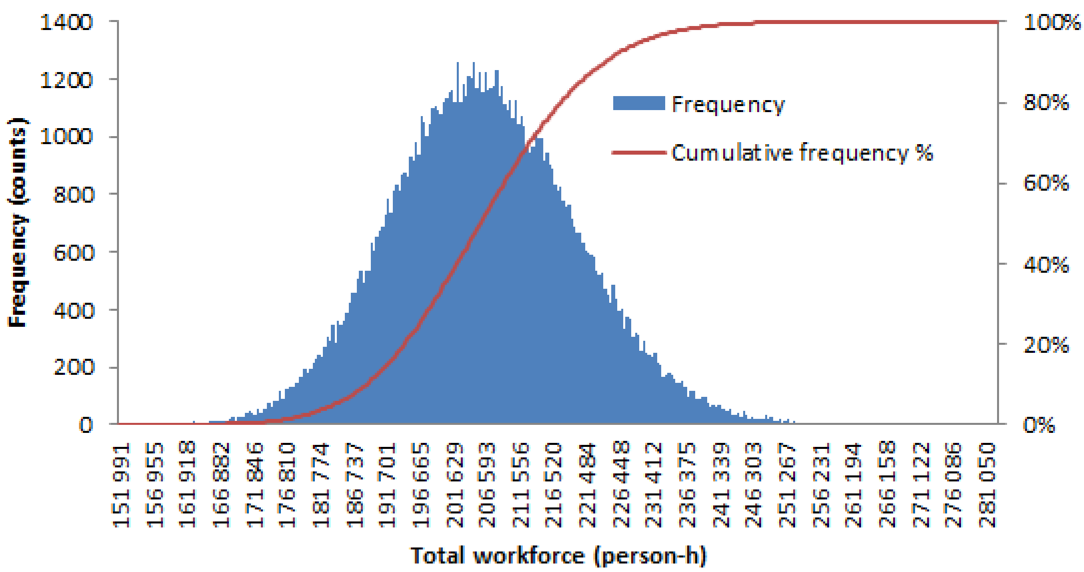


FIG. 19. Total workforce PDF and CDF for the illustrative TRIGA Mark III costing case.

TABLE 7. COMPARISON OF DETERMINISTIC AND PROBABILISTIC ESTIMATES

Name	Total cost				Total workforce			
	TRIGA Mark I–Mark II		TRIGA Mark III		TRIGA Mark I–Mark II		TRIGA Mark III	
	US $ (million)	%	US $ (million)	%	Person-h	%	Person-h	%
Deterministic estimate	16.557	100.0	19.355	100.0	233 584	100.0	206 201	100.0
Probabilistic estimate (P50)	16.498	99.6	19.322	99.8	233 343	99.9	206 179	100.0
Probabilistic estimate (P60)	17.129	103.5	20.016	103.4	237 653	101.7	209 488	101.6
Probabilistic estimate (P70)	17.831	107.7	20.787	107.4	241 964	103.6	213 211	103.4
Probabilistic estimate (P80)	18.672	112.8	21.636	111.8	247 136	105.8	217 761	105.6
Probabilistic estimate (P90)	19.864	120.0	22.947	118.6	254 463	108.9	224 380	108.8

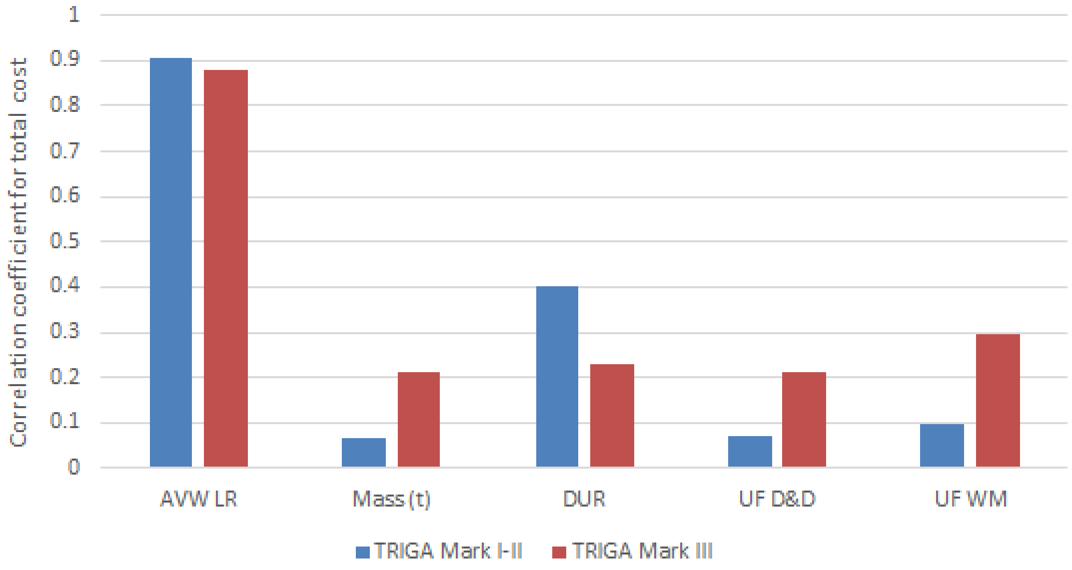


FIG. 20. Sensitivity analysis results for total cost.

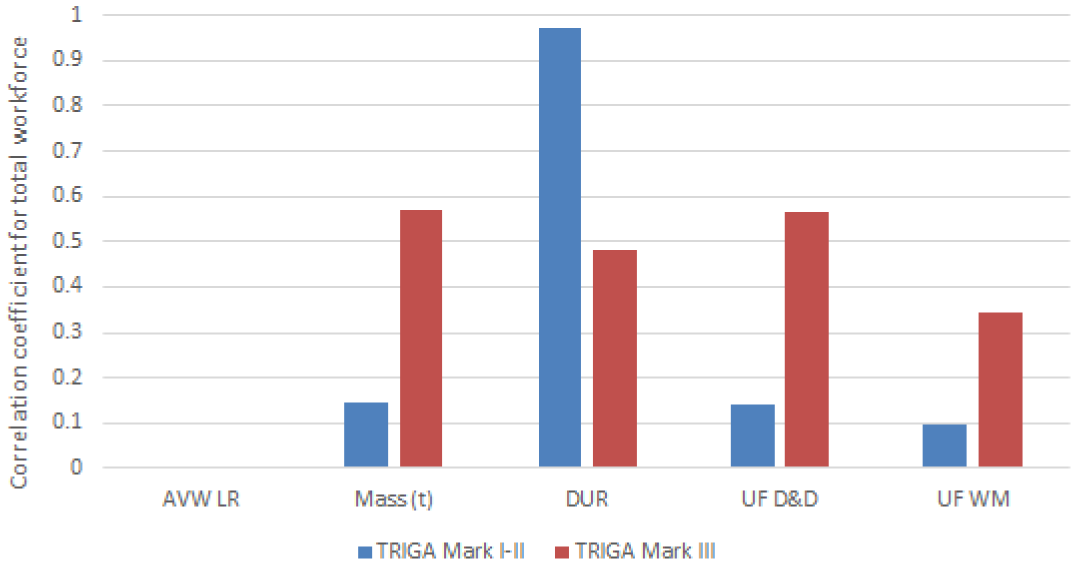


FIG. 21. Sensitivity analysis results for total workforce.

5.2. ESTIMATING IN SCOPE UNCERTAINTY

5.2.1. Description of different methods of contingency estimation in the CERREX code

The contingency estimates account for costs that are expected to occur but are not well defined. This is also typical in cost estimating of construction work (e.g. due to normal variability of environmental conditions). However, uncertainties also include the risk of outcomes which are foreseeable though not expected to occur and are not typically included within the BoE.

In the CERREX-D2 software, the contingency is calculated deterministically at the level of each elementary calculation item. The level of contingency is defined by the user for individual calculation items. Tentative values of contingency are included in the software template. Based upon the nature of this cost element, it is assumed that the contingency will be spent fully when performing the decommissioning activities; therefore, the P100 confidence interval (or very close to this value) is used in probabilistic approaches.

CERREX-D2 facilitates the calculation of contingency using an alternative, probabilistic, approach using the MC method [9]. The spreadsheet dealing with ISDC L2 includes a special module for this purpose, with the user being required to define a three point estimate (TPE)[7] percentage for individual ISDC L2 items, and the required confidence interval. A graphical presentation of the results of the MC method is provided in the spreadsheet on ISDC L1.

Default values for contingency ranges in CERREX-D2 are summarized in Table 8. More detailed values for contingency at ISDC L2 are also available in CERREX-D2.

5.2.2. Contingency ranges for the reactors studied

Ratios of contingency cost to total cost are presented in Table 9 and Fig. 22 for participating TRIGA reactors, and in Table 10 and Fig. 23 for reactors other than TRIGA. In all cases values are calculated and presented for ISDC L1 Principal Activities.[8]

TABLE 8. DEFAULT VALUES FOR CONTINGENCY RANGES IN CERREX-D2

ISDC No.	ISDC L1 Principal Activity	Contingency ranges (%)
01	Pre-decommissioning actions	0–25
02	Facility shutdown activities	0–20
03	Additional activities for safe enclosure or entombment	0–15
04	Dismantling activities within the controlled area	0–20
05	Waste processing, storage and disposal	0–20
06	Site infrastructure and operation	0–10
07	Conventional dismantling and demolition and site restoration	0–15
08	Project management, engineering and support	0–10
09	Research and development	0–10
10	Fuel and nuclear material	0–15
11	Miscellaneous expenditure	0–10

[7] Three figures are provided for each item (the best case estimate, the most likely estimate and the worst case estimate). These are then combined to yield a full probability distribution.

[8] Ratios are calculated by dividing the appropriate value for contingency (column J at the ISDC L2 level) by the given costs (column F at the ISDC L2 level).

TABLE 9. DETERMINISTIC CONTINGENCY AS A PERCENTAGE OF TOTAL COST FOR PARTICIPATING TRIGA REACTORS

ISDC No.	ISDC L1 Principal Activity	Vienna (Austria)	IPR-R1 (Brazil)	Bandung (Indonesia)	KRR-2 (Korea, Rep. of)	Puspati (Malaysia)	PRR-1 (Philippines)	JSI (Slovenia)
01	Pre-decommissioning actions	15	9	13	17	9	0	12
02	Facility shutdown activities	17	13	17	0	13	0	16
03	Additional activities for safe enclosure or entombment	0	13	0	0	0	0	0
04	Dismantling activities within the controlled area	22	15	20	17	28	3	18
05	Waste processing, storage and disposal	17	14	18	9	15	16	15
06	Site infrastructure and operation	11	9	13	0	9	0	9
07	Conventional dismantling and demolition and site restoration	0	10	13	0	13	0	0
08	Project management, engineering and support	9	9	13	17	9	0	9
09	Research and development	0	9	13	17	9	0	9
10	Fuel and nuclear material	0	13	13	0	13	0	0
11	Miscellaneous expenditure	5	0	0	0	0	1	9

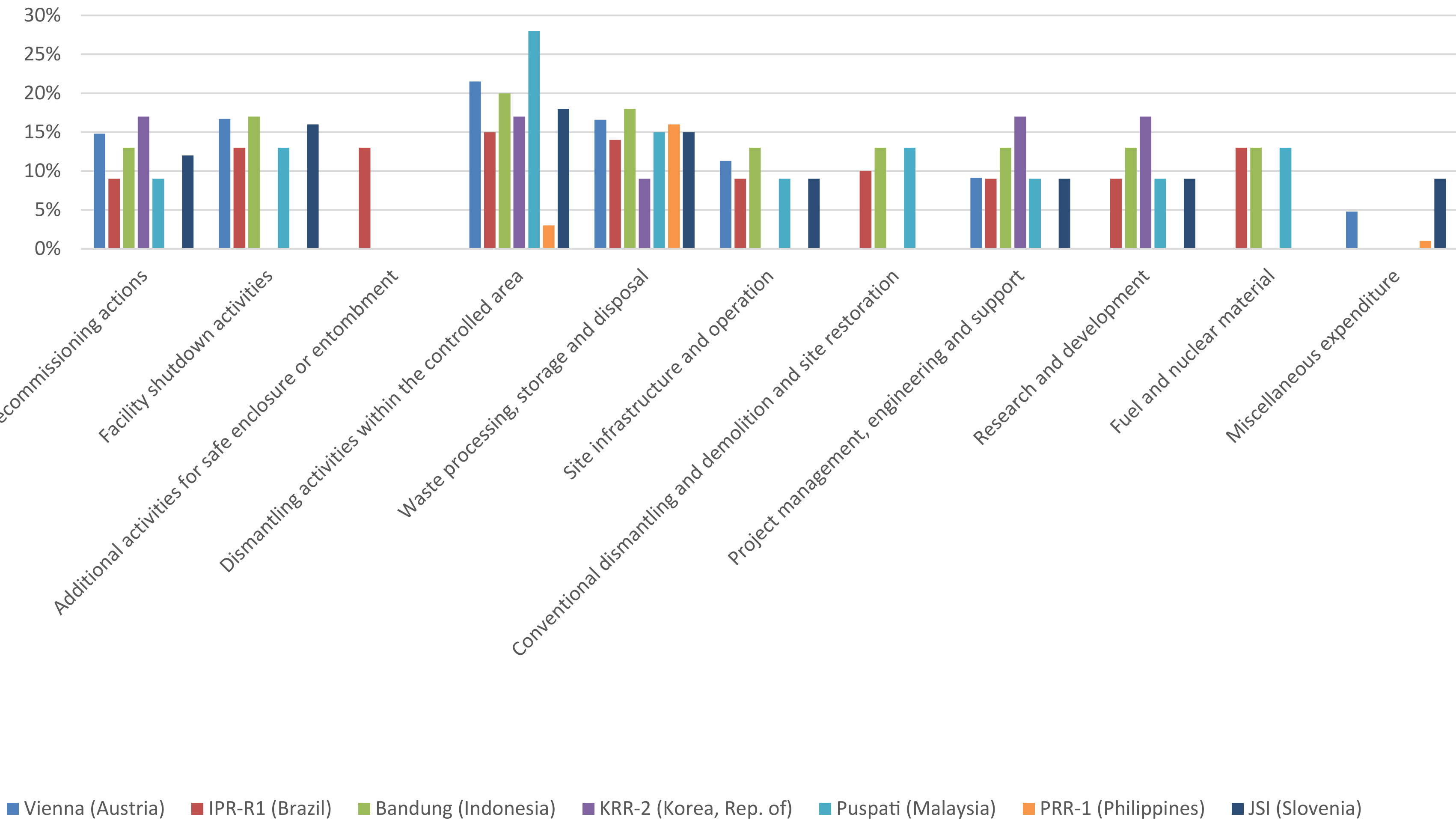


FIG. 22. Deterministic contingency calculated as a percentage of total cost for different TRIGA reactors.

TABLE 10. DETERMINISTIC CONTINGENCY AS A PERCENTAGE OF TOTAL COST FOR PARTICIPATING NON-TRIGA REACTORS

ISDC No.	ISDC L1 Principal Activity	HIFAR (Australia)	Phébus (France)	WWR-SM10 (Hungary)	L-54M (Italy)	Tammuz-2 (Iraq)	Siloëtte (France)	WWR-M (Ukraine)	PRR-1 (Philippines)	Apsara (India)
01	Pre-decommissioning actions	9	9	10	17	0	9	9	0	17
02	Facility shutdown activities	0	0	21	17	0	0	16	0	17
03	Additional activities for safe enclosure or entombment	0	0	0	0	0	0	9	0	0
04	Dismantling activities within the controlled area	20	14	21	17	17	15	7	3	17
05	Waste processing, storage and disposal	17	16	17	17	17	16	5	16	17
06	Site infrastructure and operation	9	9	17	17	0	9	5	0	17
07	Conventional dismantling and demolition and site restoration	13	0	13	17	17	0	8	0	17
08	Project management, engineering and support	9	11	16	17	0	9	5	0	17
09	Research and development	9	0	23	0	0	0	0	0	0
10	Fuel and nuclear material	0	0	0	0	0	0	0	0	17
11	Miscellaneous expenditure	4.8	0	12	0	0	0	1	1	17

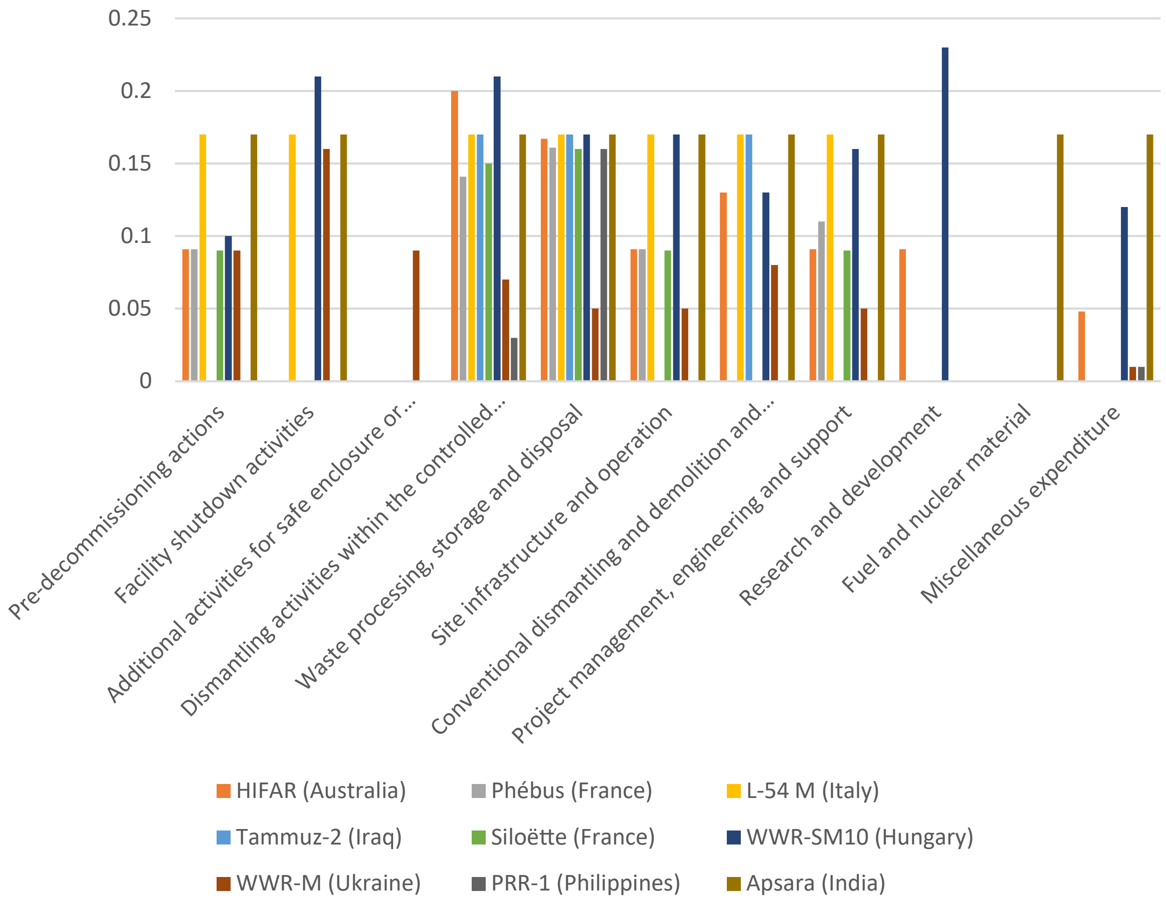


FIG. 23. Deterministic contingency calculated as a percentage of total cost for different reactors.

5.2.3. Analysis of outcomes for the JSI TRIGA Mark II

Table 11 presents the deterministic results of the costing case for the JSI TRIGA Mark II reactor in Slovenia. The calculated contingency for this reactor, expressed in percentage terms, is shown in the last column of Table 9.

The development of the probabilistic estimation of uncertainties for the JSI TRIGA Mark II costing case followed the approach used in Ref. [9], with a base cost case being defined as the sum of the labour cost, investment cost and expenses (i.e. without deterministic contingency). A TPE distribution of cost values was used, with the most probable values being equivalent to the base cost data at ISDC L2 and minimal values are –5% to the most probable value. Maximal values were derived from the deterministic contingency levels and multiplied by a factor of 2.05 (factor 2 due to the asymmetric form of the TPE distribution and 0.05 as the converse of –5% for the definition of minimal value). The estimating uncertainty (contingency) calculated according to this approach represents the full area of the probabilistic distribution.

The graphical presentation for probabilistic calculated total cost[9] for the JSI TRIGA is shown in Fig. 24. This figure presents a probabilistic distribution of project costs in local currency (€). The probabilistic contingency is the difference between the highest cost value and the lowest cost value in this distribution, following the ISDC definition of the contingency which is assumed to be spent fully in the decommissioning project. Table 12 summarizes the probabilistic values with different confidence intervals for contingency.

[9] The frequency of different total cost results being obtained from the analysis is indicated as a number of ‘counts’.

TABLE 11. DETERMINISTIC CONTINGENCY CALCULATED FOR ISDC ACTIVITIES FOR THE JSI TRIGA MARK II

ISDC No.	ISDC L1 Principal Activity	Costs before contingency (€)	Deterministic contingency (€)	Costs with contingency (€)
01	Pre-decommissioning actions	231 577	33 081	264 658
02	Facility shutdown activities	38 462	7 369	45 831
03	Additional activities for safe enclosure or entombment	0	0	0
04	Dismantling activities within the controlled area	2 176 006	480 891	2 656 897
05	Waste processing, storage and disposal	1 574 282	276 430	1 850 712
06	Site infrastructure and operation	2 028 462	202 846	2 231 308
07	Conventional dismantling and demolition and site restoration	0	0	0
08	Project management, engineering and support	5 250 000	525 000	5 775 000
09	Research and development	131 538	13 154	144 692
10	Fuel and nuclear material	0	0	0
11	Miscellaneous expenditure	150 000	15 000	165 000
	Total	11 580 327	1 553 771	13 134 098

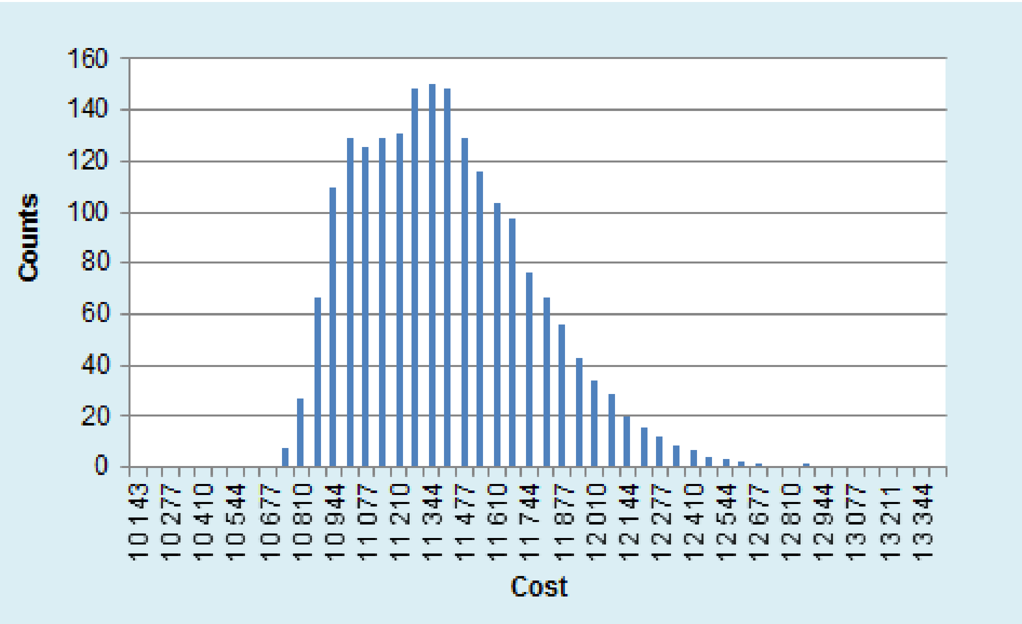


FIG. 24. Probabilistic calculated total cost (€ thousands) for the JSI TRIGA.

TABLE 12. SUMMARY OF PROBABILISTIC CONTINGENCY VALUES

Contingency basis	€
Deterministic contingency	1 553 771
Probabilistic contingency = Most probable value for contingency with P90 (confidence interval = 0.90)	1 103 687
Probabilistic contingency = Most probable value for contingency with P95 (confidence interval = 0.95)	1 272 285
Probabilistic contingency = Most probable value for contingency with P99 (confidence interval = 0.99)	1 559 406
Probabilistic contingency = Most probable value for contingency with P995 (confidence interval = 0.995)	1 770 606
Probabilistic contingency = Most probable value for contingency with P100 (confidence interval = 1)	2 743 329

The Monte Carlo tool which is incorporated into CERREX-D2 has limited computational capability due to limitations in total byte content. A confidence interval of 1.000 includes minor outlier values with very low probability; in this example the result corresponding to the confidence interval 0.995 (€1 770 606) provides a closer approximation to the deterministically calculated contingency (€1 553 771). In practice, the determination of TPE values should be made on the basis of expert judgement. The calculation details and results are presented in Annex VII.

5.3. ESTIMATING OUT OF SCOPE UNCERTAINTY

5.3.1. Background

This section is concerned with risks beyond the anticipated project plan, known as out of scope uncertainties, in line with the general approach proposed jointly by the OECD/NEA and the IAEA [9]. The methodology was applied to the JSI TRIGA Mark II reactor in Slovenia using CERREX-D2 and an additional MS Excel based Monte Carlo code.

5.3.2. Methodology

The methodology used here focuses on a specific approach using CERREX-D2 and an additional MS Excel based analysis (addressing only those ISDC items which are affected by the postulated out of scope uncertainties).

5.3.2.1. Methodology Step 1: Identification of out of scope uncertainties

Identification of out of scope uncertainties relies on a good understanding of the BoE for the decommissioning project. This should be performed through an overall risk analysis that includes both in scope and out of scope uncertainties. A risk register, such as the one presented in Appendix III, is the first step in this process. A risk matrix should then be developed, including probabilities of the identified risks, their impact if realized and risk reduction actions (mitigation of the impact or the probability of occurrence). If implemented, these mitigation actions should be incorporated into the baseline estimate.

5.3.2.2. Methodology Step 2: Determine out of scope cost impact with CERREX-D2

CERREX-D2 can be used to determine the cost impact of the out of scope uncertainties identified. An existing CERREX-D2 file with a base cost estimate can be used to model the impact of specific risks.

It is necessary to assess the cost impact of each out of scope uncertainty before calculating their total impact on the project cost. The following steps are taken in determining the impact:

- Describe the risk(s).
- Describe the impact in terms of ISDC: Identify the ISDC activities impacted and how they are affected.
- Prepare a modified CERREX-D2 cost case: For calculation of cost impacts, identify modifications to the CERREX input file correlated with the impacts described and rerun separate costing cases in CERREX-D2.
- Prepare results: The estimated cost items are presented in ISDC L1 and L2 format for use with Monte Carlo simulation to determine a cost distribution which takes the assessed risks into account.

5.3.2.3. Methodology Step 3: Use Monte Carlo simulation to quantify the cost distribution taking risks into account

A Monte Carlo analysis is applied to the results of the CERREX-D2 calculations for the risk based scenarios. Normal distributions may be considered for each out of scope uncertainty. An MS Excel tool was developed specifically to perform this analysis. Input data are developed as follows for the probability analysis:

- The most probable value is set as the cost for the ISDC item without out of scope uncertainty impact being considered.
- The maximum value is the value of the ISDC item including the out of scope condition.
- The minimum value may be set at 2% to most probable value.

The output of the analysis is a probability distribution of the total cost of the project. Given the risk appetite, the necessary related provision will be determined by selecting the appropriate confidence interval.

5.3.3. Methodology applied to the JSI TRIGA Mark II reactor

This subsection illustrates the methodology used for out of scope cost analysis, with reference to the JSI decommissioning project; the approach applied is not exhaustive, being limited to five out of scope uncertainties. Risk analysis is a project specific activity, with the identified risks associated with the facility itself, its geography, regulatory requirements, etc. The focus here is to consider their cost impact rather than on their identification, using examples based on postulated risks considered as threats for the project, but the project may also encounter risks considered as opportunities.

The JSI costing case is a preliminary cost estimate which is planned to be updated in five years. The scope of the project includes the following:

- ISDC 04: All inventory items in the controlled area will be dismantled, building surfaces will be decontaminated by chemical and mechanical methods, radiological surveys of the reactor building will be conducted and the building will be declassified, to non-active for unrestricted use as a technical museum.
- ISDC 05: All waste will be processed to the extent that it may be placed in interim storage. Waste conditioning and final disposal is not included within the scope of the costing case.
- ISDC 07: The area of the reactor site will be radiologically surveyed and released to the level of unrestricted use. The reactor building will remain at the site and will be accessible to the general public.

5.3.3.1. JSI Analysis Step 1

The five out of scope risks were selected during a risk workshop involving specialist personnel from the JSI facility. The starting point of the workshop was the risk family prompted from Ref. [10]. For each risk family, brainstorming was performed to identify possible risks. The risks identified were then determined to be in scope or out of scope considering the BoE of the project. The five out of scope uncertainties were selected according to expert judgement. In order not to complicate the example, it was decided not to include mitigation in the demonstration.

The selected out of scope risks are the following:

(1) Discovery of asbestos;
(2) Unanticipated LLW identified during decommissioning;
(3) External pressure from stakeholders to demolish the buildings;
(4) Unexpected contamination of concrete due to unknown leakage;
(5) Change of strategy — contractor will be involved instead of own staff.

5.3.3.2. JSI Analysis Step 2

The following assumptions have been made for the risks cited above.

(a) Discovery of asbestos
    (i) Description: Some hidden asbestos may remain undiscovered during the characterization campaign. It will be identified during dismantling in the controlled area. No prolongation of the project or other impacts are considered in this example.
    (ii) Identified ISDC items:
        — ISDC 04.0402: Removal of materials requiring specific procedures; removal of 2 t of asbestos containing materials;
        — ISDC 05.1000: Management of decommissioning VLLW; processing of 2 t of asbestos containing materials as VLLW.
    (iii) Input data for numerical evaluation of cost impacts:
        — 2 t of asbestos containing material were introduced in the lower part of the INV spreadsheet with the ISDC 04.0402 number;
        — Allocating standard WDFs and additionally 100% to WDF7;
        — 100% partitioning to VLLW.

The results are presented in Table 13.

TABLE 13. COST IMPACT OF DISCOVERY OF ASBESTOS

ISDC item	Cost impact (€)
04.0402	69 211
05.1000	25 487
Total	94 698

TABLE 14. COST IMPACT OF UNANTICIPATED LLW IDENTIFIED DURING DECOMMISSIONING

ISDC item	Cost impact (€)
05.0400	24 180
Total	24 180

(b) Unanticipated LLW identified during decommissioning
- (i) Description: 0.5 t of unanticipated LLW was identified during dismantling of auxiliary systems in the controlled area of the reactor building. The waste needs to be retrieved to a special container procured for this purpose. It will then be processed in the same way as the decommissioning LLW. No prolongation of the project or other impacts are considered.
- (ii) Identified ISDC items:
  - — ISDC 05.0400: Management of historical/legacy LLW.
- (iii) Input data for numerical evaluation of cost impacts:
  - — 0.5 t of unanticipated LLW were introduced in the lower part of the INV sheet with the ISDC 05.0400 number and LGW identification of the inventory item;
  - — Allocating standard WDFs and additionally 100% to WDF7;
  - — 100% partitioning to LLW;
  - — Modify unit factors in UF; set 100 staff hours/t for workforce and 1000 €/t for expenses;
  - — In the ISDC spreadsheet add €10 000 of fixed investment cost for procurement of special container for identified LLW.

The results are presented in Table 14.

(c) External pressure from stakeholders to demolish the buildings
- (i) Description: Due to stakeholder involvement, the original end state considered — conservation of the reactor building for the future purposes of a technical museum — has to be changed and part of the reactor building will be demolished to the standard level of –1 m. Prolongation of the decommissioning project for 0.3 years is considered; no other impacts are considered.
- (ii) Identified ISDC items:
  - — ISDC 07.0300: Demolition of buildings and structures; demolition of 200 t of reinforced concrete in the area out of control;
  - — ISDC 05.1301: Crushing of demolished concrete;
  - — ISDC 06: All of the period dependent items have a duration of 0.3 years;
  - — ISDC 08: All of the period dependent items have a duration of 0.3 years.
- (iii) Input data for numerical evaluation of cost impacts:
  - — 200 t of reinforced concrete were introduced in the lower part of the INV spreadsheet (designated as ISDC 07.0300);
  - — Allocation of standard WDFs for areas out of control;
  - — ISDC 06: For all of the period dependent items the duration is set to 0.3 years; other settings are unchanged;
  - — ISDC 08: For all of the period dependent items the duration is set to 0.3 years; other settings are unchanged.

The results are presented in Table 15.

(d) Unexpected contamination of concrete due to unknown leakage
   (i) Description: Some unidentified leakages occurred during the operation which were not documented. The leakages penetrated to spaces between the concrete blocks and were not detected during the radiological survey. During decontamination of floors by chemical and mechanical methods the dose rate did not decrease as expected; hidden contamination due to leakage in the past was identified as the cause. Five tonnes of concrete within the controlled area had to be removed and processed as LLW and VLLW (50%:50%) using the same procedures as for decommissioning waste. Impact of the additional activities on the duration of the project is not considered.
   (ii) Identified ISDC items:
      — ISDC 04.0702: Removal of an additional 5 t of contaminated concrete in the controlled area;
      — ISDC 05.0900: Management of decommissioning of additional 2.5 t of LLW;
      — ISDC 05.1000: Management of decommissioning of additional 2.5 t of VLLW.
   (iii) Input data for numerical evaluation of cost impacts:
      — 5 t of reinforced concrete in the controlled area were introduced in the lower part of the 'INV' spreadsheet with the number ISDC 04.0702;
      — Allocating standard WDFs and additionally 100% to WDF7;
      — 50%:50% partitioning to LLW-VLLW.

The results are presented in Table 16.

TABLE 15. COST IMPACT OF EXTERNAL PRESSURE FROM STAKEHOLDERS TO DEMOLISH THE BUILDINGS

ISDC item	Cost impact (€)
07.0300	101 936
05.1301	42 035
06	18 067
08	42 880
Total	204 918

TABLE 16. COST IMPACT OF UNEXPECTED CONTAMINATION OF CONCRETE DUE TO UNKNOWN LEAKAGE

ISDC item	Cost impact (€)
04.0702	28 128
05.0900	29 400
05.1000	6 515
Total	64 043

TABLE 17. COST IMPACT FOR CHANGE OF STRATEGY — CONTRACTOR WILL BE INVOLVED INSTEAD OF OWN STAFF

ISDC item	Cost impact (€)
06	37 470
08	219 958
Total	257 428

TABLE 18. ESTIMATED COST IMPACT FOR OUT OF SCOPE UNCERTAINTIES

ISDC No.	ISDC L1 Principal Activity	Cost impact for risk (€)[a]					Total
		1	2	3	4	5	
01	Pre-decommissioning actions	—[b]	—	—	—	—	—
02	Facility shutdown activities	—	—	—	—	—	—
03	Additional activities for safe enclosure or entombment	—	—	—	—	—	—
04	Dismantling activities within the controlled area	69 211	—	—	28 128	—	97 339
05	Waste processing and storage (disposal not addressed)	25 487	24 180	42 035	35 915	—	127 617
06	Site infrastructure and operation	—	—	18 067	—	37 470	55 537
07	Conventional dismantling and demolition and site restoration	—	—	101 936	—	—	101 936
08	Project management, engineering and support	—	—	42 880	—	219 958	262 838
09	Research and development	—	—	—	—	—	—
10	Fuel and nuclear material	—	—	—	—	—	—
11	Miscellaneous expenditures	—	—	—	—	—	—

[a] 1: Discovery of asbestos. 2: Unanticipated LLW identified during decommissioning. 3: External pressure from stakeholders to demolish the buildings. 4: Unexpected contamination of concrete due to unknown leakage. 5: Change of strategy: contractor will be involved instead of own staff.

[b] —: no significant impact.

(e) Change of the strategy — contractor will be involved instead of own staff
   (i) Description: During dismantling activities in the controlled area, it was stated that the owner's staff did not have the relevant skills to perform those activities. It was decided to tender a contractor to perform the dismantling activities in the controlled area. As a result, there was a delay of three months in the project; ISDC 06 and ISDC 08 activities were prolonged for 0.25 years[10].
   (ii) Identified ISDC items:
      — ISDC 06: All of the period dependent items will be considered with a duration of 0.5 years;
      — ISDC 08: All of the period dependent items will be considered with a duration of 0.5 years.
   (iii) Input data for numerical evaluation of cost impacts:
      — ISDC 06: All of the period dependent items will be considered with a duration of 0.5 years;
      — ISDC 08: All of the period dependent items will be considered with a duration of 0.5 years.

The results are presented in Table 17. The results from this step are summarized in Table 18.

5.3.3.3. JSI Analysis Step 3

The minimal, most probable and maximal values are determined as per Methodology Step 3 (Section 5.3.2 and Table 19). These are used to run a Monte Carlo simulation as described in the methodology.

The outcome of the simulation is presented below in Fig. 25 (probability distribution[11]) and Fig. 26 (cumulative distribution). The risk 'appetite' was defined as a confidence level of 80% that the outturn costs are bounded. The result of estimation of the required additional provision is €214 667, being 1.9% of total cost.

TABLE 19. MINIMAL, MOST PROBABLE AND MAXIMAL VALUES FOR MONTE CARLO SIMULATION

ISDC No.	ISDC L1 Principal Activity	Value (€)		
		Minimal	Most probable	Maximal
01	Pre-decommissioning actions	—[a]	—	—
02	Facility shutdown activities	—	—	—
03	Additional activities for safe enclosure or entombment	—	—	—
04	Dismantling activities within the controlled area	2 751 351	2 807 501	2 904 840
05	Waste processing and storage (i.e. disposal not addressed)	1 876 339	1 914 632	2 042 249
06	Site infrastructure and operation	2 033 180	2 074 674	2 130 211

[10] For this scenario a difference in the cost per person-hour would normally typically occur, although this has not been included here.

[11] The Y axis indicates a probability value corresponding to the cost segment shown on the X axis, such that the summation of all probability values equals 100%.

TABLE 19. MINIMAL, MOST PROBABLE AND MAXIMAL VALUES FOR MONTE CARLO SIMULATION (cont.)

ISDC No.	ISDC L1 Principal Activity	Value (€)		
		Minimal	Most probable	Maximal
07	Conventional dismantling and demolition and site restoration	0	0	101 936
08	Project management, engineering and support	4 511 057	4 603 120	4 865 958
09	Research and development	—	—	—
10	Fuel and nuclear material	—	—	—
11	Miscellaneous expenditure	—	—	—
	Total	11 171 928	11 399 927	12 045 194

[a] —: no significant impact.

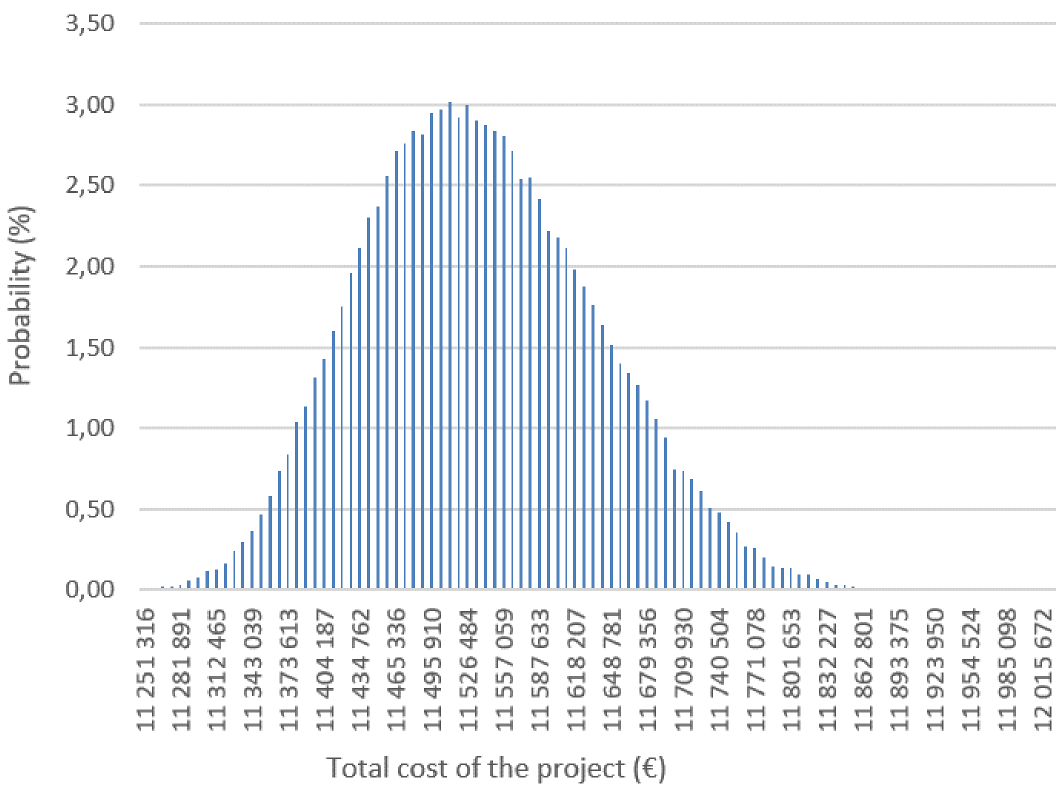


FIG. 25. Probability distribution of the total cost of the project in €, including out of scope uncertainties.

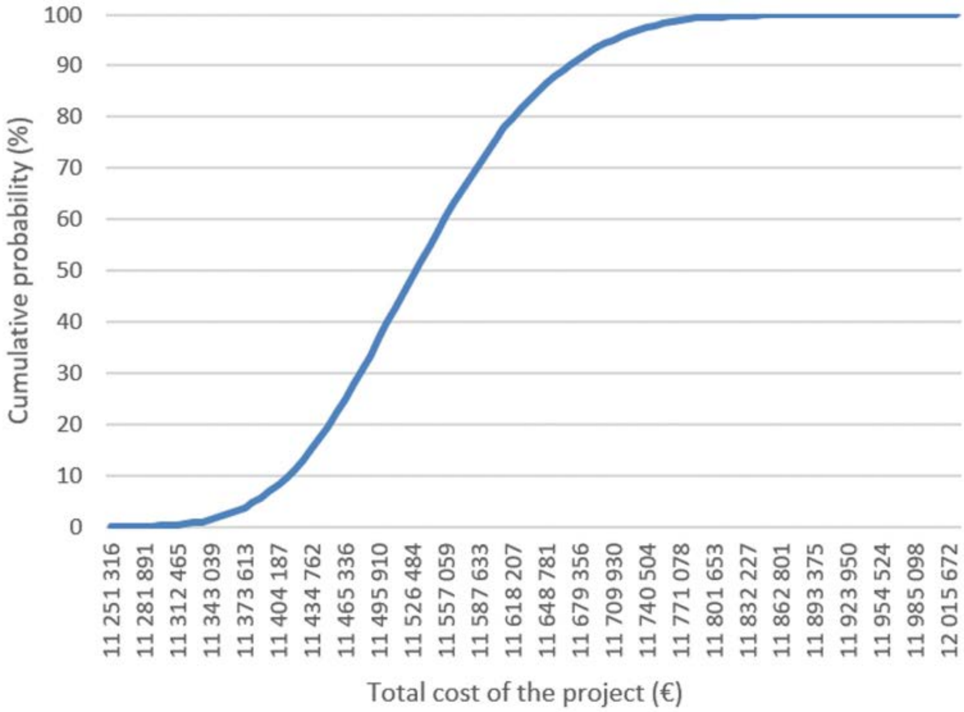


FIG. 26. Cumulative probability of the total cost of the project in €, including out of scope uncertainties.

5.4. CONCLUSIONS

The analysis of uncertainties using the improved computation tools incorporated into CERREX-D2 suggests the following:

- Probabilistic analysis improves the quality of uncertainty computation based on the input parameters.
- Probabilistic analysis generally improves the calculation of estimating uncertainties (contingency).
- Taking into account out of scope uncertainties improves the overall quality and utility of decommissioning cost estimates.

The enhanced capacity of CERREX-D2 software to perform probabilistic estimation of in scope uncertainties, together with the associated tool for estimation of out of scope uncertainties, provide the possibility of undertaking such calculations as part of preliminary cost estimations for decommissioning. It is evident that, due to the nature of probabilistic methods, the strict linkage of estimated costs and discrete (ISDC based) activities is lost; nonetheless, the main ISDC contributors to costs can still be identified (see also Ref. [9]).

6. IMPACTS OF PLANNING AND CHARACTERIZATION ON DECOMMISSIONING

6.1. OBSERVATIONS FROM PLANNING AND CHARACTERIZATION

Radiological characterization plays a central role in decommissioning planning and directly impacts the estimation of decommissioning costs. It helps to identify and estimate many of the parameters relevant to the decommissioning and management of radioactive material [11]. Furthermore, it plays a key role in providing confidence and understanding about the initial/current state of the facility. It also provides important input to both dismantling and waste management planning.

Past decommissioning projects have demonstrated that poor planning and characterization plans based on incomplete historical information negatively impact the success of a decommissioning project. Incorrect or insufficient information leads to inappropriate strategic choices associated with over- or underestimation of waste volumes and over- or under-classification of waste, discovery of unexpected contamination, etc. Several examples are provided in Appendix IV and some key observations are highlighted here.

In the case of the Siloé reactor in France, the initial activation calculation led to a dismantling scenario of the vessel by contact operation. When the operator emptied the pool, the activation was higher than expected. The origin of this activation was the presence of a cavity filled with air below the +3.20 m level of the main square pool, limiting the energy loss of the neutrons from the core. This was explained by the fact that the casing of the main pool was modified in 1988. During this renovation, an air space was created below the level +3.20 m, between the vessel and the vessel casing. Neutron scattering in this air gap led to a greater than expected activation of the vessel, the vessel casing and concrete when deciding on the initial dismantling approach. The approach was revised to remote operation and the overall schedule delay was approximately three years.

Currently, there is general recognition that accurate characterization and good planning are critical to successful dismantling projects. Accordingly, a good knowledge of the radiological and physical status of the facility and associated characterization strategy must be established well before the beginning of dismantling operations to ensure successful planning and implementation of the decommissioning project.

The Finnish TRIGA reactor FiR-1 was permanently shut down in 2015. The characterization process began in 2013 with inventory calculations, followed by sampling and analysis starting from potentially free released materials and progressing towards more radioactive components and materials. The first inventory calculations in 2013–2015 resulted in a significant overestimate of the Fluental tritium inventory (the moderator material used for boron neutron capture therapy treatments) due to a mathematical limitation in the calculation method of the ORIGEN-S point depletion code, i.e. calculating only total flux, with three shape factors used to model the flux spectrum, overestimates the extent of the thermal region with subsequent overestimation of the production rates for ^{6}Li neutron absorption reaction producing tritium. In an updated calculation performed in 2016, the estimated total activity was reduced by a factor of almost 30. The new estimate is based on calculating reaction rates with a Monte Carlo code (MCNP). As the Finnish nuclear power plant fleet consists of light water reactors (LWRs) only, no significant provisions have been made for tritium in the planning and licensing of final disposal facilities and, accordingly, accurate information on tritium inventories is critical not only for dismantling and packaging planning but also for the contracting of waste management services.

The Bulgarian IRT-2000 pool type research reactor is an example of a standardized characterization process used for partial dismantling to meet the predefined criteria for mounting of the IRT-Sofia new systems and equipment.

After permanent shutdown of the Low Flux Reactor (LFR) at Petten (Netherlands) in December 2010, a period of about five years followed for preparation of reactor decommissioning in which the radiological inventory was determined, all detailed working procedures for decommissioning were established, and the decommissioning licence application was prepared and submitted. The licence was granted in January 2015. For this project, a conservative estimate of the amount of activated concrete was adopted by the reactor operator rather than sampling at all locations. It was realized that more detailed knowledge, in this particular case of a small facility, would not significantly reduce the costs of decommissioning and waste management. The ventilation system was upgraded to accommodate decommissioning conditions.

The decommissioning project was divided into 13 work packages (WPs), many of which were executed in parallel by a small, dedicated decommissioning team. Prior to starting each WP, a task risk assessment and a radiation risk estimation were compiled into a summary report. To facilitate the decommissioning process, the reactor operator developed a sensitive measuring system and a 'track and trace' device to characterize and track all waste streams and to store associated information in a database. A lesson learned is that where materials are to be transferred to a separate waste management organization (WMO), it is important to understand the waste acceptance criteria and to agree on the proof required to show compliance with these criteria. This has a direct effect on the extent and type of characterization work that will be required and thus on the decommissioning costs.

Lessons learned from the TRIGA Mark III reactor KRR-2 in the Republic of Korea are consistent with other cases discussed above. Lack of systematic and documented inputs and preparatory work contributed to an increase in costs and delay. Drawing from the experience of the KRR-2 decommissioning project, better characterization surveys and preparation work can reduce the trial and error sequence of activities for future projects.

The preparation of the decommissioning plan for a nuclear facility requires knowledge of its operational history from design and licensing through final shutdown. This information is used to establish the nature and location of potential or known radioactive contamination, together with possible associated hazardous materials. The overall decommissioning strategy starts at the end of the operation phase with an extensive characterization of the facility, an estimate of the mass and the volume of the waste to be produced, and an assessment of its activity and level of contamination [12].

6.2. PROPOSED METHODOLOGY

In order to analyse the impacts of the decommissioning planning and characterization process on overall decommissioning costs for research reactors, a questionnaire template (Appendix V) was developed in July 2017:

- General information on the research reactor (type, power, current status and contamination incident recorded) and available existing planning documentation related to decommissioning;
- Questions regarding the decommissioning strategy considered/decided, the end state and ISDC 01.0100 data on decommissioning planning activities;
- Physical and radiological inventory data estimated, calculated and/or measured and evaluated waste streams as percentages of ILW, LLW, VLLW and EW for the main inventory items;
- Radiological characterization procedures and relevant calculation, measurement and sampling techniques used focusing on the approach and scope of work.

The questionnaire data were supplemented by additional questions on the radiological characterization of research reactors (Appendix VI). The supplemental form addressed the methods and scope of performed activities (structures, systems and components as well as the number of analysis and samples taken) for determination of activation, surface and volumetric contamination.

To evaluate the effect of the characterization process on decommissioning, it was necessary to group the reactors studied according to the extent of the characterization performed:

- Step 1: Limited or initial characterization performed mainly based on estimates from similar facilities.

— Step 2: Partial or full characterization for the approved decommissioning project based on own facility sampling and measurement.
— Step 3: Final characterization performed for the ongoing or finalized decommissioning project.

Table 20 lists all research reactors considered in this analysis and their assignment to the different levels of characterization defined in the project.

TABLE 20. RESEARCH REACTORS ANALYSED AND THEIR CHARACTERIZATION FEATURES

Country	Reactor name	Reactor type	STEP	CERREX-D2 input file	Questionnaire	Supplemental form	Inventory
Austria	Vienna	TRIGA Mark II	1	Yes	Yes	Yes	Yes
Indonesia	Bandung	TRIGA Mark II	1	Yes	Yes	Yes	Yes
Indonesia	Kartini	TRIGA Mark II	1	Yes	Yes	Yes	Yes
Malaysia	Puspati	TRIGA Mark II	1	Yes	Yes	Yes	Yes
Morocco	CENM	TRIGA Mark II	1	No	Yes	Yes	No
Slovenia	JSI	TRIGA Mark II	1	Yes	Yes	Yes	Yes
Viet Nam	Dalat	TRIGA Mark II	1	No	Yes	Yes	Yes
Brazil	IPR-R1	TRIGA Mark I	1	Yes	Yes	Yes	Yes
Egypt	ETRR1	WWR pool-in-tank	1	No	Yes	No	No
France	Phébus	Open pool	1	Yes	Yes	Yes	Yes
Hungary	WWR-SM10	WWR-SM10	1	Yes	Yes	No	Yes
Japan	JRR-4	Open pool	1	No	Yes	Yes	No
Pakistan	PARR-2	Pool-in-tank	1	No	Yes	No	Yes
Poland	Maria	Open pool	1	No	Yes	Yes	Yes
Australia	HIFAR	Dido	2	Yes	Yes	No	Yes
China	HWR	HWR	2	No	Yes	No	No

TABLE 20. RESEARCH REACTORS ANALYSED AND THEIR CHARACTERIZATION FEATURES (cont.)

Country	Reactor name	Reactor type	STEP	CERREX-D2 input file	Questionnaire	Supplemental form	Inventory
Finland	FiR-1	TRIGA Mark II	2	No	Yes	Yes	Yes
France	Phébus	Open pool	2	Yes	Yes	Yes	Yes
Greece	GRR-1	Open pool	2	Yes	Yes	Yes	Yes
India	Apsara	Open pool	2	Yes	Yes	Yes	Yes
Italy	L-54 M	Homogeneous	2	Yes	Yes	No	Yes
Bulgaria	IRT-2000	WWR	3	No	Yes	Yes	Yes
Korea, Rep. of	KRR-2	TRIGA Mark III	3	Yes	Yes	Yes	Yes
Netherlands	LFR	Argonaut	3	No	Yes	Yes	Yes
Romania	VVR-S	WWR pool-in-tank	3	No	Yes	No	No

The analysis aimed to determine the cost of characterization and planning as a percentage of the total cost of decommissioning. To facilitate this, the following lists of ISDC activities for different steps of characterization were considered in determining the cost of characterization and planning for each STEP in the CERREX-D2 costing case:

STEP 1: 01.0100 Decommissioning planning

01.0101 Strategic planning

01.0102 Preliminary planning

01.0200 Facility characterization

01.0203 Establishing a facility inventory database

STEP 2: 01.0100 Decommissioning planning

01.0101 Strategic planning

01.0102 Preliminary planning

01.0200 Facility characterization

01.0201 Detailed facility characterization

01.0203 Establishing a facility inventory database

02.0400 Radiological inventory characterization to support detailed planning

02.0401 Radiological inventory characterization

02.0402 Underground water monitoring

STEP 3: 01.0100 Decommissioning planning

01.0101 Strategic planning

01.0200 Facility characterization

01.0201 Detailed facility characterization

01.0202 Hazardous material survey and analysis

01.0203 Establishing a facility inventory database

02.0400 Radiological inventory characterization to support detailed planning

02.0401 Radiological inventory characterization

02.0402 Underground water monitoring

04.0200 Preparations and support for dismantling

04.0203 Ongoing radiation characterization during dismantling

04.0900 Final radioactivity survey for release of buildings

04.0901 Final radioactivity survey of buildings

05 Waste processing, storage and disposal

05.0201 Characterization (of historical HLW)

05.0301 Characterization (of historical ILW)

...

05.1101 Characterization (of very short lived waste (VSLW))

05.1202 Clearance measurement of EW and materials

07.0500 Final radioactivity survey of site

Since TRIGA reactors provide the majority of data from all the collected questionnaires, it was decided to evaluate all aspects of characterization impacts on decommissioning projects separately for this group of research reactors. Therefore, all collected data from questionnaires, supplemental forms, inventories and completed CERREX-D2 costing cases are evaluated for the whole group of research reactors studied, together with a separate analysis for the group of TRIGA reactors.

Summary data from the assessment of all of the questionnaires collected, as well as supplemental forms, are given in Annex VIII.

6.3. ANALYSED RESULTS

The participants provided information on 24 research reactor facilities from 23 countries. The data collected from the questionnaires, supplemental forms and CERREX-D2 costing cases relevant to characterization issues are presented in graphs and tables and analysed in the following sections. The results are grouped into five topics:

(1) General information on research reactors;
(2) Decommissioning strategy including end state;
(3) Material and radiological inventory databases;
(4) Correlation between characterization and decommissioning costs;
(5) Radiological characterization techniques and procedures applied.

6.3.1. General information on research reactors

The first part of the questionnaire was related to general information on each research reactor facility, such as research reactor type, reactor power (MW), current operational status, contamination incident/leakage recorded during operation and documentation elaborated for decommissioning. Figure 27 shows the reactor types considered in the project while Fig. 28 shows their operational status. General data for the TRIGA family of reactors are presented in Table 21.

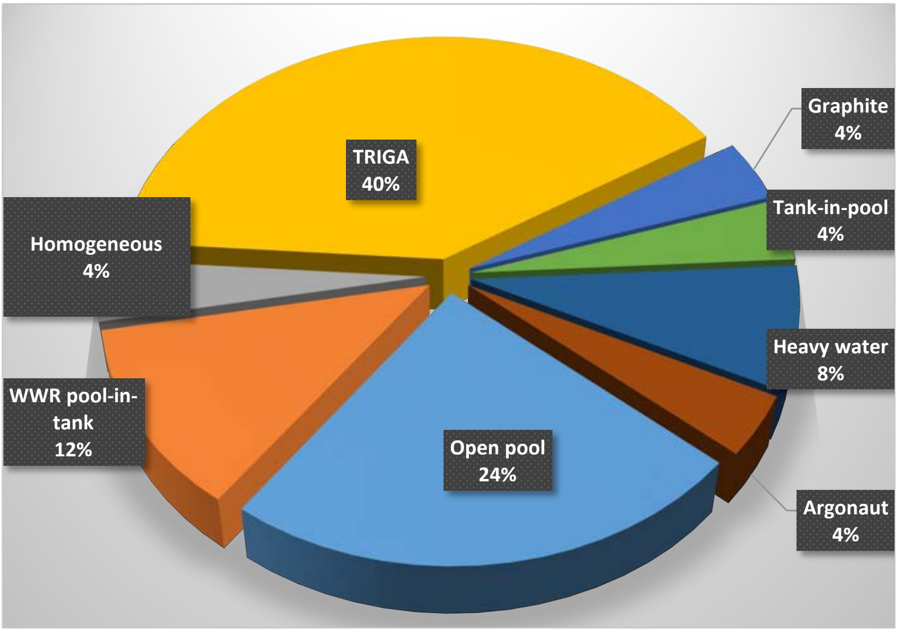


FIG. 27. Research reactor types analysed in DACCORD Phase 2.

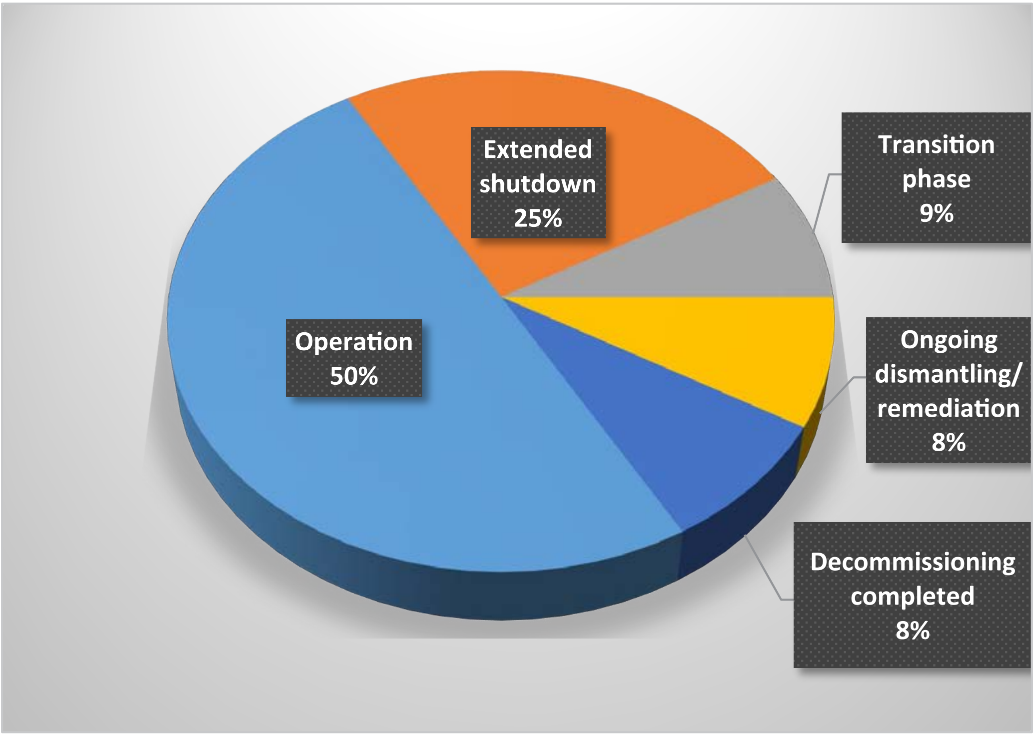


FIG. 28. Status of the research reactors analysed in DACCORD Phase 2.

TABLE 21. TRIGA REACTORS ANALYSED IN DACCORD PHASE 2

Country	Reactor name	Reactor type	Current status of the reactor	Contamination incident
Austria	Vienna	TRIGA Mark II	Operation	No
Brazil	IPR-R1	TRIGA Mark I	Operation	No
Finland	FiR-1	TRIGA Mark II	Extended shutdown	No
Indonesia	Kartini	TRIGA Mark II	Operation	No
Indonesia	Bandung	TRIGA Mark II	Operation	No
Korea, Rep. of	KRR-2	TRIGA Mark III	Decommissioning completed	Yes
Malaysia	Puspati	TRIGA Mark II	Operation	No
Morocco	CENM	TRIGA Mark II	Operation	No
Slovenia	JSI	TRIGA Mark II	Operation	Yes
Viet Nam	Dalat	TRIGA Mark II	Operation	No

The project analysed information related to decommissioning planning and implementation and considered the development of the following documents: preliminary decommissioning plan (PDP); final decommissioning plan (FDP); characterization plan; waste management plan; facility material inventory database; facility radiological inventory database; decommissioning cost estimate; final decommissioning report; and partial characterization survey reports. Not all facilities have all these documents available. Figure 29 summarizes the extent of decommissioning planning achieved by the facilities which participated in this part of Phase 2, including the proportion of facilities for which CERREX-D2 files were completed.

Data from the questionnaire on collected documentation show that the majority of reactors have already prepared a PDP and waste management plan, developed a material inventory database and performed a decommissioning cost calculation, even though 50% of the reactors are currently still in operation. For the TRIGA reactors, the PDP was prepared for all the facilities even though 80% of them are still in operation. However, the preparation of other documentation, such as the characterization plan, radiological inventory database, survey characterization data and FDP, was strongly affected by the status of the reactor and its characterization process. The package of documentation relevant for each characterization step of all reactors covered within the questionnaire is summarized in Table 22.

6.3.2. Decommissioning strategy

In IAEA Safety Standards Series No. GSR Part 6, Decommissioning of Facilities [13], the IAEA has defined two decommissioning strategies — immediate dismantling and deferred dismantling. Key factors that need to be considered in the selection of the decommissioning strategy include the following:

— Radioactive waste management methods and associated waste routes, including availability of waste storage and disposal facilities.
— The availability (or not) of a final repository or long term storage option.
— The end state and possible reuse of the site.
— Availability of defined legislation requirements for the end state (reuse of the site for the construction of a new nuclear installation or for industrial reuse, sometimes called ‘brownfield’, or return of the site to the public domain with no further regulatory control, sometimes called ‘greenfield’).

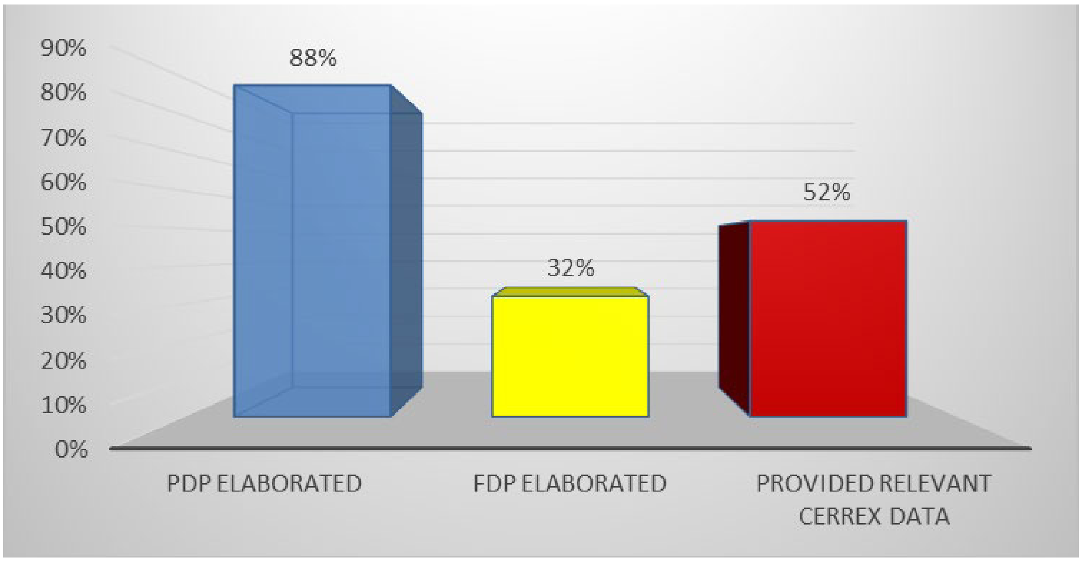


FIG. 29. Extent of decommissioning planning and costing for reactors analysed.

— Consideration, when choosing a decommissioning strategy, of long term uncertainties, including the following:
  - Regulatory developments: Historically, regulatory obligations tend to become increasingly restrictive (impact of a downward trend in the release thresholds).
  - Costs: The future cost of managing radioactive waste is unknown. The assessment of the cost of decommissioning achieved over several decades, incorporating assumptions on interest rates and discount rates, is complex and fraught with uncertainty.
  - Future of the operator: The availability of skilled operators, knowledgeable about the facility, will decrease with the increased delay from shutdown to decommissioning and dismantling.

— Availability of sufficient financial resources.
— Uncertainties associated with activities to be decided or performed in the future.
— Management of knowledge of the facilities related to staff experience.
— Physical and radiological characterization of the installations.
— Targeted final state.
— Technical scenario envisaged.
— Involvement of local stakeholders.

6.3.2.1. Decommissioning strategy selected

Of the 24 reactors reviewed, 68% selected immediate decommissioning (see Fig. 30). Only 16% selected deferred decommissioning, with the remainder still undecided. The reasons for selecting to defer decommissioning vary. For example, Japan decided to defer dismantling of the JRR-4 reactor to decrease the dose rate, while Italy decided to maintain the L-54 M reactor in a safe enclosure status (evaluating the restart/reuse of the facility) for several years before proceeding with dismantling.

6.3.2.2. End state selected

Industrial reuse ('brownfield') seems to be the preferred option for the end state (see Fig. 31). Selecting brownfield as the end state may be due to a desire to use the facility for nuclear purposes, the inability to reach unconditional release criteria, or the possible lower cost to reach a brownfield state in

TABLE 22. PERCENTAGE OF DOCUMENTATION AVAILABLE FOR THE REACTORS ANALYSED BY CHARACTERIZATION STEP

Documentation elaborated	Step 1	Step 2	Step 3
Preliminary decommissioning plan	79	86	100
Full characterization plan	14	57	75
Waste management plan	21	86	100
Material inventory database	43	57	75
Radiological inventory database	21	57	75
Decommissioning cost estimation	57	71	75
Final decommissioning report	0	0	75
Partial characterization reports	0	71	75

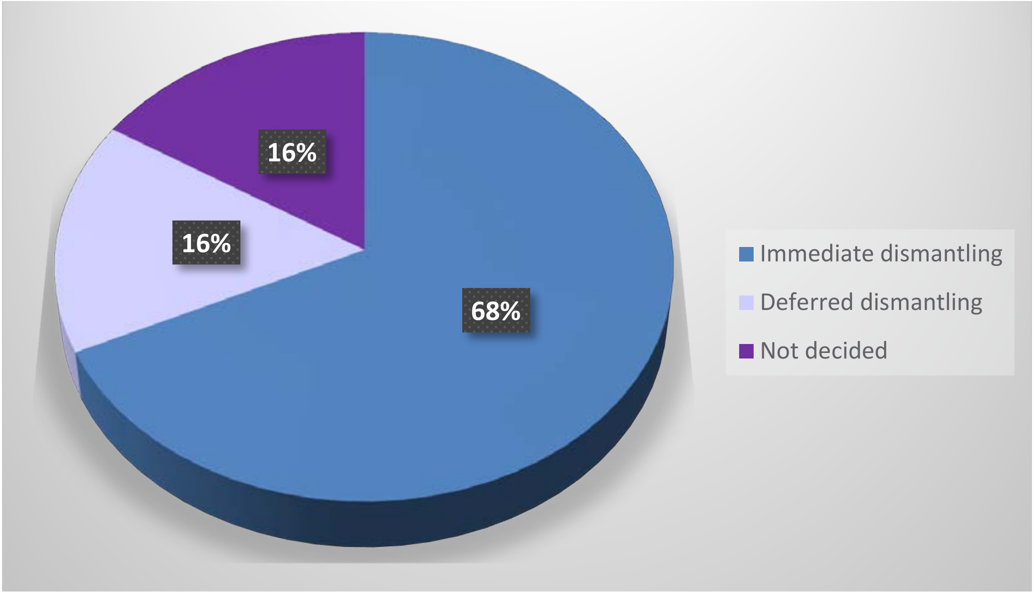


FIG. 30. Decommissioning strategy for participating reactors, as a percentage of cases studied.

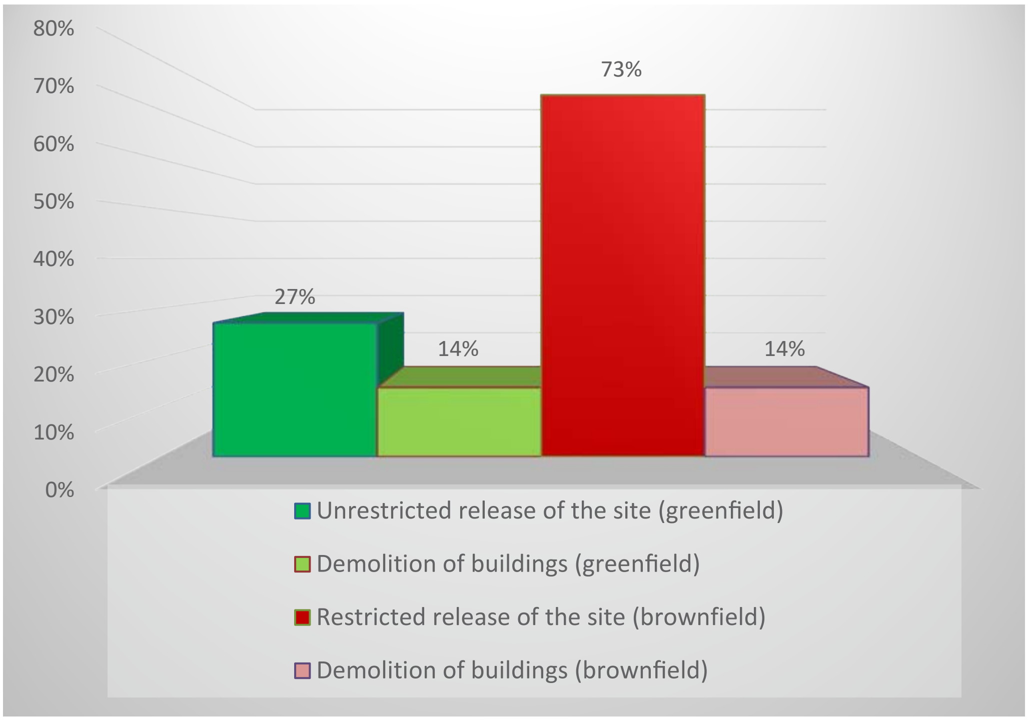


FIG. 31. Envisaged end state for participating reactors, as a percentage of cases studied.

comparison to the cost of reaching a greenfield state (the scope of site remediation is typically less). This solution keeps the possibility to reach a greenfield state in the future in case of changes in strategy.

In this study, the selected end state in 27% of the cases is unrestricted release of the site (greenfield status), with 50% of the facilities choosing to demolish the buildings (i.e. 14% of all cases studied). The remaining 73% of the cases plan to reuse the site for other industrial activities (brownfield status), with 19% of these planning to demolish the facility building (i.e. 14% of all cases studied). For deferred dismantling, 75% of the reactors envisage a site end state based on industrial reuse and 25% envisage unrestricted release (greenfield status).

6.3.3. Inventory

6.3.3.1. Inventory of TRIGA research reactors

The radioactive waste from decommissioning of the TRIGA research reactors was analysed. KRR-2 (Republic of Korea) is at characterization Step 3; the FiR-1 reactor (Finland) is at characterization Step 2 and all the other reactors are at Step 1. The KRR-2 reactor is a TRIGA Mark III, the Brazilian reactor is a TRIGA Mark I and all the others are TRIGA Mark II. Table 23 provides a listing of the main inventory items for the TRIGA research reactors which participated in the study. The results of estimated quantities of typical inventory items from DACCORD Phase 2 are compared with the Phase 1 results and also with the values for the KRR-2 reactor as the one completed decommissioning project out of all the TRIGA reactors studied. The quantities of typical inventory items and waste results for individual TRIGA reactors analysed in Phase 2 are presented in Appendix VII.

Average waste distributions from all TRIGA reactor costing cases analysed in DACCORD Phase 2 in comparison with Phase 1 are shown in Fig. 32.

The average waste partitioning for TRIGA reactors as observed in Phase 1 is comparable to that assessed in Phase 2, the only difference being the higher ratio of EW[12] [7] estimated in Phase 2. This is likely to be due to the EW category in Phase 2 also including VSLW, which is a separate quantity in Phase 1.

Total quantities and waste partitioning of total waste from all analysed TRIGA reactors are given in Fig. 33. The average partitioning results from Phase 2 are supported by the actual values from the completed TRIGA Mark II decommissioning project, KRR-2 in the Republic of Korea. The difference between the average estimated waste partitioning for Phase 2 TRIGA reactors (Fig. 32) and KRR-2 (Fig. 33) is at less than 5%.

The total quantities differ from each other because the scope of the decommissioning project as well as the total inventory is different for TRIGA Marks I–III. The scope of several of the TRIGA costing cases analysed is limited to only reactor components or the controlled area. Some cases also include the massive biological shielding and underground pit structures, such that the total inventory ranges from 71 t at minimum to 2 713 t at maximum. Moreover, estimates of RAW partitioning for typical TRIGA inventory items differ from each other (see Appendix VII). Often, the operators of the Step 1 reactors conservatively classify EW as VLLW. This is the likely explanation for the differences between EW and VLLW in Fig. 33. The overall radioactive waste quantities for TRIGA Mark II reactors, and associated classifications do not vary significantly and are very close to the KRR-2 TRIGA Mark III. The reason is that the differences in waste partitioning for massive components, such as biological shielding or graphite representing the majority of the inventory, are very small.

6.3.3.2. Inventory of other types of research reactors

The radioactive waste from the dismantling of eight research reactors of varying types other than TRIGA were analysed. Data for three of the reactors at characterization Step 1, five at Step 2 and one at Step 3 were analysed. Radioactive waste quantities and partitioning of total waste are presented in Fig. 34.

As expected, there are large differences among the inventories and waste partitioning caused by different reactor design and variations in the scope of decommissioning projects (i.e. demolition of biological shielding and/or buildings, implementation of clearance procedure, partial/full decommissioning project). Different reactor designs are at different characterization levels and knowledge on RAW partitioning. For example, Step 1 is only an estimate on resulting RAW streams and might not represent

[12] GSG-1 [7] defines EW as: “Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes.”

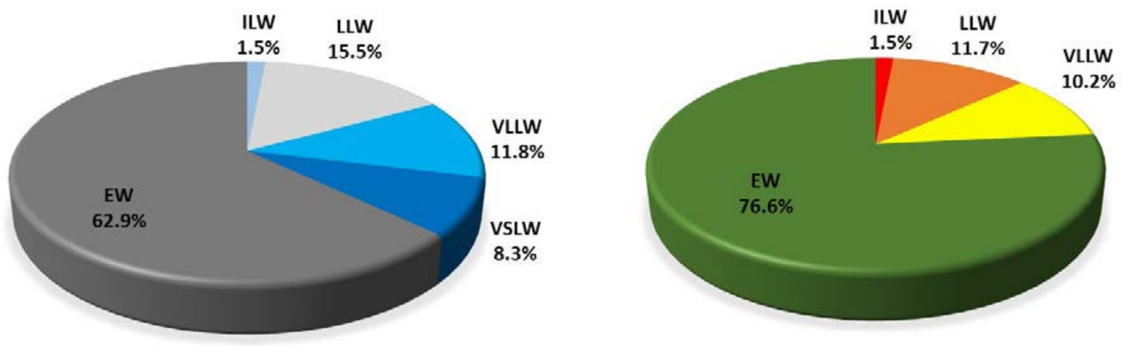
the real case, while Step 3 is an already executed project (Bulgaria). However, the Bulgarian reactor was decommissioned only partially (i.e. reactor technology was removed but building structures remained). Therefore, any similarities in radioactive waste partitioning must be studied only for the same reactor types and the same decommissioning strategy. Furthermore, the criteria for classification of waste are different from one country to another mainly due to different disposal options (different waste acceptance criteria for each disposal facility that resulted from the safety assessment of the specific facility).

TABLE 23. LIST OF MAIN INVENTORY ITEMS FOR PARTICIPATING TRIGA RESEARCH REACTORS

ISDC No.	Inventory name	Unit	Estimated quantities (Phase 2)	Estimated quantities (Phase 1)[a]	KRR-2 project (completed)
02.0500	Demineralizer resin	t	0.05–1.1	0.09–0.11	1.1
04.0503	Tanks	t	0.1–11.5	1.6–3.8	3.8
04.0503	Piping and valves	t	0.25–51.2	2.6–15	51.2
04.0503	Heat exchanger	t	0.66–15.5	1.98–2.42	15.5
04.0600	Structural equipment (stairs, core bridge, covers)	t	1.45–44.9	2.1–6	44.9
04.0502	Neutron beam tubes and port	t	0.012–5.4	1.4–3.5	3.5
04.0600	Ventilation (duct, fan, motor, stack, filter)	t	0.2–218.1	10–20	218.1
04.0501	Core assemblies (control rods, grid plate)	t	0.03–14.3	0.6–0.9	0.6
04.0501	Rotating specimen rack	t	0.06–3.5	0.5–0.8	0.8
04.0502	Graphite elements and graphite reflectors	t	0.029–7.5	2.4–6.8	7.5
04.0600	Cables and cable trays	t	0.25–5	2–4	—[b]
02.0500	Liquid water and sludge	m^3	5.0–50.5	22.5–27.5	—
04.0502	Pool liner, reactor liner	t	0.69–10.6	12–15	3.9
04.0700	Decontamination of building surface	m^2	150.0–930.5	1500–3000	930.5
04.0900	Monitoring of building surface	m^2	872.0–3000	1500–3000	2275.8
07.0300	Masonry	t	40.6–1676	39.1–106	1676
04.0506	Bioshielding concrete	t	31.69–533	359–494	440

[a] Values from DACCORD Phase 1 TRIGA cases [1].
[b] — : data not available.

There are also variations in classification of waste for the reactors in Step 1, where limited or initial characterization was performed based on estimates only or derived values from similar facilities. Often, EW in Step 1 is conservatively classified as VLLW. This observation can explain the differences between EW and VLLW in Fig. 34.



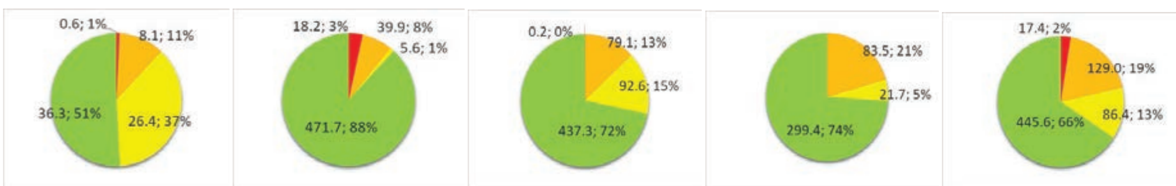
DACCORD Phase 1 **DACCORD Phase 2**

FIG. 32. Average waste generated from decommissioning estimated in DACCORD.

ILW VLLW

LLW EW

Step 1				
IPR-R1 (Brazil) TRIGA Mark I	Vienna (Austria) TRIGA Mark II	Bandung (Indonesia) TRIGA Mark II	Kartini (Indonesia) TRIGA Mark II	Puspati (Malaysia) TRIGA Mark II



Step 1	Step 2	Step 3
JSI (Slovenia) TRIGA Mark II	FiR-1 (Finland) TRIGA Mark II	KRR-2 (Korea, Rep. of) TRIGA Mark II

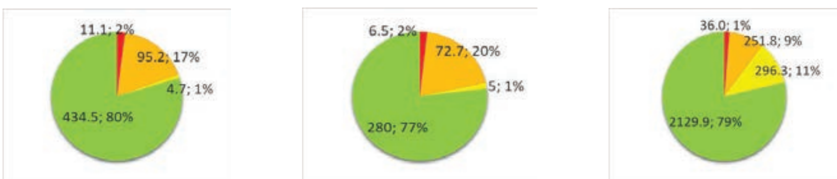


FIG. 33. RAW partitioning for TRIGA reactors analysed, in tonnes and per cent.

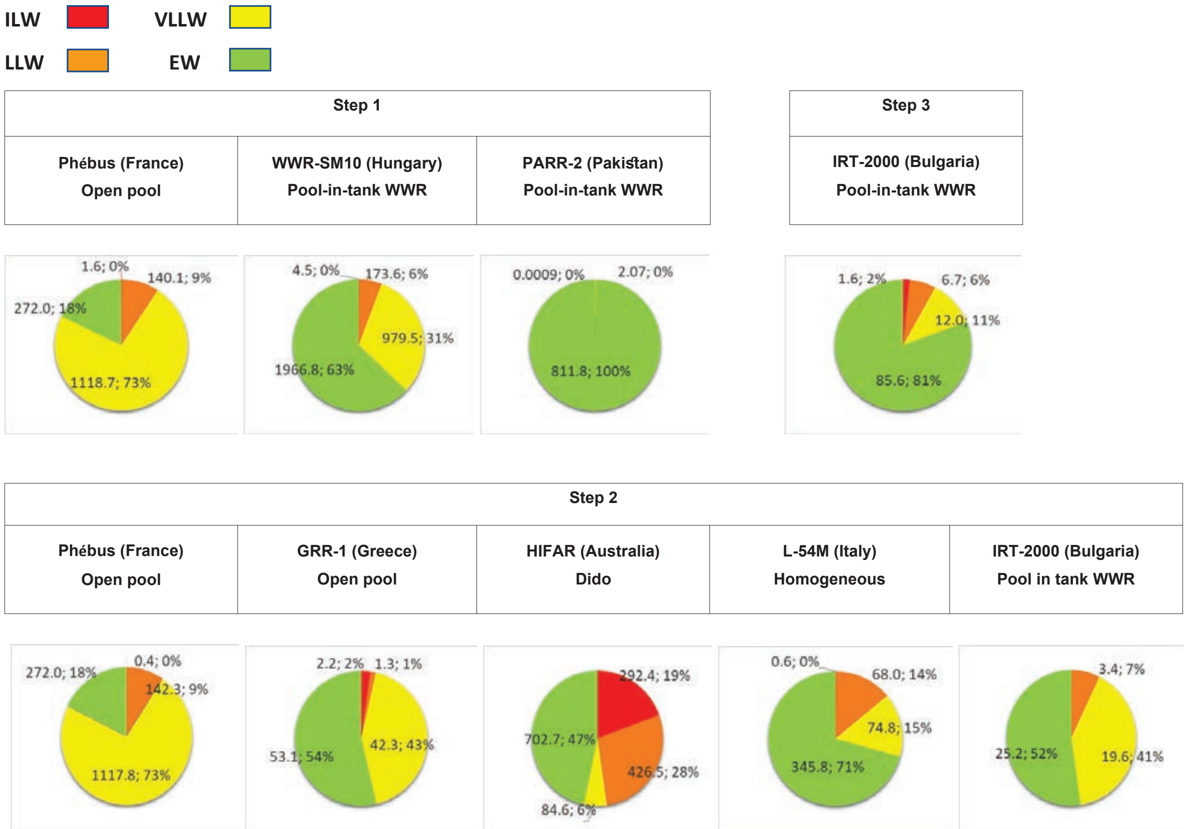


FIG. 34. RAW partitioning for reactors analysed other than TRIGA, in tonnes and per cent.

6.3.3.3. *Correlation between total waste and decommissioning costs*

The data from the CERREX-D2 files were used for correlation between total waste, radioactive waste partitioning, costs for waste management activities (ISDC 05) and their ratio to total decommissioning costs. The result of the correlation is shown in Fig. 35 for all studied reactors and in Fig. 36 for TRIGA reactors.

The ratio of waste management activity cost to total costs ranges from 5% to 36%. However, when comparing the ratio of the cost of ISDC 05 activities to total costs versus radioactive waste partitioning, the comparison can only be carried out between the reactors with similar total radioactive waste inventory. An example of similar total radioactive waste inventory at the level of 1 500 t is HIFAR and the Phébus reactor (Fig. 35). It is evident that the higher amount of ILW and LLW for HIFAR leads to a higher ratio of ISDC 05 costs to total project costs (26%) than for the Phébus reactor with lower estimated quantities of ILW and LLW categories, where ISDC 05 represents only 12%.

Similarly, for TRIGA reactors (see Fig. 36), comparing TRIGA Bandung with the Puspati costing cases, the total radioactive waste inventory is estimated to be approximately 600 t, the ratio of ISDC 05 activities is three times higher for the Puspati reactor due to higher estimated amounts of ILW and LLW.

6.3.4. Correlation between characterization and decommissioning costs

The correlation between the extent of characterization and decommissioning costs has been investigated mainly by performing CERREX-D2 cost calculations or study of selected ongoing decommissioning projects, such as FiR, IRT-2000 and the Netherlands LFR. The result of the correlation is shown in Fig. 37 for all participating reactors and in Fig. 38 specifically for TRIGA reactors.

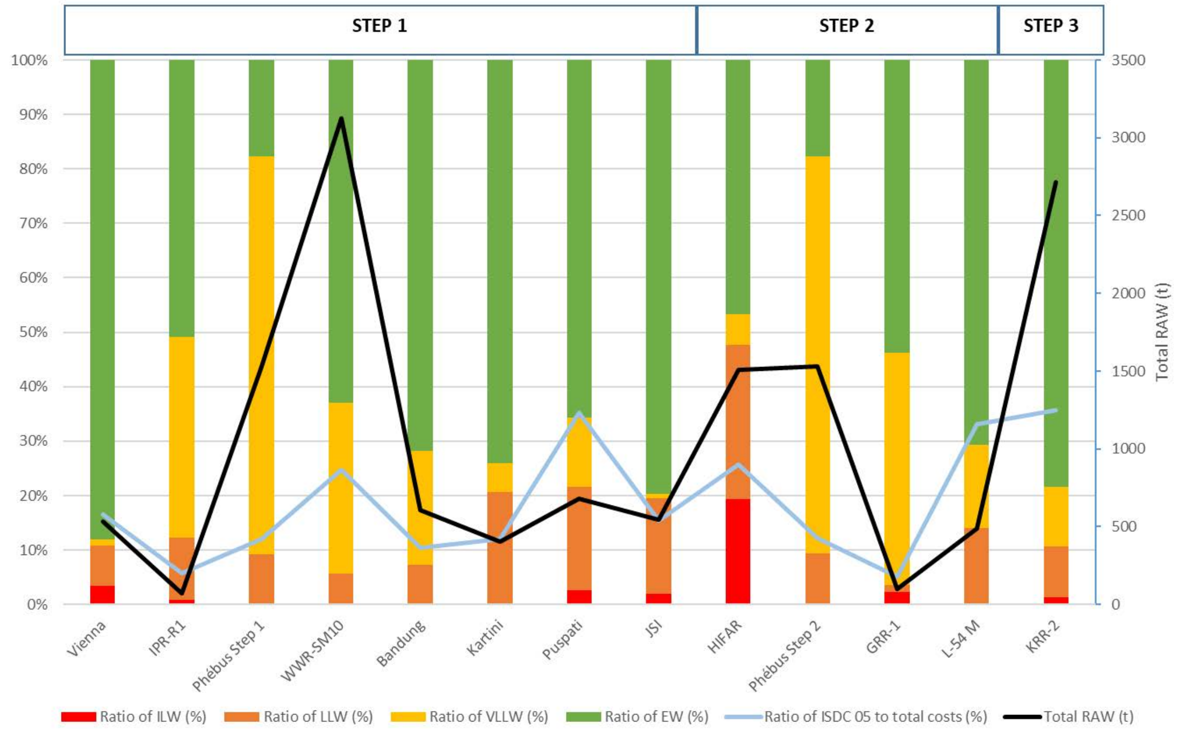


FIG. 35. Total waste, waste partitioning and ratio of ISDC 05 to total costs for all participating research reactors in DACCORD Phase 2.

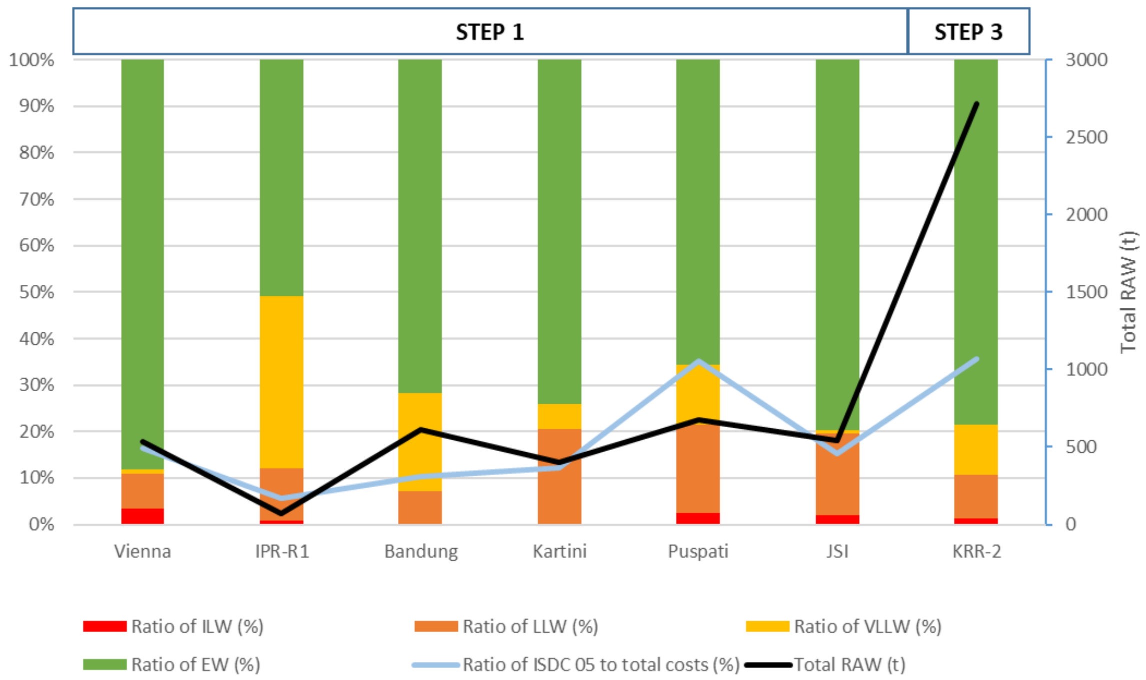


FIG. 36. Total waste, waste partitioning and ratio of ISDC 05 to total costs for all participating TRIGA research reactors in DACCORD Phase 2.

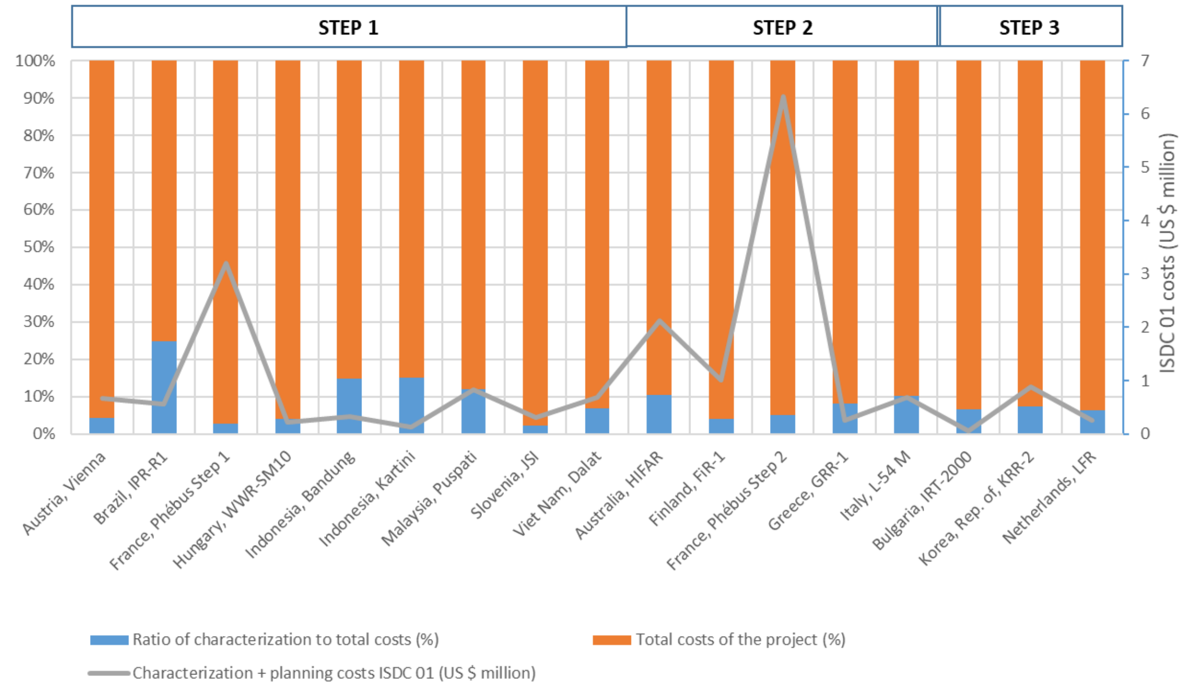


FIG. 37. Characterization and planning costs versus total decommissioning costs for all participating reactors.

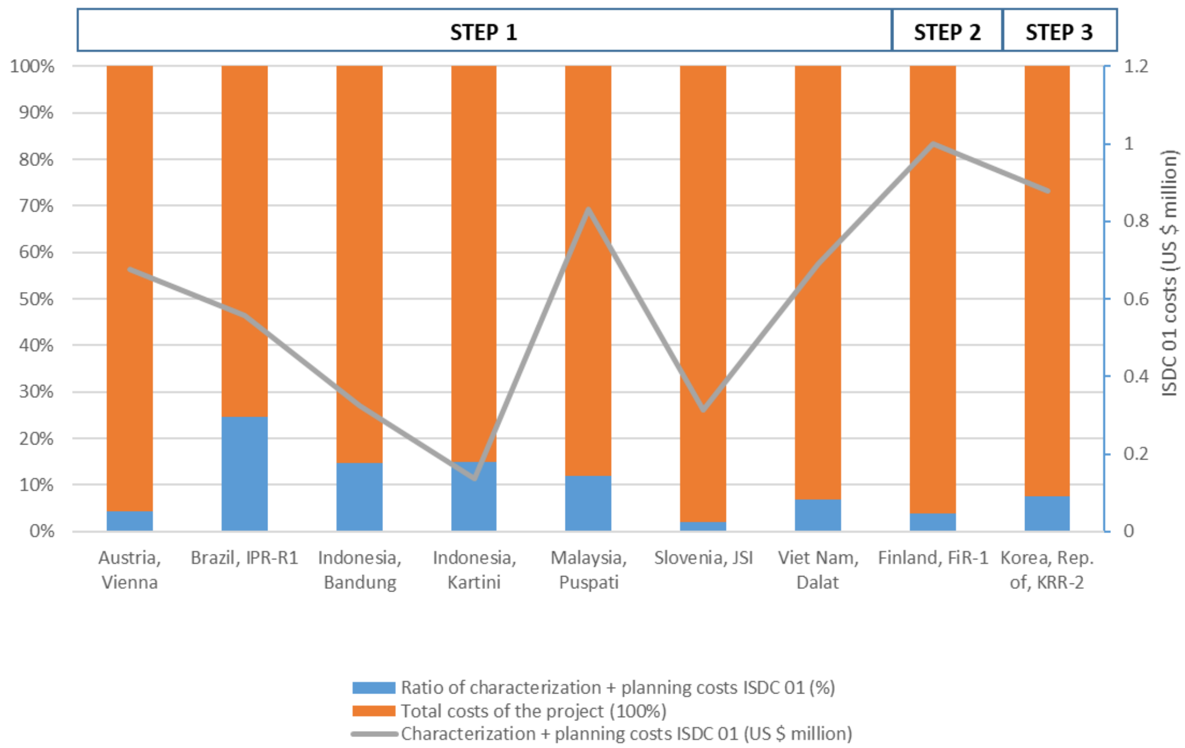


FIG. 38. Characterization and planning costs versus total decommissioning costs for participating TRIGA reactors.

Characterization and planning costs for facilities at Step 1 and Step 2 (estimated from the CERREX-D2 files), together with actual costs (Step 3 cases, including KRR-2) varied from US $0.05 million to US $6.32 million (solid grey line in Fig. 37). The ratio of ISDC 01 costs to total decommissioning costs is 8% on average (blue bars in Fig. 37). The ratio of characterization costs appears to be overestimated in the planning phase of decommissioning (Step 1 reactor cases), being up to 25% of total costs. In comparison, the ratio of characterization costs for ongoing (Step 2) or already finalized projects (Step 3) is not higher than 10% for the reactors included in this analysis.

In the case of TRIGA reactors in Fig. 38, the same decrease can be observed in characterization costs from the planning phase (Step 1) to implementation of characterization (Steps 2 and 3). During Step 1, the ratio of characterization costs is estimated to be in the range of 10–25%, while for Steps 2 and 3, when the characterization survey is carried out, the ratio decreases to less than 7% of total project costs.

In order to analyse the reason for the overestimates in planning the characterization process in comparison with characterization implementation, the general approach to facility radiological characterization was evaluated and presented in Figs 39 and 40. Three main approaches to radiological characterization data collection were considered:

(1) Results of similar reactors only (blue bars);
(2) Estimates considering the facility history and records (orange bars);
(3) Undertaking partial or complete radiological characterization of the reactor (grey bars).

As shown in Fig. 39, a majority of participating research reactors still at the stage of planning the characterization process (Step 1) use a combination of two approaches to determine the radiological characteristics of their facilities: use of data from similar reactors and own facility historical records. Only a few of them applied radiological characterization sampling. A majority of reactors already implementing a radiological characterization process, whether partially (Step 2) or fully (Step 3), use a combination of their own historical records and the results of radiological surveys. Exceptionally, for HIFAR (Step 2) and LFR (Step 3), the results from similar reactors were also considered.

The data collected through the questionnaire may suggest a tendency to overestimate the ratio of characterization costs to total costs for Step 1 reactors. This tendency is likely to be associated with a lack of locally generated characterization data resulting from sampling, as a consequence of the operational status of these reactors. Hence, the ratio of characterization costs is likely to be more realistic for Step 2 and 3 reactor cases, since mainly locally generated radiological survey data were considered.

All participating TRIGA reactors at Step 1 of the radiological characterization process are still in operation and estimates are based largely on results from similar reactors. This is a logical approach given the prevalence of TRIGA reactors (i.e. relevant data may often be readily obtained for similar facilities). For those facilities where characterization surveys are being undertaken (Step 2) or already finalized (Step 3), characterization data are typically based on results obtained exclusively from own facility data.

The next section provides details of radiological characterization, the calculations used, the measurement techniques and the procedures applied.

6.3.5. Radiological characterization techniques and procedures

This section provides details of radiological characterization, the calculations used, and the measurement techniques and procedures applied.

6.3.5.1. Questionnaire results

The last part of the questionnaire focused on the different techniques and standard procedures used in the radiological characterization process. Answers to the following questions were analysed:

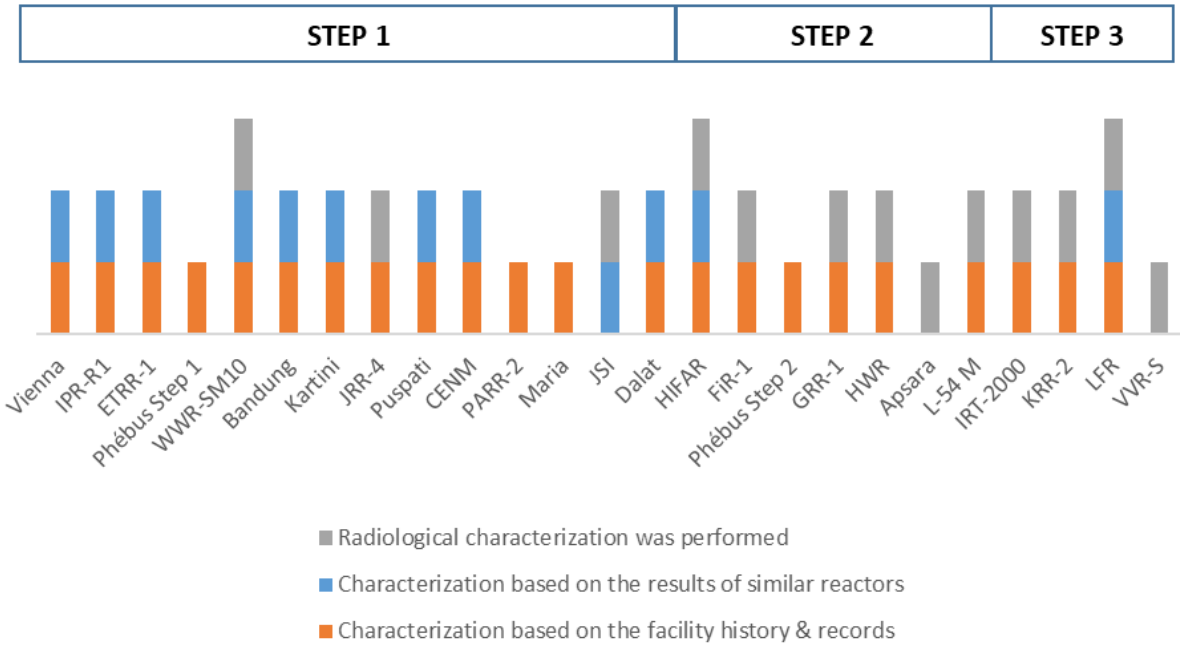


FIG. 39. Extent of reactor characterization for all participating reactors.

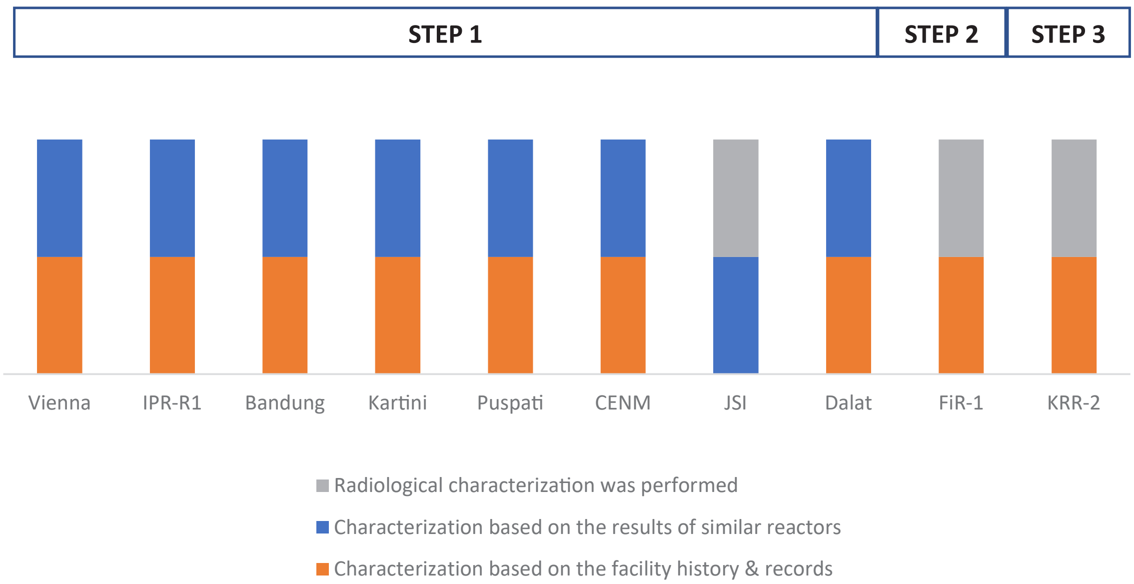


FIG. 40. An approach to reactor characterization for TRIGA reactors.

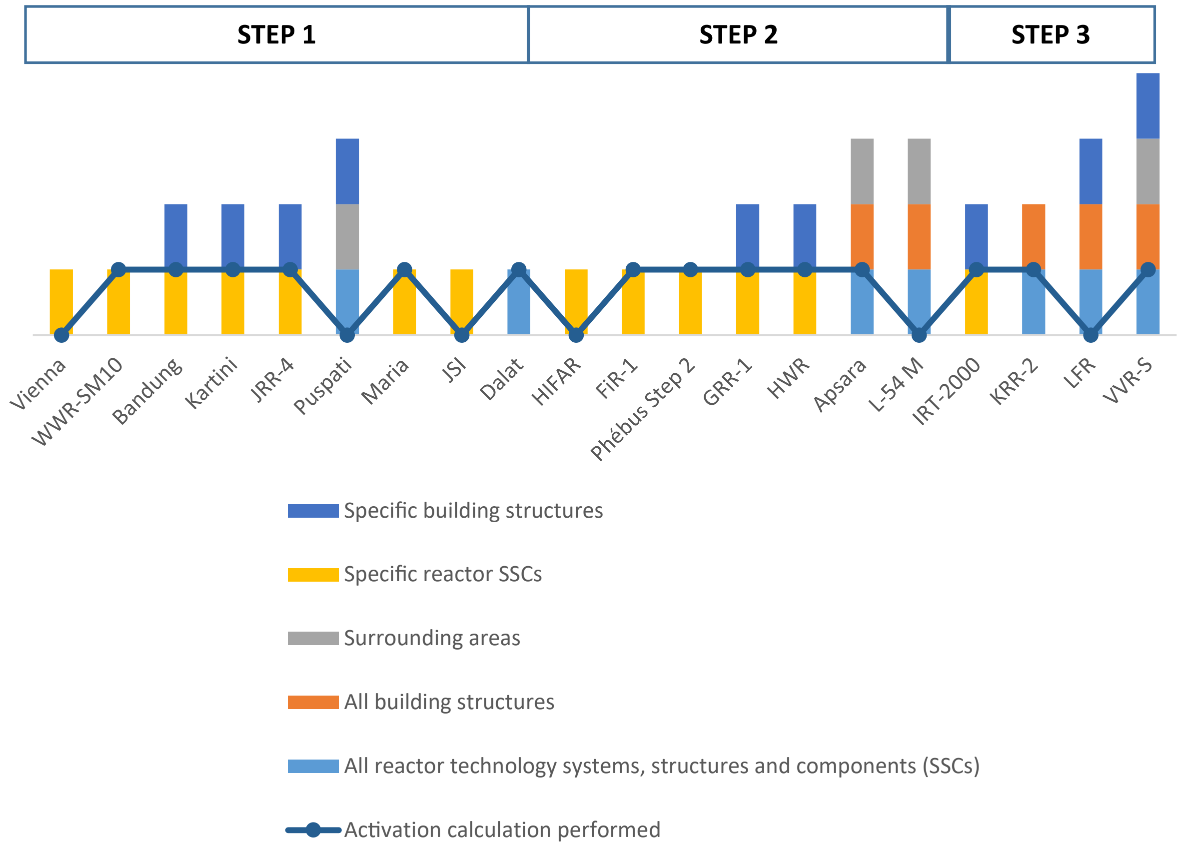


FIG. 41. Use of activation calculations and scope of characterization of all studied research reactors.

(1) Whether the characterization plan was based on:
- — Typical statistical models, such as MARSAME, MARSSIM and the geostatistical approach;
- — Sampling and measurement plan;
- — Application of surface and/or volumetric radiological characterization.

(2) Whether the scope of radiological characterization covered specific reactor systems and components, specific building structures or all technology and civil structures and surrounding areas.

(3) Whether activation calculations were performed.

(4) Which measurement techniques were used (e.g. dose rate mapping, in situ gamma spectrometry, direct contamination measurements, and the ratio of inspected surface in the controlled area).

(5) Which sampling techniques were used to take smear, scratch, core and grab samples.

(6) Whether sampling analysis consisted of gamma spectrometry and use of scaling factors only or also radiochemical analysis for difficult to measure radionuclides.

(7) Whether the measurement or sampling results are comparable with the calculated ones.

The questionnaire results suggest that only approximately one quarter of reactors at characterization Steps 2 and 3 use statistical models — such as MARSSIM or geostatistical methods — to guide the extent of measurements or sample taking during characterization. On the other hand, 90% of those facilities, where the radiological characterization process had been started or finished, had developed a sampling and measurement plan. The characterization plan of all the studied reactors is based mainly on surface characterization results (63%) and less on volumetric characterization results (38%). Nevertheless, 100% of the finalized radiological characterization processes (Step 3) performed surface characterization and 75% of them also undertook volumetric characterization.

The results for planned (Step 1) and partly or fully performed radiological characterization (Step 2 or Step 3) are shown in Fig. 41. As expected, during the planning phase of the characterization process the facilities rely mainly on results from the partial characterization of specific reactor systems, components or specific building structures. On completion of characterization, all technological and civil structures will have been characterized, supported by activation calculations and by results from site characterization (dependent on the envisaged end state). Activation calculations had already been performed in 54% of all studied reactors.

Figure 42 shows the results of the questionnaire on the variety of measurement and calculation techniques utilized and inspected surface area ratio in the controlled area for all the reactors studied. The dominant methods used during the operating period (Step 1), as well as during the decommissioning of the reactor (Steps 2 and 3), are dose rate and direct contamination measurements. These are the most frequent ones for all reactor types, including the TRIGA family. Activation calculations and the ratio of inspected surface in the controlled area are also used increasingly from Step 1 through Step 3. In situ gamma spectrometry is not used very often, either in planning of decommissioning or in its implementation.

The most commonly used sampling techniques (see Fig. 43) are standard smear samples which were taken in 88% of reactors on average and in 80% of TRIGA reactors. Other techniques (scratch, grab samples and core drills) were less often used, particularly for Step 1, although the use of these methods increased for Step 2 and 3. Core samples were taken in all finalized participating decommissioning projects (Step 3). A growing trend involves the use of gamma spectrometry in the analysis of samples. Conversely, radiochemical analysis is less frequently used since this is far more expensive, the main isotopes are generally known, and gamma spectrometry offers an alternative option for waste characterization.

Activation calculation results had been verified in several reactors by measurements and sampling and found to have good correlation in 70% of cases (i.e. in the same order of magnitude). Activation calculations were not performed by all facilities. One third of reactor cases performed measurement and sampling, but no activation calculations had been performed.

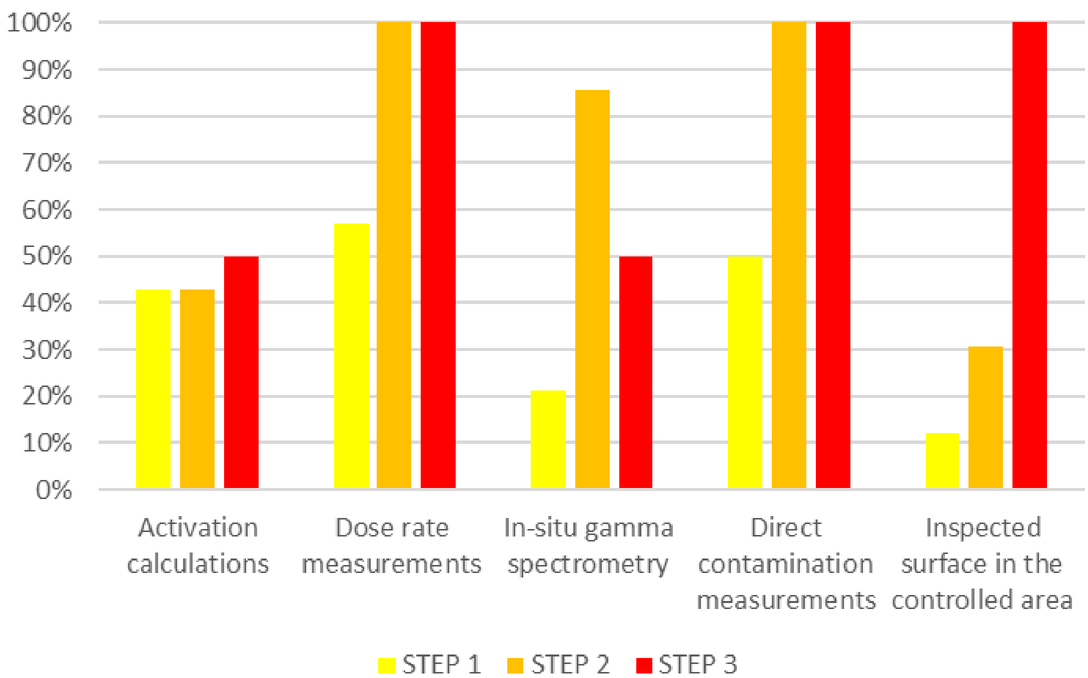


FIG. 42. Methods used in the radiological characterization of all studied reactors.

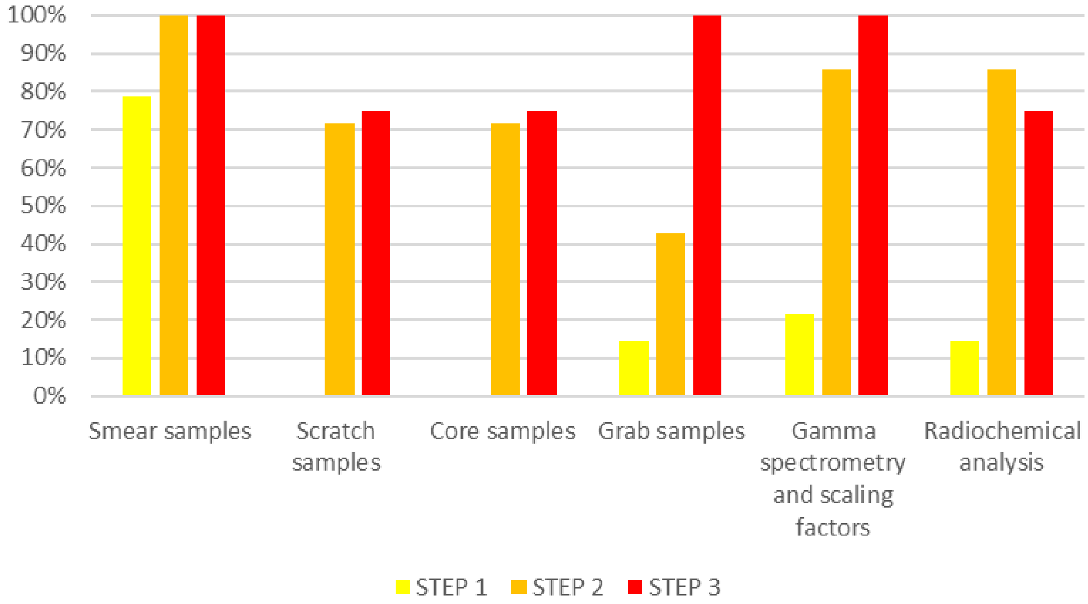


FIG. 43. Sampling and analysis techniques used in the radiological characterization of reactors.

6.3.5.2. *Additional details from the supplemental form*

The aim of the supplemental form (Appendix VI) was to provide details on the scope and methods of the following radiological characterization activities for each research reactor:

— Activation calculations;
— Surface characterization;
— Volumetric characterization;
— Facility site characterization.

The additional data from supplemental forms for the 18 reactors studied are summarized in Table 24.

6.4. CONCLUSIONS

An important step in any characterization process is the development of a material inventory database. Once the material inventory for the facility is known, the radiological data can be collected for individual inventory items. The material inventory database should be finalized well before final shutdown. The determination of the mass of reactor components is essential in estimating radioactive waste management costs (ISDC 05).

Sampling and characterization strategies should be defined according to dismantling and cleanup objectives. These strategies vary during the dismantling project. As the investigations progress, the precision, the time obtained and the cost of the information increase. In order to optimize the initial characterization, it is advisable to gather as much information as possible in terms of historical and functional analysis in order to rationalize later in situ investigation campaigns. The quality and cost of historical and functional data are typically small, while the quantity of data is very large. The converse applies in the case of sampling and laboratory analysis; these techniques are costly and yield a relatively small quantity of data, albeit with higher quality and precision.

TABLE 24. DATA FROM SUPPLEMENTAL FORMS DURING DACCORD PHASE 2

Issue	Additional information	Result
Activation	Calculation code used	MCNP was used in 12 cases and ORIGEN was used in 6 cases
	Calculation scope	In 12 cases from 15 reactors (where calculation was performed) the scope includes not only reactor internals but also graphite, concrete and other relevant activated parts
	Radiological analysis of core samples from reactor components used for the calculation	Five reactor sampling analyses supported the calculations, apart from ten activation calculations that were performed
	Data taken from other similar reactors	Feature of all TRIGA reactors, excluding CENM in Morocco and Dalat in Viet Nam. Half of TRIGA reactors derived data without performing calculations for themselves. The LFR in Netherlands derived data from Argonaut type reactors, while HIFAR in Australia derived information from the DIDO family of reactors
Surface characterization	Methods applied (smears, in situ gamma spectrometry, direct contamination) per system or component	Technological equipment surface characterization performed in 11 out of 19 cases reviewed
	Scope (systems, components); number of samples/measurements per system or component	Mainly hot spots only or typically primary circuit components for Step 1 reactors. Complete or full contaminated parts in 40% of Step 2 reactors; fully completed for Step 3 reactors
	Building surface characterization scope, number of samples, measurements, historical assessment	One case for Step 1. Partially in 50% of reviewed reactors in Step 2. Scope grid scheme applied in all cases in Step 3
Volumetric characterization	Methods applied (core drills, grab samples, in situ gamma spectrometry contamination)	No concrete or thermal column core drills for Step 1; 71% core drills for Step 2; 100% core drills performed for fully completed projects
	Scope (systems, components) and number of samples per system or component	Relevant to the bioshield and/or thermal column
Facility site characterization	Contaminated underground pipes and structures	Two examples for Step 2. Performed for all fully completed projects in Step 3
	Contaminated surface soils and other contaminated items	18% (2 cases in Indonesia out of 11 reviewed) of Step 1 reactors. Grid approach to 75% of reviewed Step 2 reactors. Performed for all fully completed projects of Step 3
	Underground water monitoring	Up to 9% of Step 1 reactors (Bandung reactor out of 11 reviewed cases). For Step 2, 25% (only Apsara reactor). Fully completed for partially or fully dismantled completed projects in Step 3
	Geological subsurface undergrounds (bedrocks, soils, etc.)	Up to 25% of Step 2 (only Apsara reactor), Fully achieved for partially or fully dismantled completed projects in Step 3

The limits defining different classes of radioactive waste as well as those designating material suitable for release to the environment must be defined for the location of the facility before costing or executing decommissioning activities because they are directly linked to the total costs. Characterization activities should be focused on precise radioactive waste partitioning of the heaviest and most voluminous components (e.g. biological shielding, graphite), as these represent a significant proportion of the reactor inventory, and thereby have a significant impact on waste management costs.

7. OVERALL CONCLUSIONS

7.1. COSTS OF DECOMMISSIONING RESEARCH REACTORS

The second phase of the DACCORD project aimed to extend the analysis of research reactor decommissioning costs undertaken during the first phase, through collection of more detailed information relevant to decommissioning from participating projects, enhancing the tools provided to enable cost estimation to be undertaken, including analysis of uncertainties and the impact of different characterization strategies.

The analysis performed in DACCORD Phase 2 confirms the general conclusions reached in Phase 1, including the following:

— Decommissioning costs and workforce levels show a broadly proportional increase with increasing power levels, with a cost threshold at very low power ratings and for zero power installations (e.g. those below 50–100 kW(th)). There are many factors which affect the cost for a specific reactor (e.g. its type, operational history, end state and waste management strategy), such that individual cost estimations should be done for each research reactor decommissioning project. Careful selection of UFs and reflection of relevant national conditions are of key importance.
— Analysis of unit cost of dismantling/demolition activities (ISDC 04, 07 — US \$/t) shows a general tendency of relative cost reduction with increasing reactor power rating, with high unit cost figures being more applicable to low reactor power costing cases, especially in the case of reactor structures. There are two basic cost components: the dismantling itself, which is broadly proportional to inventory levels, and the preparatory and finishing activities, which are less directly related to inventory levels. The second component increases unit cost for small reactors. The decommissioning cost per tonne of inventory is likely to be significantly higher for research reactors than for nuclear power plants, with comparable levels only being approached at very high thermal power ratings (several tens of MW(th)).
— Labour cost is the most significant cost category, with an average percentage of around 50% of total cost; consequently, variations in labour rates have a large impact on the total estimated decommissioning cost. Accordingly, non-inventory dependent activities (ISDC 06, 08, 01, 02) represent a significant component of the decommissioning cost and workforce.
— The analysis undertaken confirms the conclusion of DACCORD Phase 1, where ISDC 04 (dismantling activities), 08 (project management and support), 05 (waste management), 06 (site infrastructure and operation) and 01 (preparatory activities) are identified as the most significant contributors to the total cost.
— Waste management assumptions — and associated waste management costs — may differ significantly, from a minimalist approach involving putting the waste into storage, to full treatment, conditioning, storage and final disposal.

7.2. UNCERTAINTY ANALYSIS

Current approaches to understanding the cost implications of uncertainties in decommissioning are aided by the availability of computational tools which implement probabilistic methods, in addition to the deterministic approaches traditionally used for decommissioning cost estimation. The option of performing probabilistic calculations is now also available using the CERREX-D2 software code. The implications of using such approaches were analysed with reference to the cost cases described in Section 3 and a cost case developed based on the JSI TRIGA Mark II reactor in Slovenia.

The sensitivity analysis for total cost for the two cases studied, TRIGA Marks I–II and TRIGA Mark III, also illustrates that labour rates have the greatest impact on the total cost estimation, while the uncertainty of other input parameters has a much lower impact on the total cost estimate.

Accounting for costs that are expected to be incurred but are not well defined (i.e. estimating uncertainty or contingency costs) is a fundamental aspect of decommissioning cost estimation. The analysis undertaken in this project indicates that probabilistic approaches for the estimation of uncertainties provide a viable alternative to calculating such costs as compared with the traditional deterministic approach, whereby the cost of each individual activity is increased by a percentage determined by expert judgement. It is evident that, due to the nature of probabilistic methods, the strict linkage of estimated costs and discrete (ISDC-based) activities is lost; nonetheless, the main ISDC contributors to costs can still be identified.

The project also tested a methodology for assessing the impact on total decommissioning cost for risk outcomes which are foreseeable though not expected to occur and are not typically described in the BoE (i.e. out of scope uncertainties). The analysis demonstrated a viable approach to estimating such costs. This involved the definition of alternative scenarios corresponding to a set of risks to the baseline scenario, identified by means of a risk workshop. The extent to which funding needs to be set aside to cover the costs of such risks needs to be determined by the authorities responsible for the project.

7.3. IMPACT OF PLANNING AND CHARACTERIZATION ON DECOMMISSIONING

An important prerequisite in developing a radiological inventory to support decommissioning planning is the development of a material inventory database. Sampling and characterization strategies must be defined according to the dismantling and project end state objectives. These strategies evolve during the dismantling project. As the investigations progress, the precision of when the information was obtained and its cost all increase. In order to optimize the initial characterization, it is therefore advisable to gather as much information as possible in historical and functional analysis in order to rationalize later in situ investigation campaigns. The quality and cost of historical and functional data are low while the quantity of data are very large. The converse applies in the case of sampling and laboratory analysis; these are more costly and yield a relatively small quantity of data.

Characterization activities should be focused on precise radioactive waste partitioning of the most massive components (e.g. biological shielding, graphite), as these represent a major part of the reactor inventory, and thereby have a significant impact on waste management costs. Initial characterization and planning activities represent a significant portion of overall decommissioning costs, on the order of 10% of total project costs. It is noteworthy that the reactors participating in the project at a more advanced decommissioning stage appear to have a lower ratio of plant characterization costs (<10%) than those at an earlier implementation stage.

The cases considered during the project suggest that early characterization studies rely to a significant extent on the use of data from similar reactors due to the operational status of the facilities, together with analysis of the historical records of the facility, whereas later studies combine the results of radiological sampling and analysis of the historical records. There appears to be a tendency to overestimate the ratio of characterization costs to total decommissioning costs for the former, due to the need for conservatism in the absence of characterization data resulting from sampling.

This project considered the different techniques and standard procedures used in the radiological characterization process. Most facilities, where the radiological characterization process is under way, rely on a sampling and measurement plan, typically based on surface characterization results and less on volumetric characterization results. Nevertheless, all finalized radiological characterization processes studied have included surface characterization and a majority of them also included volumetric characterization. The results suggest that a minority of reactor facilities use statistical models, such as MARSSIM or geostatistical methods, to guide measurement and sampling strategies during characterization.

In the planning phase of the characterization process, projects typically rely mainly on results from partial characterization of specific reactor systems, components or specific building structures. By the end of implementation, all technology and civil structures will be characterized, supported also in many cases by activation calculations and, depending on the end state, also by results from site characterization. Activation calculations had already been performed for half of all of the reactors studied and in many of these cases the results were verified by measurements and sampling, showing good levels of correlation. The measurement and calculation techniques most frequently being used currently are dose rate and direct contamination measurements for all reactor types, including TRIGA reactors. In situ gamma spectrometry appears to be rarely used in the planning of decommissioning or in its implementation.

The most commonly used sampling techniques are standard smears, which were taken in a large majority of reactors, including TRIGA reactors. Other methods (scratch, grab samples and core drills) were used less frequently, particularly in the early stages of radiological characterization. Core samples were taken in all finalized decommissioning projects included in the project. There appears to be a growing trend in the use of gamma spectrometry analysis of samples. By the same token, radiochemical analysis is used less since this is far more expensive and not all samples are analysed to determine difficult to measure radionuclides.

Appendix I

UNIT FACTORS FOR RESEARCH REACTOR DECOMMISSIONING

This Appendix presents an analysis of the UF data used in the cost assessments provided for the participating research reactors, including providing average values for ease of reference. The method of analysis used is also described.

I.1. ANALYSIS METHOD OF THE UNIT FACTORS

A total of 21 calculations were processed, of which 14 were from DACCORD Phase 1 and the other 7 from Phase 2. The calculations from DACCORD Phase 1 were converted to the new version of the CERREX software (CERREX-D2). A range of difficult approaches were used to arrive at the cost factors used in the different cost assessments. In several cases these were based on literature studies or expert judgements based on the engineering work involved. In four cases the UFs related to completed projects; they were calculated from an analysis of the performance levels achieved during decommissioning:

— ASTRA (Austria);
— JEN-1 (Spain);
— KRR-2 (Republic of Korea);
— Siloëtte (France).

Because the cost estimates were made at different time periods and in different currencies, the data were converted to a common time frame (2019) and currency (US $). After performing the above-mentioned conversion of each cost calculation, the UFs used in the cost calculations were copied to the first worksheet of the new MS Excel calculation file. The two calculated averages have been designated as 'Average-I' and 'Average-II'.

The Average-I method calculated those UFs which were used for the cost calculations, prior to the actual decommissioning activities being performed (17 cases). This method shows the average cost UFs which were used in the cost calculations of the successfully completed projects (four cases).

The two averaging approaches were used because many of the cost cases analysed in Phase 1 of the DACCORD project were based on the 'default values' available in the CERREX software. As these values are not case specific, averages based on a limited data set would tend to be skewed towards the default data. The use of two different averaging approaches allows this effect to be understood, as well as permitting an average based on case specific information to be determined. In some of the figures presented below, not all 21 data points are available. This situation occurs when a calculation did not use certain UFs.

I.2. RESULTS OF THE ANALYSIS

The analysis results are provided in a table of averages (Table 25), and in graphical format in Annex II[13]. Graphical presentation of the data is generally very helpful in gaining a good understanding of the basis for a particular average number, including the extent to which it is a reflection of the CERREX default values. Additional important information from the figures is the number of data points reflected in the average calculation and the degree of data scatter.

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[13] Available on the publication's individual web page at www.iaea.org/publications.

For each figure in Annex II, the following four diagrams are provided in the same order:

— Workforce UFs (original values not modified by work difficulty factors;
— Investment UFs;
— Expense UFs;
— Total UFs.

These diagrams show data from DACCORD Phase 1 and Phase 2. The graphs do not show the facilities, but in this case, similar to the other diagrams in the publication, the higher values typically belong to more advanced countries with higher labour costs.

The average values of the UF data are also shown in Table 25. These data should be used with caution, given the case specific nature of decommissioning costs, as noted in Section 2.5.

TABLE 25. AVERAGE VALUES OF UNIT FACTORS

Category No.	Category title	Type of average	Average workforce UFs	Average investment cost UFs	Average expense cost UFs	Average total cost UFs	Unit
			person-h/[unit]	US $/[unit]			
INV1	Workforce in controlled area	Average-I Average-II	1.0 1.0	0.0 0.0	4.2 4.8	37.2 58.9	t
INV2	General technological equipment	Average-I Average-II	16.9 19.3	16.8 16.8	8.4 11.2	532.4 1 061.2	t
INV3	Massive and thick wall equipment	Average-I Average-II	13.5 15.1	11.8 14.4	55.8 113.0	506.3 902.9	t
INV4	Auxiliary and thin wall equipment	Average-I Average-II	37.2 34.1	12.7 14.4	56.3 113.7	1 226.1 1 950.3	t
INV5	Small core components (<50 kg)	Average-I Average-II	886.6 759.0	168.9 126.7	141.2 290.8	26 636.0 40 442.7	t
INV6	Medium core components (50–200 kg)	Average-I Average-II	218.9 171.5	81.6 63.4	206.0 326.6	6 976.9 8 344.3	t
INV7	Large reactor components (>200 kg)	Average-I Average-II	54.6 143.5	42.2 37.1	149.6 478.7	1 763.4 6 033.9	t
INV8	Massive concrete in control area	Average-I Average-II	11.6 7.3	19.7 15.6	45.4 72.8	489.8 422.7	t
INV9	Graphite elements, thermal columns	Average-I Average-II	75.6 76.9	14.0 16.8	7.4 11.2	2 455.1 4 148.4	t

TABLE 25. AVERAGE VALUES OF UNIT FACTORS (cont.)

Category No.	Category title	Type of average	Average workforce UFs	Average investment cost UFs	Average expense cost UFs	Average total cost UFs	Unit
			person-h/[unit]	US $/[unit]			
INV10	Low density and specific materials	Average-I Average-II	200.0 200.0	28.7 38.4	7.7 10.2	5 947.6 10 582.0	t
INV11	Other materials in control area	Average-I Average-II	29.7 31.5	20.3 19.2	19.6 247.3	894.9 1 976.3	t
INV12	Contaminated material in area not under control	Average-I Average-II	11.1 n.c.*	5.3 n.c.	103.9 n.c.	316.7 n.c.	t
INV14	Removal of solid waste and materials	Average-I Average-II	5.1 7.4	4.2 6.4	8.4 12.8	146.8 353.7	t
INV15	Removal of liquid waste and sludge	Average-I Average-II	5.2 5.0	3.7 6.4	34.6 12.8	216.2 282.5	t
INV16	Chemical decontamination of surfaces	Average-I Average-II	0.5 1.6	3.7 4.8	5.8 9.0	28.3 75.3	m^2
INV17	Mechanical decontamination of surfaces	Average-I Average-II	1.4 1.9	8.6 7.8	15.9 30.3	78.3 141.1	m^2
INV18	Radiological survey of buildings	Average-I Average-II	1.2 0.5	6.9 4.8	5.9 7.6	31.9 38.6	m^2
INV19	Radiological survey of the site	Average-I Average-II	0.5 0.5	4.8 6.4	4.8 6.4	24.4 39.1	m^2
INV21	Piping, valves, pumps	Average-I Average-II	27.4 26.6	12.1 14.4	117.9 244.6	1 067.5 1 781.4	t
INV22	Tanks, heat exchangers	Average-I Average-II	20.5 21.9	11.1 14.4	84.4 174.4	785.5 1 353.9	t
INV23	Steel linings	Average-I Average-II	26.9 38.7	11.1 14.4	129.8 270.9	1 077.9 2 114.2	t
INV24	Ventilation and thin wall equipment	Average-I Average-II	43.9 44.5	11.1 14.4	253.7 534.2	1 852.4 3 154.1	t
INV25	Handling equipment	Average-I Average-II	26.1 27.4	13.1 14.4	110.2 227.1	1 012.7 1 733.5	t

TABLE 25. AVERAGE VALUES OF UNIT FACTORS (cont.)

Category No.	Category title	Type of average	Average workforce UFs	Average investment cost UFs	Average expense cost UFs	Average total cost UFs	Unit
			person-h/ [unit]	US $/[unit]			
INV26	Cables and cable trays	Average-I Average-II	25.1 25.3	11.1 14.4	84.4 174.4	928.0 1 559.8	t
INV27	Switchboards, electric cabinets	Average-I Average-II	16.6 21.6	13.1 14.4	205.2 270.9	934.9 1 397.1	t
INV28	Embedded elements	Average-I Average-II	46.6 38.6	12.1 14.4	168.8 351.8	1 680.3 2 762.7	t
INV29	Thermal insulation	Average-I Average-II	100.0 78.2	28.7 28.8	7.7 95.4	2 992.0 4 260.0	t
INV30	Asbestos and hazardous materials	Average-I Average-II	190.0 200.0	25.3 38.4	6.7 10.2	5 726.5 10 582.0	t
INV31	Massive lead shielding	Average-I Average-II	8.4 20.9	12.7 19.2	64.6 10.2	392.8 810.5	t
INV32	Lead shielding bricks and plates	Average-I Average-II	7.3 6.4	14.1 14.4	36.4 69.1	299.6 464.2	t
INV33	Other shielding	Average-I Average-II	6.9 7.0	12.7 19.2	24.5 10.2	261.1 398.1	t
INV34	Glove boxes	Average-I Average-II	20.0 20.0	14.8 19.2	7.9 10.2	613.8 1 082.7	t
INV35	Miscellaneous items	Average-I Average-II	12.0 14.1	15.3 14.4	86.2 174.4	543.3 967.3	t
INV37	General equipment area not under control	Average-I Average-II	12.0 12.0	9.6 12.8	11.5 15.3	375.7 660.1	t
INV38	Structural metal constructions	Average-I Average-II	7.5 10.9	15.2 19.2	7.6 10.2	235.5 512.8	t
INV39	Massive reinforced concrete	Average-I Average-II	8.0 8.0	15.3 25.6	15.3 25.6	253.7 472.5	t
INV40	Masonry, plain concrete	Average-I Average-II	5.1 3.9	15.6 19.2	7.8 10.2	171.6 259.1	t
INV41	Other material area not under control	Average-I Average-II	2.4 0.5	20.9 6.4	20.9 6.4	144.7 39.1	t

TABLE 25. AVERAGE VALUES OF UNIT FACTORS (cont.)

Category No.	Category title	Type of average	Average workforce UFs	Average investment cost UFs	Average expense cost UFs	Average total cost UFs	Unit
			person-h/ [unit]	US $/[unit]			
INV42	Final site remediation	Average-I Average-II	4.3 n.c.	26.7 n.c.	9.5 n.c.	59.7 n.c.	m^2
HLW1	Management of HLW	Average-I Average-II	300.0 n.c.	1 139.4 n.c.	56 967.8 n.c.	70 584.2 n.c.	t
ILW1	Management of ILW	Average-I Average-II	108.2 236.7	602.8 459.9	10 909.1 18 434.7	14 370.3 39 574.9	t
LLW1	Management of LLW	Average-I Average-II	45.6 55.3	613.9 179.1	11 406.0 29 353.7	13 355.4 33 822.2	t
VLLW1	Management of VLLW	Average-I Average-II	9.0 5.7	29.7 29.9	663.1 1 991.3	961.3 2 212.0	t
VSLW1	Management of VSLW	Average-I Average-II	10.0 10.0	13.7 12.5	13.7 12.5	237.6 662.6	t
EW1	Management of EW and materials	Average-I Average-II	8.4 5.9	118.2 179.1	333.3 362.3	692.2 910.0	t
RCC1	Recycling of concrete	Average-I Average-II	3.8 4.0	8.3 10.7	4.3 5.3	101.4 226.6	t
RCM1	Treatment and recycling of other material	Average-I Average-II	7.0 7.0	13.4 16.0	4.5 5.3	196.9 390.0	t
HZW1	Disposal of hazardous waste	Average-I Average-II	18.6 20.0	41.2 53.3	4.3 5.3	527.2 1 111.9	t
CNW1	Disposal of conventional waste	Average-I Average-II	9.4 10.0	24.7 32.0	20.5 5.3	298.1 564.0	t
NRW1	Management of waste outside area of control	Average-I Average-II	9.5 10.0	19.8 26.6	7.6 5.3	331.4 558.6	t
RHLW	Management of historical/ legacy HLW	Average-I Average-II	471.9 500.0	59.0 52.7	259.5 368.9	15 253.9 27 484.5	t
RILW	Management of historical/ legacy ILW	Average-I Average-II	95.0 100.0	20.8 21.1	74.1 105.4	3 110.5 5 539.1	t

TABLE 25. AVERAGE VALUES OF UNIT FACTORS (cont.)

Category No.	Category title	Type of average	Average workforce UFs	Average investment cost UFs	Average expense cost UFs	Average total cost UFs	Unit
			person-h/[unit]	US $/[unit]			
RLLW	Management of historical/ legacy LLW	Average-I Average-II	19.7 20.0	10.9 15.8	7.4 10.5	652.8 1 108.9	t
RVLLW	Management of historical/ legacy VLLW	Average-I Average-II	5.0 5.0	3.8 5.3	3.7 5.3	169.6 281.2	t
REW	Management of historical/ legacy EW and materials	Average-I Average-II	5.0 5.0	3.8 5.3	3.7 5.3	169.6 281.2	t

* n.c.: not calculated.

Appendix II

USER DEFINED UNIT FACTORS FROM BANDUNG TRIGA 2000 RESEARCH REACTOR CASE

The ISDC costing methodology applied in CERREX-D2 requires definition of three UFs for each decommissioning category:

- Workforce UFs used for calculation of person-hours related to individual activities to support calculation of the labour cost;
- Investment cost UFs used for calculation of investment cost for individual activities; UFs should cover all related investment costs;
- Expenses cost UFs used for calculation of expenses for individual activities; UFs should cover all related expenses according to the ISDC definition.

For the user with limited experience with real/actual decommissioning activities, CERREX-D2 provides default UFs that can be used. However, in order to perform a country, site and facility specific cost estimate, users should develop UFs based on their national conditions before calculation begins. The calculations are significantly impacted by the UFs chosen and care needs to be taken to define them more accurately, if possible. The following is an example of how to determine facility specific UFs.

In this case, the user sets all activities from preparatory to finishing activities for individual inventory dependent activities (ISDC 04) and for individual waste management dependent activities (ISDC 05). For each activity (from preparatory until finishing activities) users should define:

- Duration (hour);
- Quantity of person-hours for specific staff categories;
- Quantity and cost per unit of equipment and materials;
- Allocation of the equipment and materials as either expenses or investment.

The above defined inputs were entered into MS Excel tables (see Annex III) that calculate the UFs as a function of the inputs listed above. These tables present data for the TRIGA 2000 Bandung reactor, resulting in the UFs for the dismantling of some core components, surrounding systems and cooling systems (Annex III, Tables III–1 to III–11).

An example of this is provided in Table 26.

TABLE 26. CALCULATION OF UFs FOR DISMANTLING THE ROTARY SPECIMEN RACK OF THE BANDUNG RESEARCH REACTOR

Working task:	Dismantling of Rotary Specimen Rack (RSR)	Specification of the RSR:	Mass [t]: 0.8		
Dismantling style:	One piece removal of RSR with segmentation on dismantling site	57.5			
End state:	Segmented RSR is located at the temporary shelter on site.	Total workforce [man.h]:	46		

04.0501	46.0	WF UF	57.5	man.h/t
05.0902	0.0	IC UF	0.0	USD/t
	46	EXP UF	1 416.9	USD/t

No	Name of the Component		Dismantling Activities	Duration [hour]	Professions: Spv	Technician/ Operator	PRO	Staff [Pers.]	Work-force [man.h]
	RSR		CERREX professions		ENG	TCN	TCN		
1.		**1**	***Preparatory:***						
			Prepare all equipment						
			Check the crane						
			Placed /put the absorber paper on the floor according to the route of the RSR transportation						
	04.0501	1a	*Subtotal:*	0.5	1	2	1	4	2
			Placed the Pb shielding of RSR on bulk shielding and						
			placed the wooden pallet at reactor hall and container at reactor deck						
	04.0501	1b	*Subtotal:*	1	1	4	1	6	6
		2	***Dismantling:***						
			Remove the drive and indicator assembly and put on the container						
	04.0501	2a	*Subtotal:*	0.5	1	2	1	4	2
			Remove the tube and shaft assembly and put on the container						
	04.0501	2b	*Subtotal:*	0.5	1	2	1	4	2
			Remove the specimen-removal tube and put on the container						
	04.0501	2c	*Subtotal:*	0.5	1	4	1	6	3
			Open the screw at fastener plate of RSR and put the screw on the container						
	04.0501	2d	*Subtotal:*	1	1	4	1	6	6
			Transport the container to temporary storage						
	04.0501	2e	*Subtotal:*	0.5	1	2	1	4	2
			Remove the RSR by crane and place on the Pb shielding on bulk shielding						
	04.0501	2f	*Subtotal:*	2	1	4	1	6	12
			Remove the Pb shielding (with RSR inside) from bulk shielding and put on wooden pallet at reactor hall						
	04.0501	2g	*Subtotal:*	1	1	4	1	6	6
			Transport the Pb shielding (with RSR inside)to temporary storage						
	04.0501	2h	*Subtotal:*	0.5	1	4	1	6	3
		3	***Finishing:***						
			Clean up the site						
			Collect all of waste that is generated from this dismantled and put at the temporary bin						
			Replace all equipment into tool storage						
	04.0501	3a	*Subtotal:*	0.5	1	2	1	4	2

Equipment, materiaRSR, expenses Type	Ac	In	Ex	Unit	Quantity of units	Cost per unit USD/unit	Investm. per item USD	Expenses per item USD
							0.0	1 133.5
Crane			1	w.hour	10	10	0.0	0.0
Absorbent paper	1		1	1 m2	50	0.5	0.0	25.0
Personal Protective equipment	1		1	[man.h]	46	1	0.0	46.0
Power tool kit	1		1	w.hour	2.5	1	0.0	2.5
Mechanical tool kit			1	w.hour	2.5	0.5	0.0	0.0
Box/container	1		1	piece	1	50	0.0	50.0
Pb shielding	1		1	piece	1	1000	0.0	1 000.0
Forklift			1	w.hour	1	10	0.0	0.0
Wooden pallet	1		1	piece	1	10	0.0	10.0
							0.0	0.0
							0.0	0.0
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Appendix III

ILLUSTRATIVE RISK REGISTER FOR THE SLOVENIAN TRIGA MARK II

Starting from the risk groups for a decommissioning project, as described in Ref. [12], several risks were identified for the Slovenian TRIGA Mark II research reactor decommissioning project. The register is presented in Tables 27–36, showing potential mitigation measures to address some of the key risks. A risk analysis for this type of facility would typically involve the probability and impacts of the identified risks being assessed by expert judgement.

TABLE 27. INITIAL CONDITIONS OF THE FACILITY

Category	Item	Mitigation
Physical status	Some records are not reliable	Check records with investigations in the field Check records with people having knowledge of the facility
	Some records are not available (e.g. the initial plans of the facility are not available)	—
	Unexpected contamination of the concrete	Plan for facility characterization before planning the decommissioning activities
Radiological status and characterization	It is not possible to characterize some components, or it is very expensive	—
Waste and materials status	Underestimation of asbestos	Check areas or equipment frequently composed of asbestos and make samples

TABLE 28. END STATE OF DECOMMISSIONING PROJECT

Category	Item	Mitigation
Definition of the end state of the project	External pressure from stakeholders to choose for building demolition	Address as part of environmental impact assessment exercise
Difficulty to achieve the end state	The background is higher than the release criteria, it is difficult to achieve the greenfield state	—

TABLE 29. WASTE AND MATERIALS MANAGEMENT

Category	Item	Mitigation
Waste management policy	Change of the release criteria due to national or international changes in regulations	—
	Filling of the waste package not optimized	—
Waste estimation and characterization	Waste package is refused at the storage because it is not compliant with the policy of the storage site	Verify storage site requirement prior to packaging the waste. Implement control of the produced waste package.
	Unexpected discovery of legacy waste	Investigation
Waste management infrastructure (on-site off-site)	No waste route available for unexpected waste	—
	The treatment facility is not available during the decommissioning (technical issue)	Provide redundancy in buffer storage to allow time to develop alternative arrangements
	Interim storage or disposal site facility changes its technical specifications	—
	Temporary or definitive unavailability of waste management stream	—
	Saturation of storage areas on-site	—

TABLE 30. ORGANIZATION AND HUMAN RESOURCES

Category	Item	Mitigation
Organizational structure	Qualified people from the project not available to perform a task	For each activity, establish in advance the skills needed to perform it. Take this into account in the planning to ensure that skilled people will be available
	Unplanned change of project manager	Prepare periodic reports on the status of the project to facilitate the transfer of knowledge to the new project manager
Human resources	Lack of experience in specific decommissioning activities in the staff of the project	—
	Difficulties for the current staffing to change job from operation to decommissioning	Implement change management programmes

TABLE 31. FINANCE

Category	Item	Mitigation
Cost	Wrong estimation of the project costs	—
Funding	Delay in obtaining funds	—

TABLE 32. INTERFACES WITH CONTRACTORS AND SUPPLIERS

Category	Item	Mitigation
Contractor and supplier management	Contract does not include an adequate risk management approach	Ensure that tenders for major contracts are subject to independent review prior to issue
	No bid in response to a call for a tender	—
	Contractor does not reach the planned end state (restructuring of company, bankruptcy during the implementation of the contract, contractor does not wish to finish planned work, etc.)	—
Contractor and supplier oversight	Supplier does not obtain regulatory approvals in the relevant country in case of international contracting	—

TABLE 33. STRATEGY AND TECHNOLOGY

Category	Item	Mitigation
Technology	Failure in the implementation of a new technology	Contractual requirement to undertake mock-up testing in sufficient time to address technology failures

TABLE 34. LEGAL AND REGULATORY FRAMEWORK

Category	Item	Mitigation
Laws and regulations	Incorrect interpretation of the applicable regulation due to unexpected multiple regulation sources for the same topic (e.g. to assess the allowed release concentration of a radionuclide in the environment, it is necessary to consider both radiological and chemical regulation)	—
	Change of the working regulation (asbestos), safety, waste, environment, nuclear transports, purchases	—
Licensing process	Difficulties in the implementation of the licensing process	—
	Licence refusal	Implement regular dialogue with regulatory body to justify technical choices, follow recommendations to maximize chances of obtaining a licence

TABLE 35. SAFETY

Category	Item	Mitigation
Radiological safety	Irradiation of worker	—
	Contamination of worker implementing a decommissioning activity	—
Safety	Malicious act	—
	Fire due to thermal cutting technologies	—
	Serious accident of a worker during implementation of an activity	—
	Internal flooding	—

TABLE 36. INTERESTED PARTIES

Category	Item	Mitigation
Communication	Opposition to the project by the general public	Communicate with public
	Unplanned co-activity preventing performance of an activity	—

Appendix IV

EXAMPLES OF IMPLICATIONS OF DIFFERENT PLANNING AND CHARACTERIZATION STRATEGIES ON COSTS

IV.1. FRENCH REACTOR SILOÉ

IV.1.1. Presentation of the reactor

The Siloé facility is an open pool type research reactor built in France in 1961 by the French Alternative Energies and Atomic Energy Commission (CEA) (Fig. 44). Located on the Grenoble site, it has been used mainly for fundamental research experiments, production of radioisotopes for medical use, materials testing and production of spiked silicon for industry.

The reactor started operation in 1963. With an initial operating power of 15 MW, in 1967 it increased to an operating power of 30 MW and in 1972 to an operating power of 35 MW. In December 1997, the reactor was shut down and the post-operational cleanout phase began, lasting until 2005. On 26 January 2005, the Nuclear Safety Authority authorized the CEA to permanently shut down the facility in order to start dismantling activities.

The dismantling strategy is immediate dismantling through to release conditions, with reuse of the buildings.

FIG. 44. The Siloé reactor. (Reproduced courtesy of CEA.)

IV.1.2. Activation calculation process

IV.1.2.1. Objective of the calculation

The objective of the calculation is to model and quantify the physical phenomena that led to the activation of structures subjected to a neutron flux (pool block in the case of Siloé). The activation calculations took place in two steps:

(1) In the first step, a 'conventional' reactor calculation is performed (critical reactor calculation). This makes it possible to determine the distribution of neutron flux in space and energy in the core and in all structural materials that may have been activated. The neutron flux is normalized to the maximum nominal power of the reactor (i.e. 35 MW in the case of Siloé).
(2) In the second step, the previously calculated neutron flux is used, together with the irradiation and decay history, to estimate the activity of the different materials as a function of time and their position in the reactor.

In addition to these two steps, the study consisted of defining the input data necessary for the calculations and, in particular, to do the following:

— Accurately model the geometry of the reactor (i.e. the reactor core and the experimental channels). Two geometries were modelled: one corresponding to the geometry of the reactor before 1986 and one corresponding to the geometry of the reactor after 1986.
— Choose the fuel configuration which would result in highest activation levels from those used during the operation phase of the Siloé reactor. First, flux measurements obtained by experimental measurements during the operation phase on each configuration were compared. Two configurations were modelled.
— Determine the isotopic composition of the materials. Several analyses were conducted from March to July 2006. Some materials could not be analysed. Isotopic compositions from other facilities were therefore used for these materials (the Triton reactor, Mélusine reactor and the Strasbourg university reactor).
— Trace the history of irradiation and decay.

The results of these studies show four zones of main pool activation:

— The entire front, from the raft to the +3.20 m level;
— The entire left side, from the raft to the +3.20 m level;
— The entire front right, from the raft to the +3.20 m level;
— All of the left rear face, from the raft to the +2.00 m level.

The working pool is not activated except at the floor on the left side above the tangential channel. The activation zone extends over almost the entire length of the canal and to a maximum depth of 40 cm.

The base of the main pool is locally activated. The depth to reach a concrete activity of 1 Bq/g is about 40 cm. However, in the most highly activated areas, all steel reinforcement is activated, the deepest of which is 62.5 cm. The activated surface follows a U-shape.

The modelling results were validated by comparison with experimental data (sampling). The samples taken confirm the activation calculations.

IV.1.2.2. Organization and planning

Studies were performed by CEA and samplings were subcontracted. The studies lasted 25 months. The total cost (not included CEA work labour) was €47 000. The following observations were made.

IV.1.2.3. Necessary competences for the calculation

The calculation of activation requires specific competence in the use of the software and modelling techniques (often used for radioprotection calculations). Thus, it is necessary to plan this activity well in advance.

IV.1.2.4. Impurity in activated materials

The characterization of the activated materials is essential for the activation calculations because the elements that are activated are present in trace amounts in the concretes or the reinforcement (europium for the concretes, cobalt for the reinforcement) and vary significantly depending on the type of concrete (barium and iron for heavy concretes).

IV.1.2.5. Importance of historical data for treatment optimization

Careful analysis of historical data is essential to optimize the removal of material on activated surfaces. This avoids overestimation of the extent of the activation and, accordingly, designation of waste in categories higher than strictly necessary.

IV.1.3. Pool draining

The main pool draining, which began on 26 March 2004, was suspended on 15 April 2004 following a significant and unexpected increase in the poolside dose rate. The activity of the main pool casing was found to be higher than originally modelled. The origin of this activity is the presence of a cavity filled with air below the +3.20 m level and the main square pool limiting the energy loss of the neutrons from the core. This was explained by the fact that when the main pool casing was modified in 1988, an air space was created, below the level +3.20 m, between the vessel and the vessel casing. Neutron scattering in this air gap led to greater than expected activation of the vessel, vessel casing and concrete in the initial dismantling scenario.

This activation could not be detected before the main pool was emptied because:

— The presence of water above the step acted as a screen that impeded the measurement of the radiation emitted by the activated concrete from the reactor hall.
— The radiological measurement tests carried out in the pool before it was emptied did not allow discrimination between the dose rate due to the activation of the structures and the dose rate generated by irradiated objects present in the pool.

Thus, for the dismantling of the main pool, close interventions by operators, as planned in the dismantling scenario, were no longer possible. An in-depth analysis of several scenarios was conducted. A solution based on the purchase of commercial tools was then implemented. This optimal solution in terms of dosimetry, financial cost and technical feasibility is a tele-operated and manual mixed solution comprising two chronological phases. A remotely operated demolition robot, using a Brokk located on a mobile platform in the pool, was installed (Fig. 45). This solution made it possible to maintain the overall personnel doses of the operation under the initially calculated acceptable conditions.

— Tele-operated phase between June 2006 and September 2007, for the removal of the most activated elements, namely the tank, the casing and the neutron channel noses. They were treated by tele-operating between +3.2 m (high vat) and –2.5 m (bottom of the neutron channel noses).
— Mixed manual/tele-operated phase between September 2007 and September 2008 for withdrawal of the rest of the equipment. This involved coring of the channels and cutting of the high parts (from +7.00 to +3.20) and low parts (from –2.50 to –3.80) of the swimming pool.

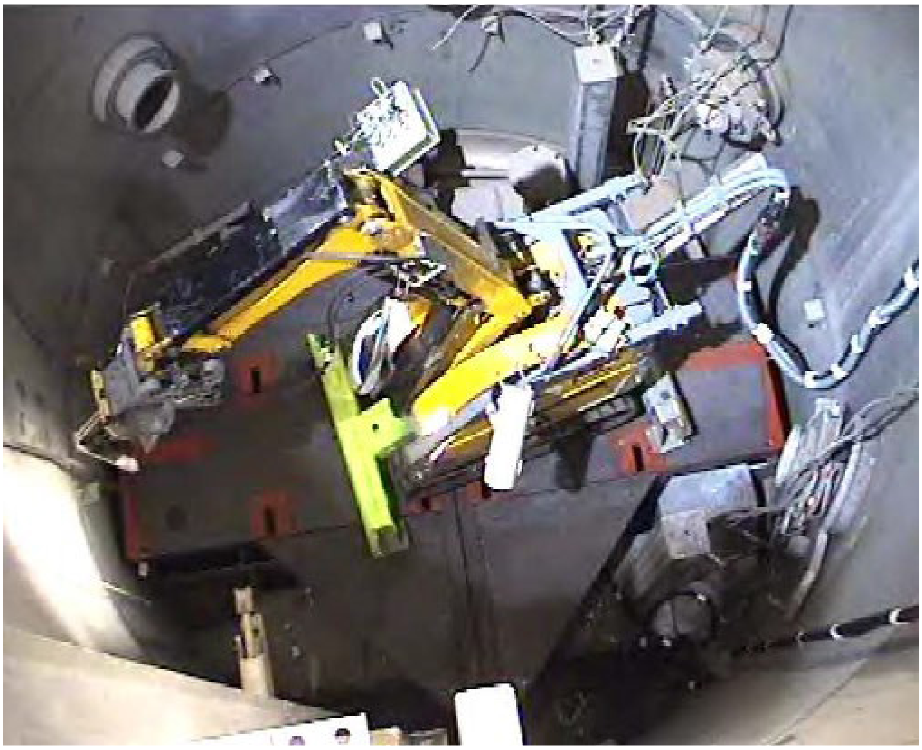

FIG. 45. Brokk inside the pool of the Siloé research reactor. (Reproduced courtesy of CEA.)

IV.1.4. Conclusions

The initial dismantling scenario was manual tank dismantling for a one year period, as high activation was not anticipated, with an estimated collective dose of 50 person-mSv. The evidence of tank + tank structure activation led to a new estimated collective dose of 5627 person-mSv, which led to a new remote dismantling scenario.

The modification of the initial scenario took another ten months compared with the initial planning for the main pool tank removal operations. In total, this work lasted approximately 24 months (i.e. an additional three years were required to reach completion). The end of the dismantling works was initially planned for the end of 2007 and was eventually completed at the end of 2010.

IV.2. FINNISH TRIGA

IV.2.1. Presentation of the reactor

The Finnish TRIGA FiR-1 (Finland Reactor 1) is located in Espoo, Finland, on the Otaniemi campus. There are numerous buildings in the neighbourhood, including Aalto University and the VTT Technical Research Centre of Finland, a student village, and an underground station with a variety of commercial services, sports and other facilities.

The reactor was purchased from the United States of America and started operation in 1962. As described in Ref. [14], FiR 1 was a water cooled, pool type TRIGA reactor, with a fission power of 250 kW. In 1971, the Finnish Government transferred responsibility for the reactor from Helsinki University of Technology to VTT. The reactor was initially used for neutron and reactor physics research and for educational purposes, but its scope of activity was later expanded to provide radiotherapy treatment for cancer patients (boron neutron capture therapy, BNCT[14]), using material moderator technology developed by VTT. This service was discontinued in January 2012 and, since then, the reactor has only been used for minor activities.

In February 2015, VTT received a statement from the Ministry of Economic Affairs and Employment concerning its environmental impact assessment report on the decommissioning and dismantling of the reactor. FiR 1 was shut down permanently later that year. In 2017, VTT submitted an application for permission from the Council of State to decommission the reactor and was under licensing for decommissioning at the end of 2018.

IV.2.1.1. Brief description of the reactor

FiR-1 was purchased through an agreement between the IAEA and the Government of Finland, following a request by Finland for assistance in establishing a research reactor project. The supplier, General Atomics, designed the TRIGA reactors (from training research isotopes General Atomics) for use in university environments.

In 1981, to extend operation for another 10–20 years, a renewal of the reactor control instrumentation was carried out, including the automatic power control system and the control console. For BNCT treatments, the thermal column and part of the concrete shielding of the reactor were replaced with a treatment station (Fig. 46). Core loading was modified to maximize the flux towards the aperture. VTT developed a specific moderator material to reduce the dose from direct gamma radiation and fast neutrons — the Fluental moderator, consisting of 69% aluminium fluoride I (AlF^3), 30% metallic aluminium and 1% lithium fluoride (LiF), to absorb thermal neutrons. The operation with this new configuration, including BNCT treatments, started in 1997.

IV.2.2. Decommissioning strategy

- Initial state at shutdown: The permanent shutdown state is expected to last about six years. The core has been made subcritical by removing a number of fuel elements.
- Decommissioning scenario: The reactor will be decommissioned as described in Ref. [14]:

> “The reactor structures (concrete radiation shielding, aluminium pool and core structures, cooling circuits and instrumentation) will be dismantled in stages after the spent nuclear fuel has been removed from the reactor. This will result in a few dozen cubic metres of low and intermediate-level radioactive concrete, steel, aluminium, graphite and Fluental moderator material used for radiotherapy. These materials will be non combustible. Part of the concrete in the reactor has not been radioactive and, after precautionary measurements, can be recycled as normal construction waste. If possible, some reactor components and materials will be re-used in other research reactors, which will reduce the amount of waste. A small amount of low-level radioactive waste, such as overalls and cleaning resins, will also result from the operation and decommissioning of the reactor. Account will be taken of fire safety during the packaging and storage of these materials.”

- End state: “Once the reactor has been dismantled, the surfaces of the reactor building will be decontaminated and careful radiation measurements will be taken to ensure its safety for other purposes.” [14]

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[14] Boron neutron capture therapy is a high linear energy transfer radiotherapy used in cancer treatment. It is based on nuclear capture and fission reactions.

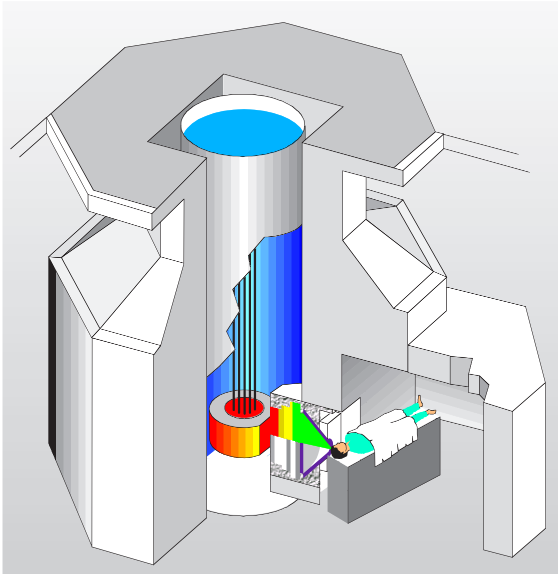

FIG. 46. Schematic of FiR-1 with the BNCT treatment facility.[15] *(Reproduced courtesy of VTT.)*

IV.2.3. Characterization process

Characterization began in 2013 with inventory calculations, followed by sampling and analysis starting from potentially free released materials and progressing towards more radioactive components and materials. By the end of 2018, characterization had been completed for several low activity samples.

Special attention was paid to BNCT facility components containing lithium, and consequently tritium as an activation product. Two materials of specific interest are the Fluental moderator, used to produce an optimized epithermal neutron beam for BNCT, and a special lithium enriched plastic used for shielding the BNCT concrete structures from neutrons. As the Finnish nuclear power plant fleet consists of light water reactors only, no significant provisions have been made for tritium in the planning and licensing of final disposal facilities. While the overall waste inventory of FiR-1 is small in comparison to nuclear power plants, it could take up a relatively significant part of the capacity of waste disposal facilities with respect to tritium. Therefore, accurate information on tritium inventories is critical not only for dismantling and packaging planning, but also for the contracting of waste management services.

IV.2.3.1. Inventory calculations and irradiation experiments on Fluental

The first inventory calculations in 2013–2015 yielded a significant overestimate of Fluental tritium inventory due to a mathematical limitation in the calculation method of the ORIGEN-S point depletion code. Using just the total flux and three group shape factors to model the flux spectrum overestimates the thermal region, which had caused higher production rates for ^{6}Li neutron absorption reaction producing tritium. In the revised calculation in 2016, the estimated total activity of tritium was reduced to 1.3 TBq (by a factor of almost 30). The new estimate is based on calculating reaction rates with continuous energy Monte Carlo code MCNP.

In practice, used Fluental from the FiR-1 BNCT facility can be sampled only during the dismantling phase of the reactor. For the validation of inventory calculations, dedicated irradiations of small samples

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[15] See also https://www.vttresearch.com/services/low-carbon-energy/nuclear-energy/decommissioning-of-finlands-first-nuclear-reactor

were carried out at ICN Pitesti, Romania, and studied using a series of full combustion measurements at the Horia Hulubei National Institute for Physics and Nuclear Engineering, Romania. In addition to the tritium content of the samples, the diffusion of tritium from the samples into water over six months was also determined. Concerning the comparison of simulations with these measurements, significant uncertainty (factor of 2.5) remains due to the observed inhomogeneity of ^{6}Li in the Fluental samples. The tritium content of the samples is consistent with the simulated values for the lowest ^{6}Li concentration. Moreover, diffusion to water was observed to be slow despite the small size of the samples. The conclusion is that the safety of dismantling as well as the waste acceptance criteria of the recipient can be fulfilled by ensuring appropriate packaging of the material.

IV.2.3.2. Inventory estimates and measurements on lithium enriched plastic

As described in Ref. [15], lithium enriched plastic was used to shield the structures in the BNCT irradiation room from neutrons. The mixture contained lithium carbonate and polyethylene paraffin. Owing to the thermal neutron absorption of 6Li, tritium was also present. Neutron fluxes inside the BNCT irradiation room were estimated to be 106 n/s·cm2 at maximum, although with significant flux variation. Based on the assumed flux, specific tritium activities in the plastic are calculated to be no more than a few hundred Bq/g. Although no other significant activity was expected to have occurred, total activity may have been close to the clearance limits as a result of a large part of the tritium being released through the porous material [15].

Analysis of the plastic samples was performed at Horia Hulubei National Institute for Physics and Nuclear Engineering, Romania, using a full combustion method. The highest observed local activity values were about 1000 Bq/g. While the activity level exceeds the limit for general clearance (100 Bq/g), the measurements confirmed that the total activity of the 2200 kg material batch remains below 1 GBq. On this basis VTT obtained the regulator’s approval for the transfer of the plastics for reuse by another licence holder in Finland according to the case specific clearance procedure.[16]

IV.3. BULGARIAN RESEARCH REACTOR IRT-2000

The IRT-2000 (IRT-Sofia) research reactor was designed and constructed between 1958 and 1961. First criticality was reached in September 1961 and the reactor was in operation for 28 years, until July 1989 when it was shut down. It was started up 4189 times, running for a total of 24 623 h at different power levels (by 2 MW) agreed upon with the users at regular weekly meetings. The reactor is pool type, cooled and moderated with light water. In order to implement the reconstruction project of this research reactor, it has been necessary to develop and execute a plan for partial dismantling.

The partial dismantling activities are part of the overall process of refurbishment of the IRT-Sofia research reactor. The final stage, after partial dismantling, will also be the initial stage of installing the new systems and equipment.

IV.3.1. Characterization process

The process of characterization of the research reactor’s materials is carried out in stages. It was decided at first to carry out characterization of the equipment that is to be dismantled in the reactor pool, primary cooling loop and thermal column. It was carried out by measuring, taking samples and smears and through a calculation method that also includes the following basic activities:

— Review of the data from the history of IRT-2000 operation;
— Selection and introduction of a method for calculation of component activations;

[16] The applicable regulation is accessible at https://www.stuklex.fi/en/ohje/YVLD-4.

— Development of a plan for measurements and taking samples and smears;
— Performing the measurements and taking samples and smears;
— Comparison of the data obtained from the calculations with the results of the measurements.

IV.3.2. Results

The results of the preliminary characterization are a basis for planning for the radiation protection of employees and determination of waste quantities and categorization. During the implementation of dismantling activities, the various materials were measured and characterized, and the results were recorded and compared with the previous results.

After removal of all equipment planned to be dismantled, the final radiological survey of the remaining facilities and the reactor hall was performed. Surveys for alpha, beta and gamma contamination were completed. Smear samples were taken and measured for determination of total alpha and beta activity (Bq/cm^2). The samples were taken from those areas (walls and floors) with higher than average values. The results of the final survey were used to prove that the surface contamination levels of the remaining equipment met the established success criteria.

IV.4. NETHERLANDS LOW FLUX REACTOR, PETTEN

IV.4.1. Reactor details

IV.4.1.1. Location

The Low Flux Reactor (LFR) is located at the ‘Onderzoekslocatie Petten’ (OLP), the research site Petten in the northwestern part of the Netherlands. The OLP is situated a few hundred metres from the North Sea in a nature conservation area with sand dunes and typical dune vegetation.

IV.4.1.2. History of the reactor

Construction of the LFR started in 1959, and first criticality was achieved in 1960. The reactor was an Argonaut type, initially having a thermal power rating of 10 kW; in the 1980s this was increased to 30 kW thermal.

The LFR was operated for approximately 50 years for research and education purposes. Many engineers and power and research reactor operators received training at the LFR facilities. Research areas included medical applications, materials science and even the arts, such as authentication of paintings. In 2010, reactor operation was discontinued by NRG, the operator and licensee, for economic reasons.

IV.4.1.3. Brief description of the reactor

The LFR was a modular research reactor which used light water as coolant and moderator. The ring shaped core had internal and external graphite reflectors. Several core configurations were applied during its lifetime. The shielding consisted for the most part of stacked blocks of barite concrete (‘biological shield’). Figure 47 shows the reactor in its reactor hall. The ‘irradiation car’, or removable lock in the foreground, served as the entrance to an irradiation chamber for large objects. The extension at the right side was used for performing research on clinical BNCT.

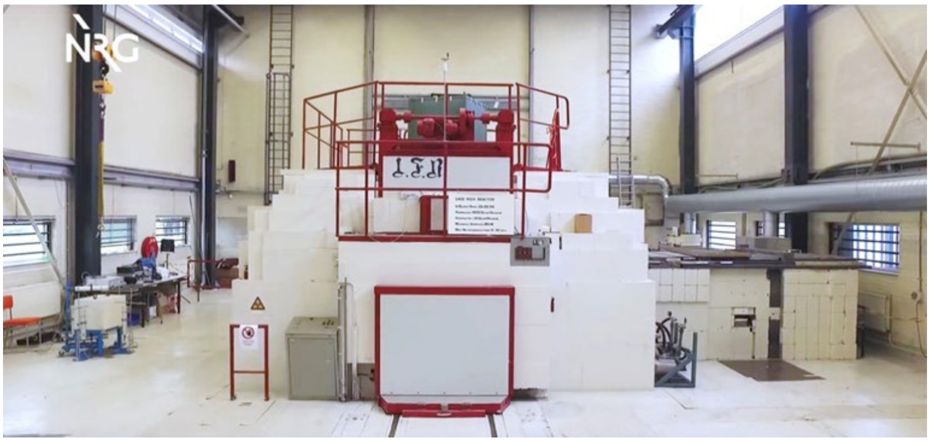


FIG. 47. The Low Flux Reactor of NRG with shielding of stacked concrete blocks (the facility for BNCT medical research is on the right). (Reproduced courtesy of NRG.)

IV.4.2. Decommissioning strategy

IV.4.2.1. Initial state at shutdown

At permanent shutdown, the LFR was a fully functional and well maintained research reactor.

IV.4.2.2. Decommissioning scenario

The strategy after shutdown was ‘immediate dismantling’. After permanent shutdown in December 2010, a period of about five years followed for preparation of the decommissioning of the reactor in which the radiological inventory was determined, the decommissioning licence application prepared and submitted and the licence granted (January 2015), and all detailed working procedures were established. In addition, the ventilation system was upgraded to accommodate the decommissioning conditions. The actual decommissioning started at the beginning of 2016 with the uncoupling of the main power supply.

The decommissioning project was divided into 13 WPs, many of which were executed in subsequent and sometimes parallel order by a small, dedicated team. At the start of each WP, a task risk assessment, including a radiation evaluation, was done (Fig. 48). At the end of each WP, an evaluation and a summary report were prepared.

To facilitate the decommissioning process, NRG developed a sensitive measuring system and a ‘track and trace’ device to characterize and track all waste streams and store associated information in a database (Fig. 49). The radioactive waste was declared with the central radioactive waste management organization in the Netherlands (COVRA) by using the fingerprint method and radiochemical analysis for confirmation. By the end of 2017, the LFR had been completely removed. In 2018, all radioactive waste was transferred to COVRA and the reactor hall was released for conventional demolition. In January 2019, the decommissioning licence was withdrawn.

IV.4.2.3. End state

The end state was greenfield. After completion of the decommissioning of the LFR and the conventional demolition of the reactor hall and free release measurements of the LFR premises, a sandy terrain remained. Marram grass was planted in the appropriate planting season. The final decommissioning report (demonstrating completed dismantling) was approved in January 2019, marking the completion of the decommissioning of the LFR.

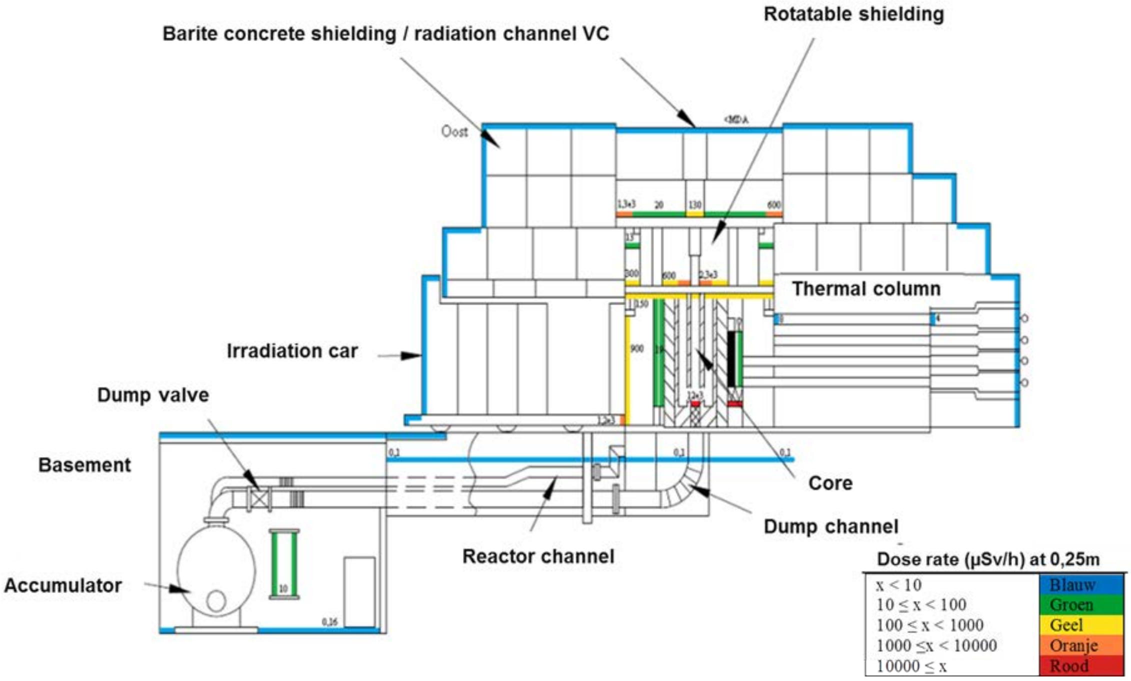


FIG. 48. Dose rate map of reactor parts. (Reproduced courtesy of NRG.)

FIG. 49. Digital track and trace system of all disposed components and materials, using a tablet device for entering data and photographs into the database. (Reproduced courtesy of NRG.)

IV.4.3. Characterization and waste management experience

Characterization work was essential in most steps of the decommissioning process. Following shutdown of the reactor in 2010, preparation for reactor decommissioning was ongoing for a period of about five years, including determination of the radiological inventory, preparation of the decommissioning licence, and establishment of working procedures. The actual decommissioning started in 2016 with the uncoupling of the main power supply. The reactor had been completely removed by the end of 2017. By 2018, all waste had been transferred to the national WMO and the reactor hall was released for conventional demolition, which was also completed in 2018, followed by the release of the facility site. The decommissioning project was formally completed on 30 January 2019, with the approval of the decommissioning report, demonstrating the completion of dismantling. The documentation and registration of disposed components and materials benefitted from NRG's digital track and trace system; during decommissioning, staff used a tablet device for entering data and photographs into a database.

IV.4.3.1. Waste packaging considerations

Before starting the decommissioning project, agreement must be reached about the various disposal routes, characterization methods and waste packages to be used. In the case of the LFR, this required discussion with stakeholders such as the supervising competent regulatory authority (ANVS), the radiochemical laboratory of operator NRG, the national WMO for radioactive wastes (COVRA) and other WMOs, e.g. those operating landfill sites.

For the disposal of larger components, including concrete blocks, for the LFR decommissioning project, Konrad type II containers were selected by NRG. For the national WMO, this was a new type of package. The agreement reached with the WMO should have been made in an earlier stage, which would have enabled a somewhat earlier delivery of these containers to the LFR premises.

If the waste packages are present at the decommissioning site at the required time, waste arising from decommissioning can swiftly leave the workplace to be put into the packages. In this way the workplace will be kept tidy and the worker dose contribution from the waste will be reduced. Such a procedure would also prevent the need to move material several times in the workplace due to decommissioning activities.

In the case of LFR decommissioning, the agreement about the packages (Konrad II containers) was reached during decommissioning, which resulted in temporary storage of materials and some moving of materials during the activities.

Economic considerations have an impact on the selection of types of waste packages (Fig. 50). For larger components, like concrete blocks, the blue 90 L drums were not an option. The yellow 400 L drums were cheaper per volume of waste than Konrad II containers. However, the rectangular form of the Konrad II container minimized the extent of cutting of components, which saved time and budget and thus also worker dose. Therefore, they were used extensively in the project.

A smaller quantity of concrete was eventually classified as radioactive waste than the amount estimated from the characterization carried out during decommissioning. At the beginning of the project, it was accepted by NRG that the estimation of the amount of activated concrete might be conservative and

Konrad type II container
for 3300 L of waste

400 L drum with insert
for 200 L of waste

Blue drum
for 90 L of waste

FIG. 50. Three types of waste packages used during decommissioning. (Reproduced courtesy of NRG.)

that it was not feasible to sample at all locations. Also, it was realized that the actual amount of activated concrete would not significantly reduce the costs of decommissioning and waste management, due the small size of the facility. Therefore, it was decided to apply a procedure for quickly classifying every block of concrete from the LFR during the decommissioning.

During preparations for the decommissioning of the LFR, the project team performed a conservative estimate of the waste inventory, based on available documentation, past assessments and new measurements. It was known that the inventory of concrete waste might be conservative. At the end of the project, it turned out that about 23 t of barite concrete were disposed of as radioactive waste against an estimate of about 42 t. Also, the amount of concrete in the foundation plate that had to be disposed of as radioactive waste (2.6 t) was less than estimated (5.9 t).

IV.4.3.2. Past estimates

In the past, MCNP calculations had been made, and for some very small parts of the installation (irradiation chambers) these calculations were updated as recently as 2013. However, it was decided not to rely on old data for the major part of the installation. Therefore, an effort started with bore cores, sampling and successive laboratory analysis, dose rate measurements, and smear/wipe tests for characterization and radiation protection purposes. It should be noted that the LFR during its operating life was not in a permanently critical state; it was only operating during experiments and for educational use during training. Neutron irradiation of materials, such as the internals and concrete, had been far from continuous and much less than with many other research reactors.

IV.4.3.3. Procedure for classifying waste during decommissioning

A dedicated measuring device was constructed to measure the activation in the barite concrete blocks, among others. Figure 51 shows this tool while loaded with one of the concrete blocks. The steel rack was equipped with sensitive gamma detectors to measure the degree of activation at each surface of the concrete blocks. The device is able to perform measurements over a wide range, from nano-Sv/h to Sv/h. The corresponding software to operate the tool was also developed by NRG.

The degree of activation measured with this tool served as a basis for categorizing the concrete blocks in three waste classes: radioactive waste, exempt waste and 'waste in doubt'. Waste in doubt could only be categorized after radiochemical analysis, which was done in the NRG laboratories. The majority of all blocks was declared as exempt waste after gamma spectrometry measurements and could be discharged as conventional construction/demolition waste. A few blocks were reused for various purposes at the Petten site. Exempt waste with a measurable surface activity was discharged to a landfill site.

FIG. 51. Measuring device for determination of activation in barite concrete shielding blocks. (Reproduced courtesy of NRG.)

FIG. 52. Shielded measurement setup. (Reproduced courtesy of NRG.)

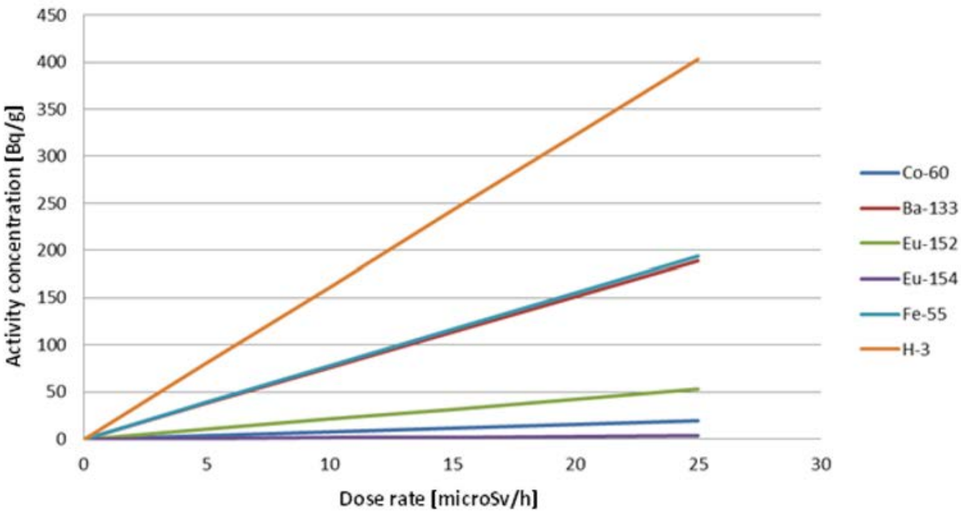


FIG. 53. Nuclide activity concentration of concrete as a function of the measured gamma dose rate. (Reproduced courtesy of NRG.)

Vacuum hoisting (a conventional tool) proved to be valuable to speed up the handling of the blocks during characterization. 'Clean' blocks were used as shielding of the measuring device (Fig. 52).

In the case of detection of activation of a concrete block, an additional radiochemical analysis of the concrete was performed. After taking samples from the blocks, destruction and chemical separation were performed at NRG's laboratory using a vacuum box system, followed by a radiological characterization using gamma spectrometry and liquid scintillation counting. The main radionuclides present in the concrete were found to be ^{3}H, ^{55}Fe, ^{60}Co, ^{133}Ba, ^{152}Eu and ^{154}Eu.

After analysis of the concrete samples for activation products by means of beta analysis, the resulting activities of key nuclides were compared with the results of non-intrusive gamma measurements. This resulted in a correlation between the average activity concentrations of the key nuclides in the concrete blocks and the gamma dose rate at the surface. The result is given in Fig. 53. This methodology determines the average nuclide concentrations in the concrete blocks by means of gamma dose rate measurements on the concrete surface only. In this case, ^{60}Co was taken as the reference nuclide.

The activated concrete blocks were mainly declared as LLW, implying that the blocks had to be transported in dedicated (Konrad) containers to the national WMO premises and stored there. The radiological characterization was also required for transfer to the national WMO. An important factor was the track and trace device (on a tablet) developed by NRG to characterize and track all waste streams, including pictures taken of the objects handled.

The extension of the LFR, which in the past was used to perform research on clinical BNCT, was dismantled and removed with characterization in a manner similar to the biological shield. No artificial radionuclides were found here.

IV.5. KRR-2 (REPUBLIC OF KOREA): LESSONS LEARNED

IV.5.1. Governmental budget management

Following a study initiated by the government, the project timeframe of three years was extended and the budget increased to US $19.7 million in two increments. These revisions were accompanied by the development of decommissioning related technologies.

IV.5.2. Planning

The first nuclear decommissioning project in the Republic of Korea was successfully completed for the Korea Research Reactor-2 (KRR-2). However, evaluation of the completed project revealed that there are some improvements that could be implemented in future projects. For instance, more detailed decommissioning planning is necessary; short preparation time and lack of experience created challenges, and there was not enough preparation and evaluation of the following engineering system infrastructure:

- Detailed facility characteristics analysis and coding;
- Decommissioning cost evaluation criteria and methodology;
- Establishment and evaluation of working process procedures;
- Establishment of the technical standards;
- Establishment of the equipment procurement plan;
- Plan for cost execution;
- Proper staff placement/input and management of equipment and materials, etc.

As a result, the optimal decommissioning process could not be delivered, leading to delays. In addition, the preparation of the system for comparative evaluation of the process plan established at the time of the decommissioning design and the actual execution performance was weak, and the decommissioning project could not be prepared in advance. After project completion, the results of the decommissioning project should be assessed and documented, to prepare the groundwork for future decommissioning of other nuclear facilities.

IV.5.3. Evaluation of inventory

An important factor to be considered in the decommissioning of nuclear facilities are the characterization surveys undertaken by domestic and international experts. This is because the surveys are an essential element in planning, decommissioning, waste management and remediation. As a result of the experience with the KRR-2 decommissioning project, it was concluded that if the characterization survey and preparations were carried out in advance, the trial and error would have been reduced. This issue, and the repetitive work, added staff effort, and the waiting time was long, lengthening the entire decommissioning period. In this study, it was decided to select the decommissioning methods, as well as the decommissioning schedule and cost, to establish an efficient decommissioning plan in preparation for the decommissioning of the water tank concrete of KRR-2. An accurate characterization survey of the radioactive concrete was an important prerequisite. For this purpose, samples were collected from the surface and depth of the water tank concrete and the results analysed. Based on the evaluation results, the wastes from decommissioning were divided into radioactive and non-radioactive, allowing the potential quantities of radioactive waste to be significantly reduced. Due to the decommissioning project schedule at the time, a characterization survey was not performed for many hours. The staff effort and time spent on the characterization resulted in a significant reduction in the quantity of radioactive waste, of the order of 50%, as a result of the separation step. Undertaking the detailed characterization survey during the preparation stage would help to reduce the time and staff effort required for decommissioning, together with reducing the overall quantities of radioactive waste.

IV.5.4. Other

Several challenges were encountered while carrying out decommissioning projects in the Republic of Korea:

- Prior cost estimation did not adequately reflect project uncertainties.
- The decision making process did not sufficiently take into account the views of the surrounding residents and local governments.
- Changes were made to the radioactive waste classification criteria during the course of decommissioning of KRR-2.
- Taking account of R&D results obtained over the course of the project, including performance and safety implications, was difficult.
- The project was initiated with no knowledge of decommissioning technology, experience and understanding.

Appendix V

QUESTIONNAIRE FROM DACCORD PROJECT PHASE 2 — RADIOLOGICAL CHARACTERIZATION

The questionnaire requesting information on participating research reactors is reproduced below.[17] A summary of the collected data is provided in Annex VIII to this publication.[18]

[17] The material in the Appendix has not been edited by the editorial staff of the IAEA.
[18] Available on the publication's individual web page at www.iaea.org/publications

1 GENERAL INFORMATION

Provide, if available in English the following existing documentation:

- Decommissioning plan ☐
- Characterization plan ☐
- Waste management plan ☐
- Facility material inventory database ☐
- Facility radiological inventory database ☐
- Decommissioning cost estimation ☐
- Final decommissioning report ☐
- Partial characterization/survey reports ☐
- Any other relevant document ☐

If the above listed documents are not available, please fill in the following questions and provide associated data:

1.1 TYPE OF THE RESEARCH REACTOR:

OPEN POOL	☐	TRIGA	☐	SLOWPOKE	☐	POOL IN TANK	☐
WWR POOL-IN-TANK	☐	GRAPHITE	☐	FAST	☐	HEAVY WATER	☐
HOMOGENEOUS LIQUID	☐	OTHER:	☐				

- If other, please specify:

1.2 POWER OF THE REACTOR (MW):

1.3 CURRENT REACTOR STATUS:

Licensing/ construction	☐	Operation	☐	Extended shutdown	☐	Transition phase	☐
Ongoing dismantling/ remediation	☐	Site release	☐	Decommissioning is completed	☐		

1.4 CONTAMINATION INCIDENT/LEAKAGE RECORDED DURING OPERATION:

Yes ☐ No ☐

2 DECOMMISSIONING STRATEGY

2.1 STRATEGY:

Immediate dismantling	☐	Deferred dismantling	☐	Other (e.g. entombment)	☐	Not decided yet	☐

End state:

Unrestricted release of the site (greenfield): ☐ Demolition of buildings: Yes ☐ No ☐

Restricted release of the site (brownfield): ☐ Demolition of buildings: Yes ☐ No ☐

2.2 DECOMMISSIONING PLAN:

Preliminary decommissioning plan elaborated: Yes ☐ No ☐
If yes, please provide the plan

Final decommissioning plan elaborated: Yes ☐ No ☐
If yes, please provide the plan

Provide relevant CERREX data if available (ISDC 01.0100)

3 INVENTORY

Complete estimated or calculated and measured inventory data

ESTIMATED INVENTORY DATA FOR CERREX-D2			EXPECTED WASTE PARTITIONING				
Example of main inventory items	Unit	Estimated Quantities	HLW (%)	ILW (%)	LLW (%)	VLLW (%)	EX (%)
Demineralizer Resin	[t]						
Tanks	[t]						
Piping and valves	[t]						
Heat exchanger	[t]						
Structural equipment (stairs, core bridge, covers)	[t]						
Neutron Beam Tubes and Port	[t]						
Ventilation (duct, fan, motor, stack, filter)	[t]						
Core Assemblies (Control rods, Grid Plate)	[t]						
Rotating Specimen Rack (RSR)	[t]						
Graphite elements and graphite reflectors	[t]						
Cables and Cable Trays	[t]						
Liquid water and sludge	[m^3]						
Pool liner, Reactor liner	[t]						
Decontamination Building Surface	[m^2]						
Monitoring Building Surface	[m^2]						
Masonry	[t]						
Bio-shielding concrete	[t]						
Additional inventory items needed							
Be components etc.							

INVENTORY DATA FOR CERREX D2 WITH RADIOLOGICAL PARAMETERS

ISDC No.	Inventory Category (**)	Example of main inventory items	Unit	Quantity	Expected WASTE Partitioning					Activity at final shut down (Bq)	Radionuclide Vector	Radiological parameter (*)		
					HLW (%)	ILW (%)	LLW (%)	VLLW (%)	EX (%)			E	C	M
02.0500	INV14	Demineralizer Resin	[t]											
04.0503	INV21	Tanks	[t]											
04.0503	INV20	Piping and valves	[t]											
04.0503	INV21	Heat exchanger	[t]											
04.0600	INV11	Structural equipment (stairs, core bridge, covers)	[t]											
04.0502	INV7	Neutron Beam Tubes and Port	[t]											
04.0600	INV23	Ventilation (duct, fan, motor, stack, filter)	[t]											
04.0501	INV6	Core Assemblies (Control rods, Grid Plate)	[t]											
04.0501	INV5	Rotating Specimen Rack (RSR)	[t]											
04.0502	INV9	Graphite elements and graphite reflectors	[t]											
04.0600	INV25	Cables and Cable Trays	[t]											
02.0500	INV14	Liquid water and sludge	[m^3]											
04.0502	INV22	Pool liner, Reactor liner	[t]											
04.0700	INV16	Decontamination Building Surface	[m^2]											
04.0900	INV18	Monitoring Building Surface	[m^2]											
07.0300	INV38	Masonry	[t]											
04.0506	INV8	Bio-shielding concrete	[t]											
		Additional inventory items needed...												

(*) Select source of information: E - Estimated, C - Calculated, M- Measured. Once you have filled radiological parameter, there is no need to fill in expected waste partitioning
(**) Acronym from CERREX List

4 RADIOLOGICAL CHARACTERIZATION PROCEDURES & TECHNOLOGY

4.1 GENERAL APPROACH TO RADIOLOGICAL CHARACTERIZATION (CHOOSE MORE THAN ONE IF THIS IS THE CASE):

Based on the results of similar reactors ☐ Based on the facility history & records ☐

Radiological characterization was performed ☐

4.2 IN CASE OF RADIOLOGICAL CHARACTERIZATION, THE PLAN WAS BASED ON (CHOOSE MORE THAN ONE IF THIS IS THE CASE). PLEASE PROVIDE RELEVANT DOCUMENTS:

Statistical models: MARSAME ☐ MARSSIM ☐ Geostatistical approach ☐

Sampling and measurement plan: ☐

Surface characterization: ☐ Volumetric characterization: ☐

4.3 THE RADIOLOGICAL CHARACTERIZATION CONCERNS:

All reactor technology systems, structures and components (SSCs) ☐

All building structures ☐

Surrounding areas ☐

Specific reactor SSCs ☐ Please, specify which SSCs:

Specific building structures ☐ Please, specify which building structures:

4.4 ACTIVATION CALCULATIONS PERFORMED:

Yes ☐ No ☐

4.5 RADIOLOGICAL CHARACTERIZATION MEASUREMENTS:

Dose rate measurements ☐ In-situ gamma spectrometry ☐ Direct contamination measurements ☐

Inspected surface in the controlled area % :

4.6 RADIOLOGICAL CHARACTERIZATION SAMPLING:

Smear samples ☐ Scratch samples ☐ Core samples ☐ Grab samples ☐

4.7 RADIOLOGICAL CHARACTERIZATION SAMPLING ANALYSIS:

Gamma spectrometry and use of scaling factors ☐ Radiochemical analysis ☐

4.8 ARE THE MEASUREMENTS OR SAMPLING COMPARABLE (SAME ORDER OF MAGNITUDE) WITH CALCULATIONS?

Yes ☐ No ☐

Appendix VI

SUPPLEMENTAL INFORMATION FORM

The form requesting supplementary information on participating research reactors is reproduced below. A summary of the collected data is provided in Annex VIII to this publication[19].

SUMMARY INFORMATION ON RESEARCH REACTOR CHARACTERIZATION

DACCORD Project Phase 2 – WG2 Radiological Characterization

Please, summarize an information on characterization current status if the relevant report is not available in English, French or Russian language. Provide us with data available.

(1) Country:
(2) Reactor name:
(3) Activation calculation performed:
  - Calculation code use
  - Scope of calculation
  - Reactor components included within the calculation
  - Radiological analysis made on core samples from reactor components used for the calculation
  - Data taken over from other similar reactors

(4) Surface characterization performed:
  - Methods applied (smears, in situ gamma spectrometry, direct contamination) per system or component
  - Scope of characterization (systems, components) and corresponding number of samples/measurements per given system or component
  - Building surface characterization scope, number of samples/measurements/historical assessment

(5) Volumetric characterization performed:
  - Methods applied (core drills, grab samples, in situ gamma spectrometry contamination)
  - Scope of characterization (systems, components) and corresponding number of samples per given system or component

(6) Facility site characterization out of the controlled area performed:
  - Contaminated underground pipes and structures
  - Contaminated surface soils and other contaminated items
  - Underground water monitoring
  - Geological subsurface undergrounds (bedrocks, soils...)

[19] Available on the publication's individual web page at www.iaea.org/publications

Appendix VII

TRIGA INVENTORY AND WASTE PARTITIONING

The quantities of typical inventory items and waste partitioning results for the individual TRIGA reactors studied in DACCORD Phase 2 are given in Figs 54–71.

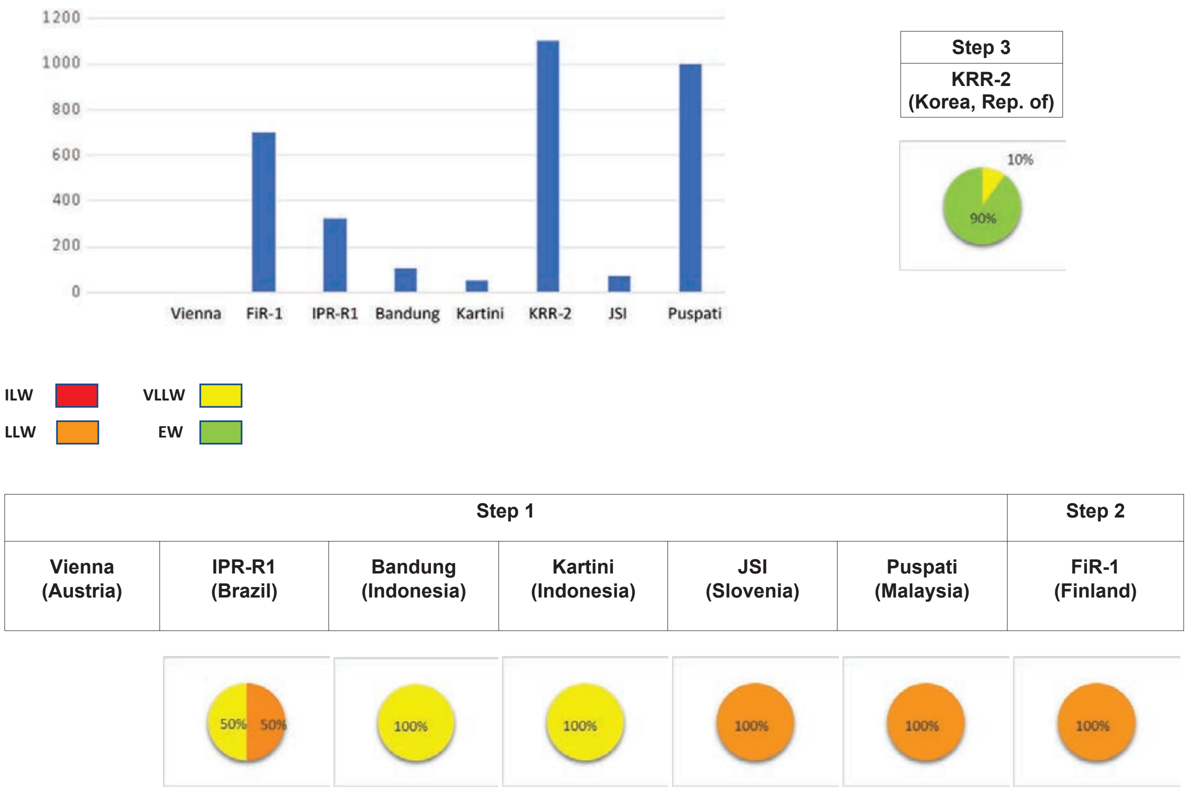


FIG. 54. Demineralizer resin (ISDC 02.0500).

FIG. 55. Tanks (ISDC 04.0503).

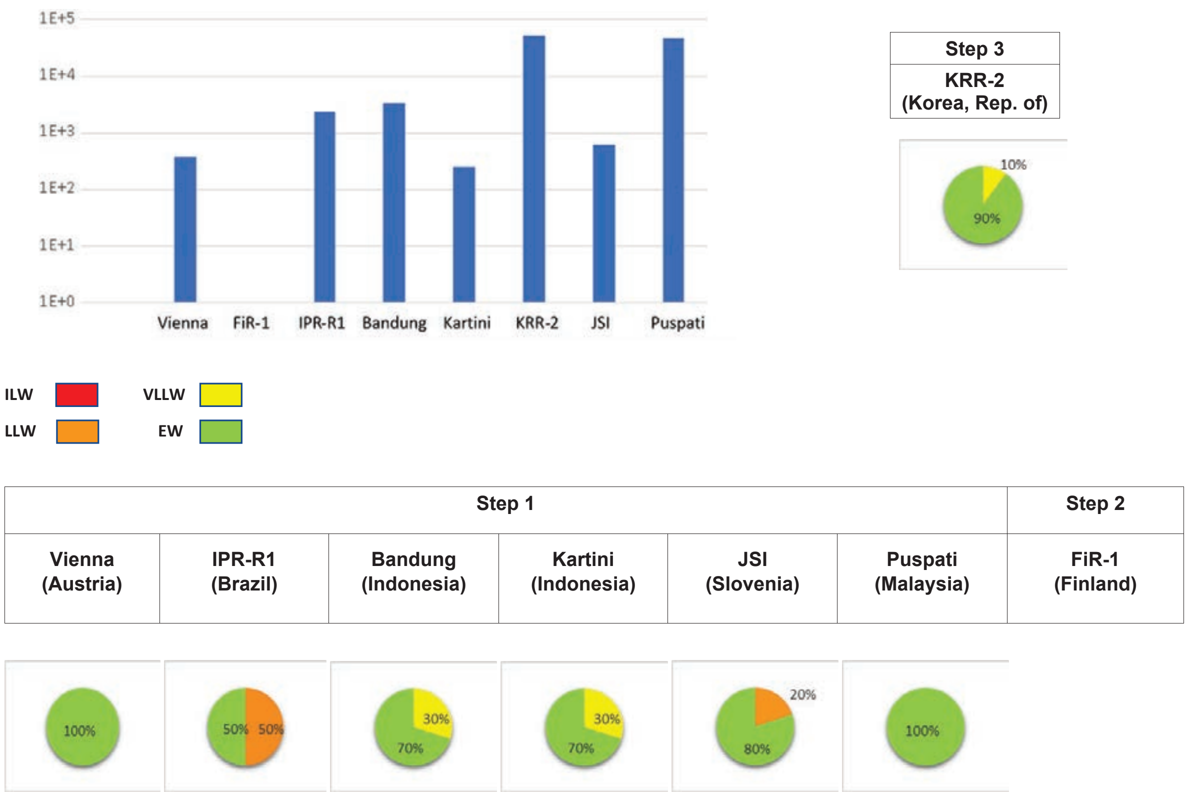


FIG. 56. Piping and valves (ISDC 04.0503).

FIG. 57. Heat exchangers (ISDC 04.0503).

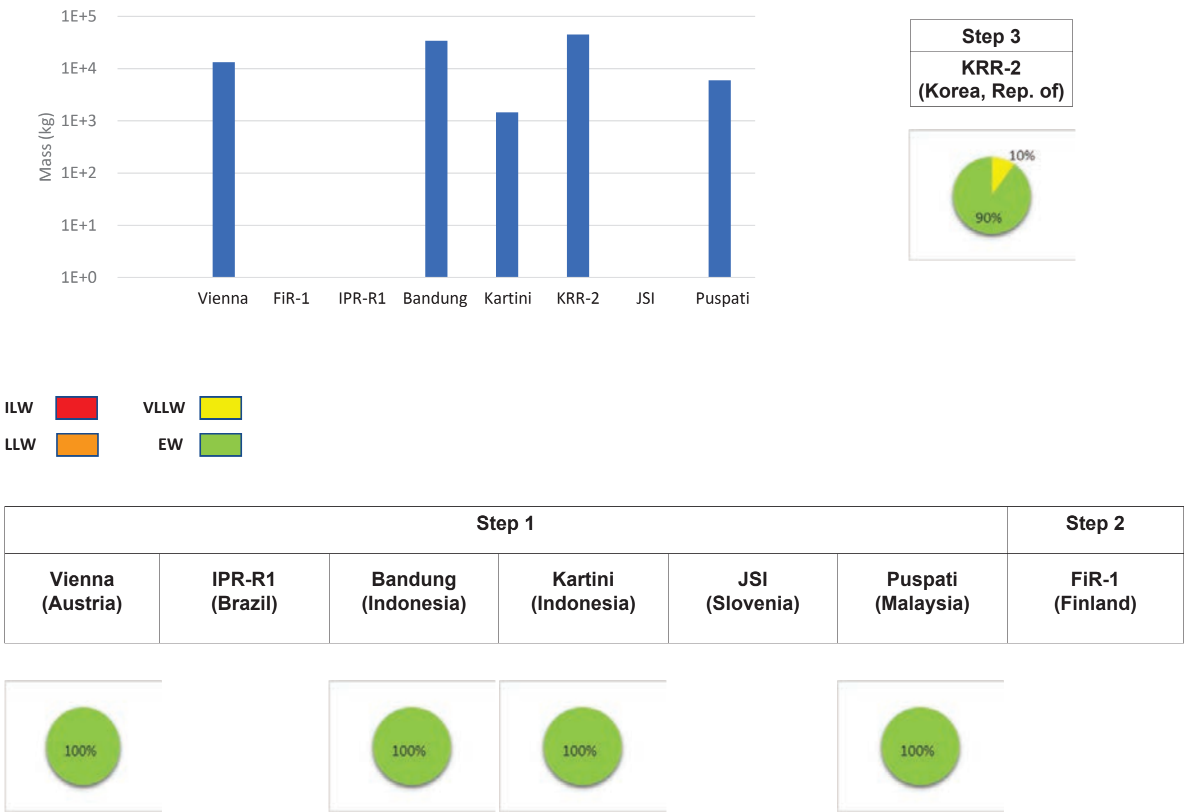
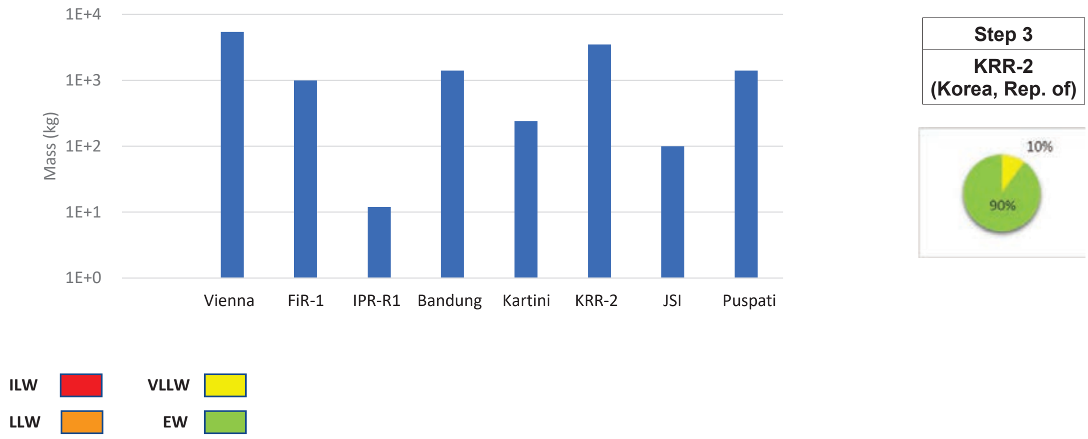


FIG. 58. Structural equipment (stairs, core bridge, covers) (ISDC 04.0600).



Step 1						Step 2
Vienna (Austria)	IPR-R1 (Brazil)	Bandung (Indonesia)	Kartini (Indonesia)	JSI (Slovenia)	Puspati (Malaysia)	FiR-1 (Finland)

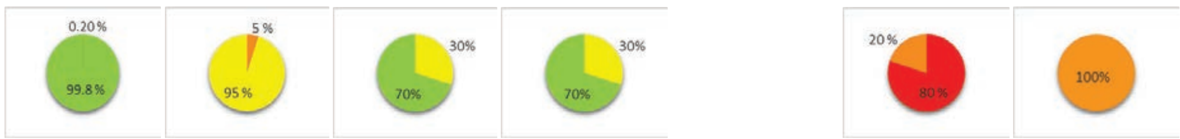
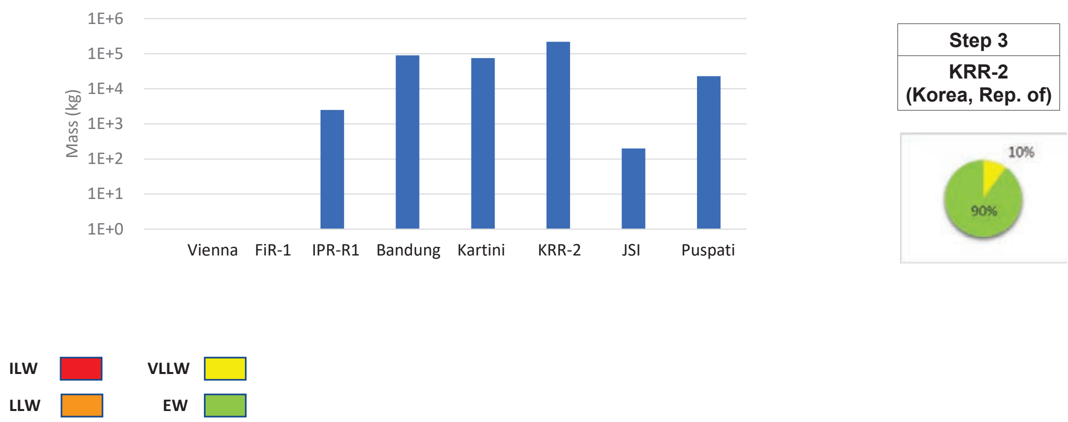


FIG. 59. Neutron beam tubes and port (ISDC 04.0502).



Step 1						Step 2
Vienna (Austria)	IPR-R1 (Brazil)	Bandung (Indonesia)	Kartini (Indonesia)	JSI (Slovenia)	Puspati (Malaysia)	FiR-1 (Finland)

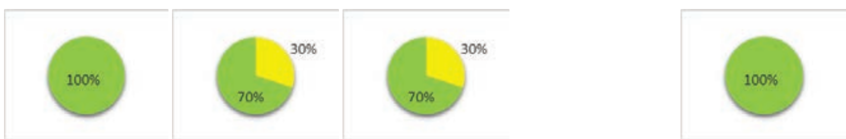


FIG. 60. Ventilation (duct, fan, motor, stack, filter) (ISDC 04.0600).

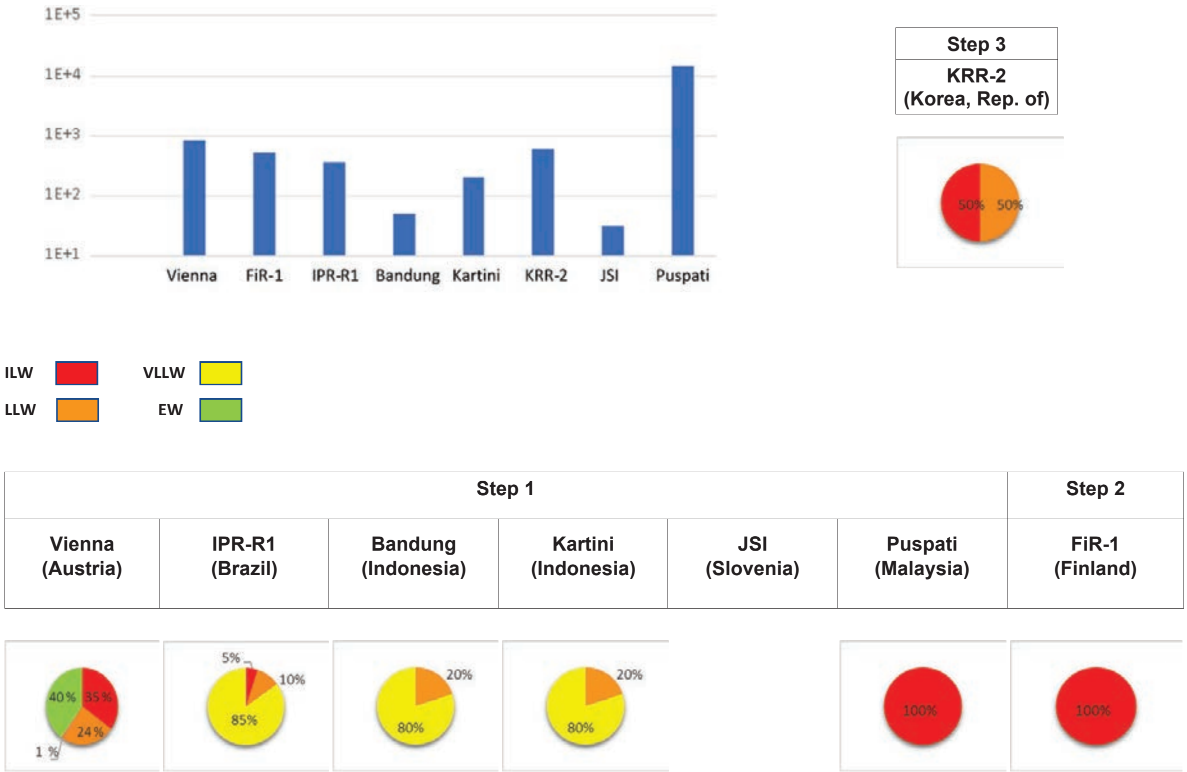
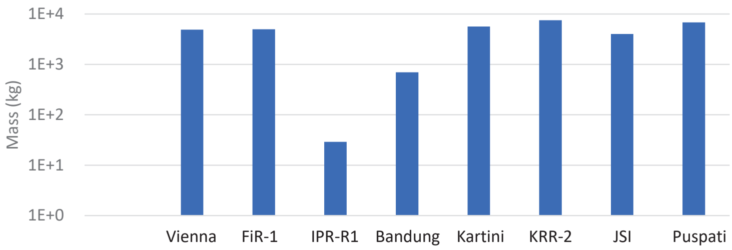
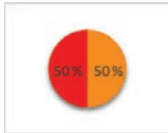


FIG. 61. Core assemblies (control rods, grid plate) (ISDC 04.0501).

FIG. 62. Rotating specimen rack (ISDC 04.0501).



Step 3
KRR-2 (Korea, Rep. of)



Step 1						Step 2
Vienna (Austria)	IPR-R1 (Brazil)	Bandung (Indonesia)	Kartini (Indonesia)	JSI (Slovenia)	Puspati (Malaysia)	FiR-1 (Finland)

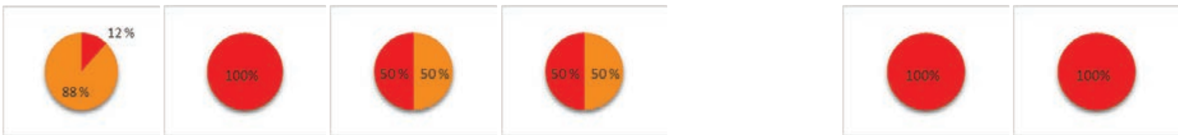
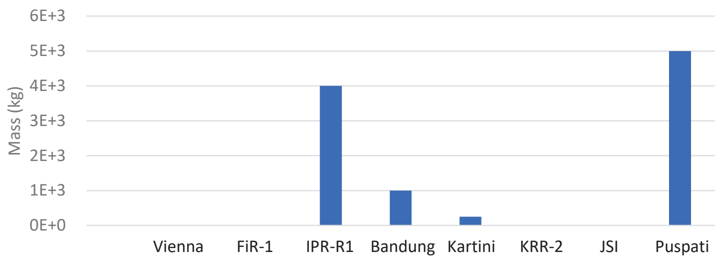


FIG. 63. Graphite elements and graphite reflectors (ISDC 04.0502).



Step 1						Step 2
Vienna (Austria)	IPR-R1 (Brazil)	Bandung (Indonesia)	Kartini (Indonesia)	JSI (Slovenia)	Puspati (Malaysia)	FiR-1 (Finland)

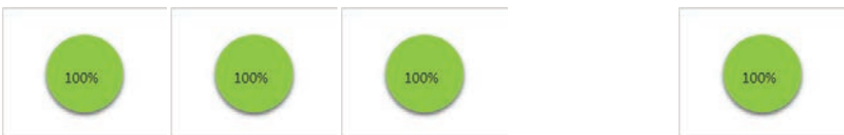
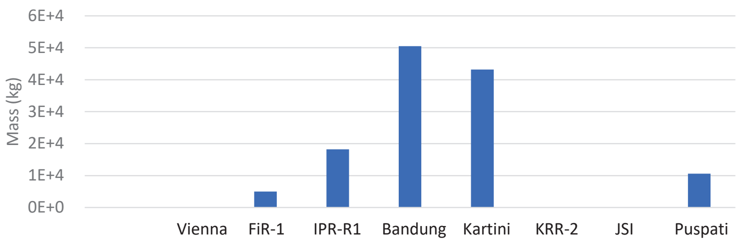
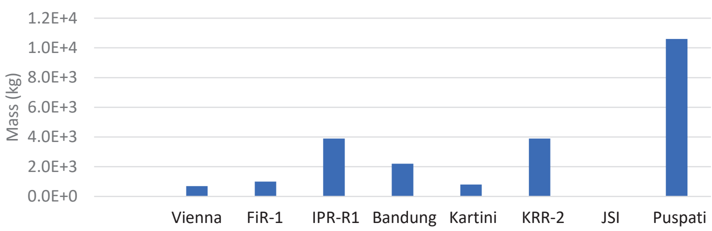


FIG. 64. Cables and cable trays (ISDC 04.0600).

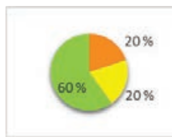


Step 1						Step 2
Vienna (Austria)	IPR-R1 (Brazil)	Bandung (Indonesia)	Kartini (Indonesia)	JSI (Slovenia)	Puspati (Malaysia)	FiR-1 (Finland)

FIG. 65. *Liquid water and sludge (ISDC 02.0500).*



Step 3
KRR-2 (Korea, Rep. of)



Step 1						Step 2
Vienna (Austria)	IPR-R1 (Brazil)	Bandung (Indonesia)	Kartini (Indonesia)	JSI (Slovenia)	Puspati (Malaysia)	FiR-1 (Finland)

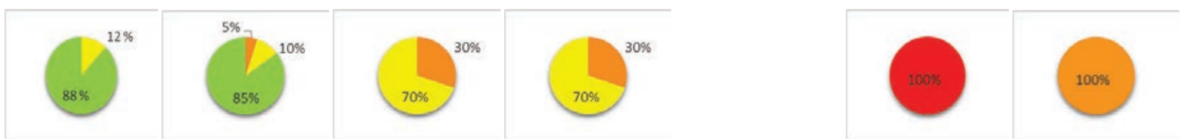


FIG. 66. *Pool liner, reactor liner (ISDC 04.0502).*

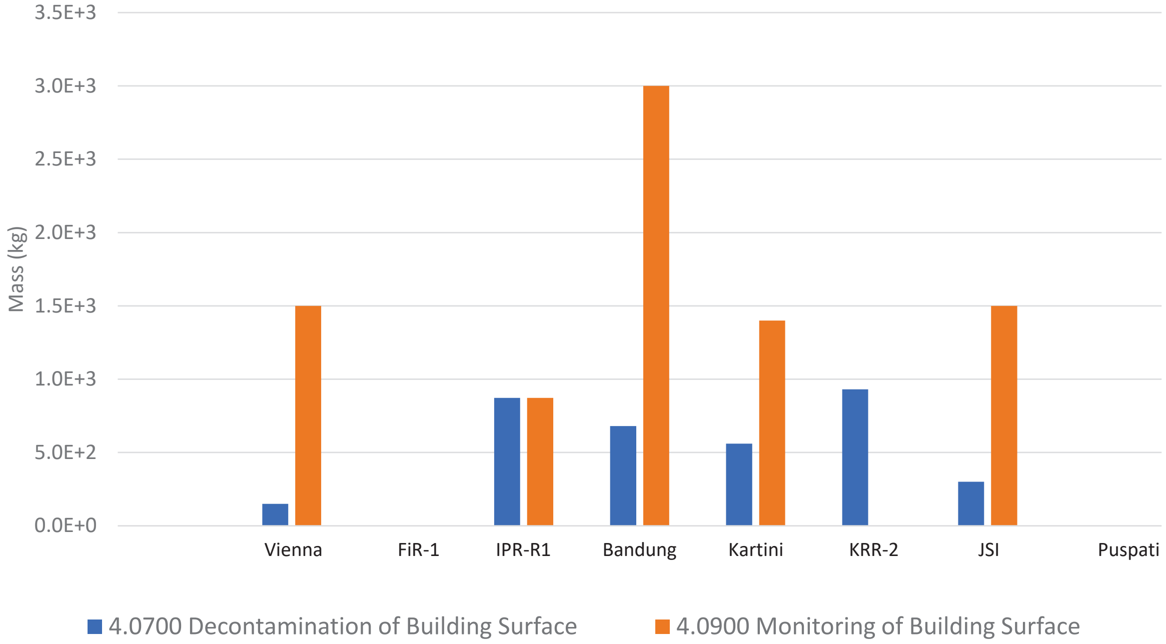


FIG. 67. Decontamination of building surface (m^2) (ISDC 04.0700); monitoring of building surfaces (m^2) (ISDC 04.0900).

FIG. 68. Masonry (ISDC 07.0300).

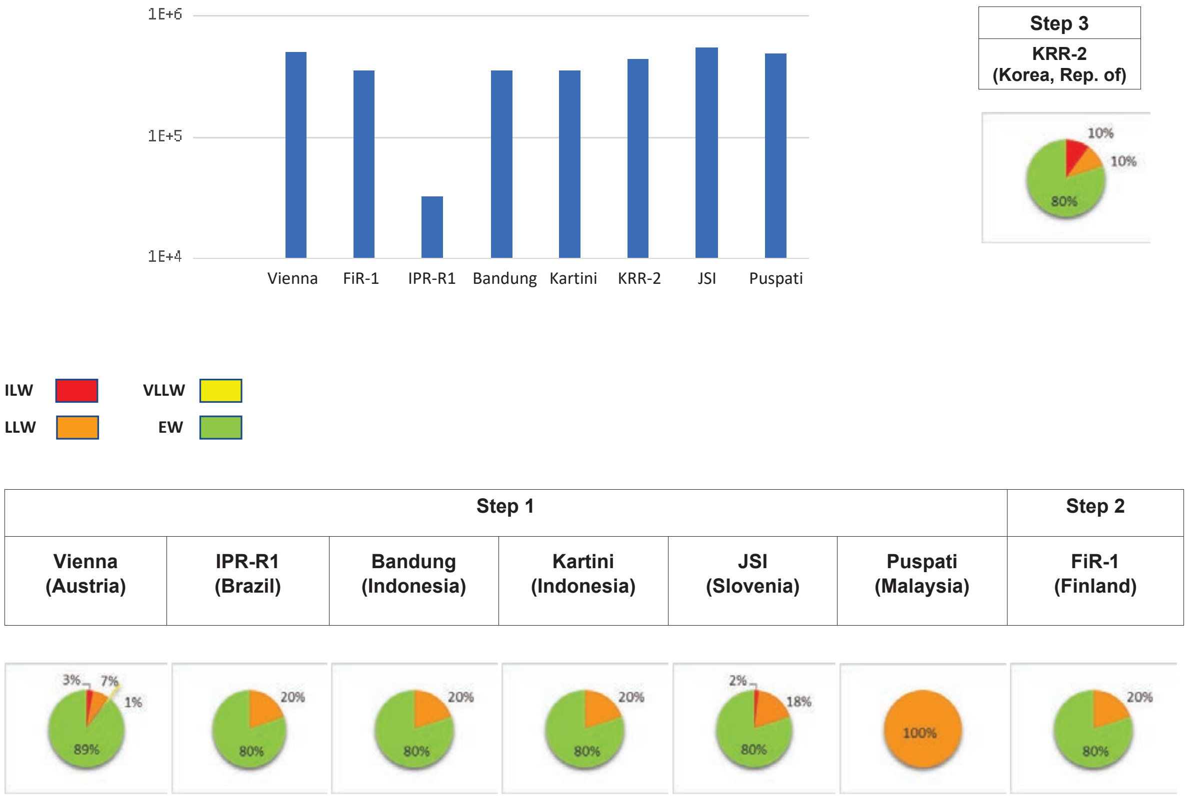


FIG. 69. Bioshielding concrete (ISDC 04.0506).

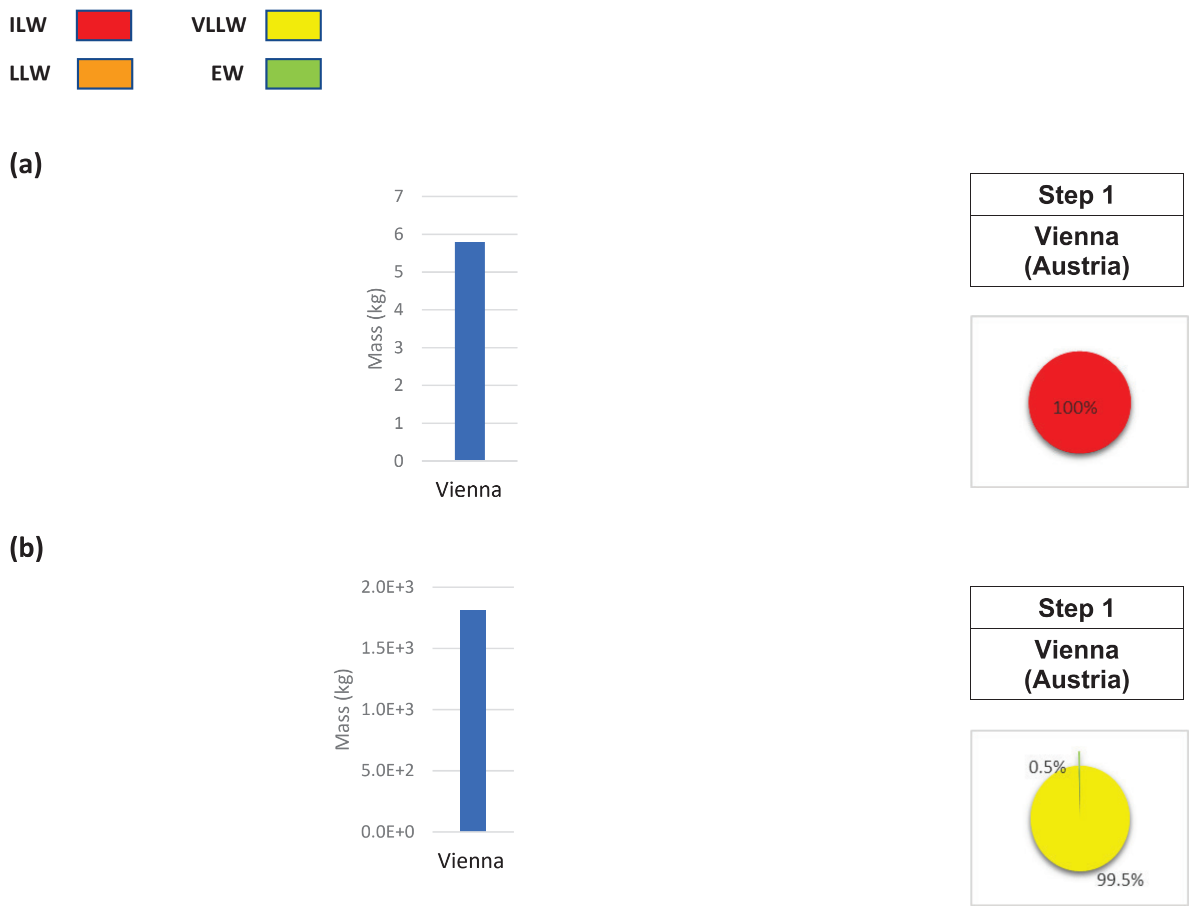


FIG. 70. (a) Reactor internals — steel parts (ISDC 04.0502); (b) fuel storage parts (ISDC 04.0502).

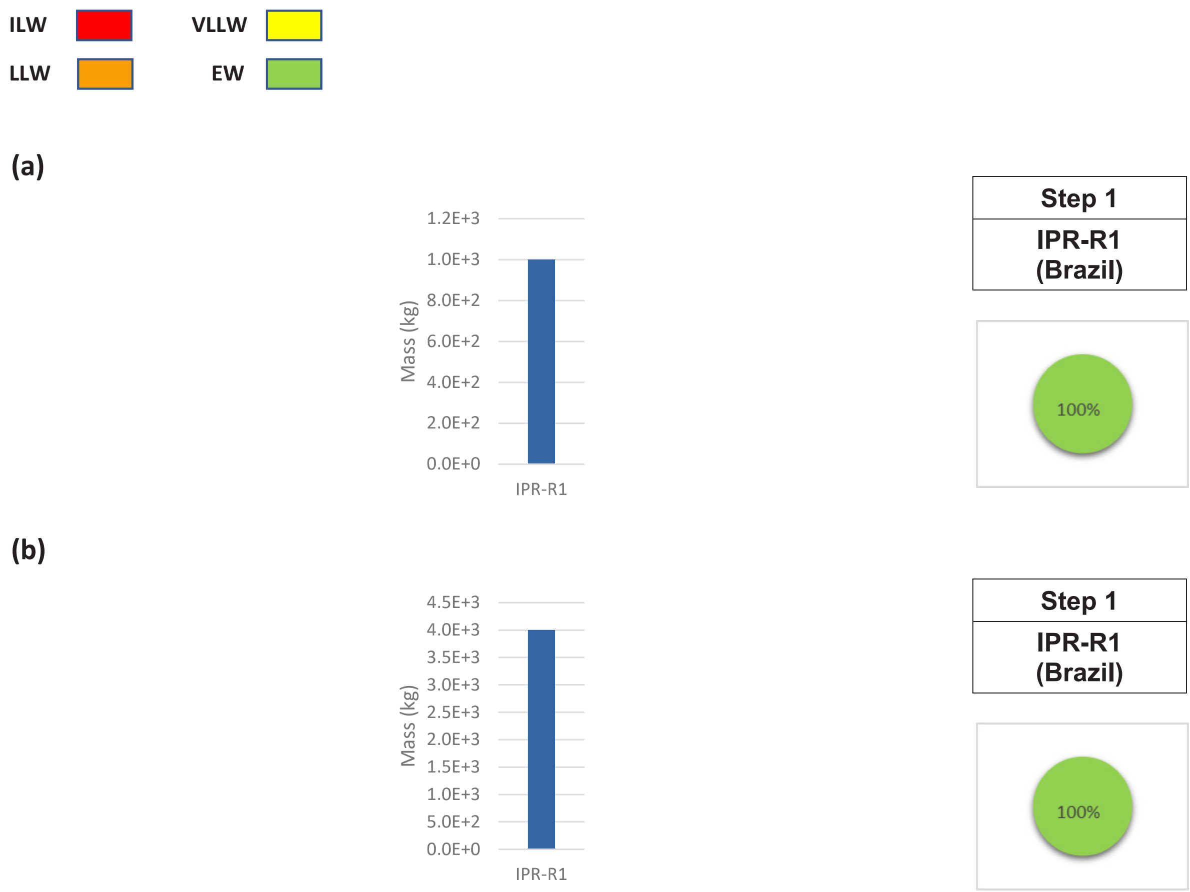


FIG. 71. (a) Cooling tower (ISDC 07.0302); (b) lead shielding bricks and plates (ISDC 02.0501).

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ANNEXES

The following annexes are available as supplementary files on the publication's individual web page.[1]

Annex I	User Manual for CERREX-D2 Computational Code
Annex II	Graphical Representation of Unit Factors for Research Reactor Decommissioning
Annex III	User Defined Unit Factor Calculation: Bandung TRIGA 2000 Research Reactor
Annex IV	Illustrative Costing Case for TRIGA Mark I/Mark II Reactors
Annex V	Illustrative Costing Case for TRIGA Mark III Reactor
Annex VI	Summary Data for DACCORD Phase 2 Costing Cases
Annex VII	Jožef Stefan Institute TRIGA Mark II Costing Case
Annex VIII	Radiological Characterization: Summary Data from Questionnaire and Supplemental Form

[1] www.iaea.org/publications

ABBREVIATIONS

ADIN	advanced inventory database
AVW LR	average worker labour rate
BNCT	boron neutron capture therapy
CC or PCC	Pearson correlation coefficient
CDF	cumulative distribution function
CERREX	Cost Estimation for Research Reactors In Excel
DACCORD	data analysis and collection for costing of research reactor decommissioning
DR	Danish research reactor
EW	exempt waste
FDP	final decommissioning plan
FiR	Finnish research reactor
GRR	Greek research reactor
HIFAR	high flux Australian reactor
HWR	heavy water moderated research reactor (China)
ILW	intermediate level waste
IQR	interquartile range
ISDC	International Structure for Decommissioning Costing of Nuclear Facilities
JEN-1	'Juan Vigón' Nuclear Research Centre JEN-1 experimental Spanish reactor
JSI	Jožef Stefan Institute (Slovenia)
KRR	Korean research reactor
kW(th)	kilowatt (thermal)
LFR	Low Flux Reactor (Netherlands)
LLW	low level waste
MARSAME	multi-agency radiation survey and assessment of materials and equipment manual
MARSSIM	multi-agency radiation survey and site investigation manual
MC	Monte Carlo
MCNP	Monte Carlo N-particle Transport (software code)
MW(th)	megawatt (thermal)
OFAT	one factor at a time
PDF	probability density function
PDP	preliminary decommissioning plan
PRR	Philippines research reactor
TPE	three point estimate
TRIGA	training, research, isotopes, General Atomics
UF	unit factor
UF D&D	unit factor — decommissioning
UF WM	unit factor — waste management
VLLW	very low level waste
VTT	VTT Technical Research Centre of Finland
WDF	work difficulty factor
WG	working group
WM	waste management
WMO	waste management organization
WP	work package
WWR	water cooled and moderated reactor

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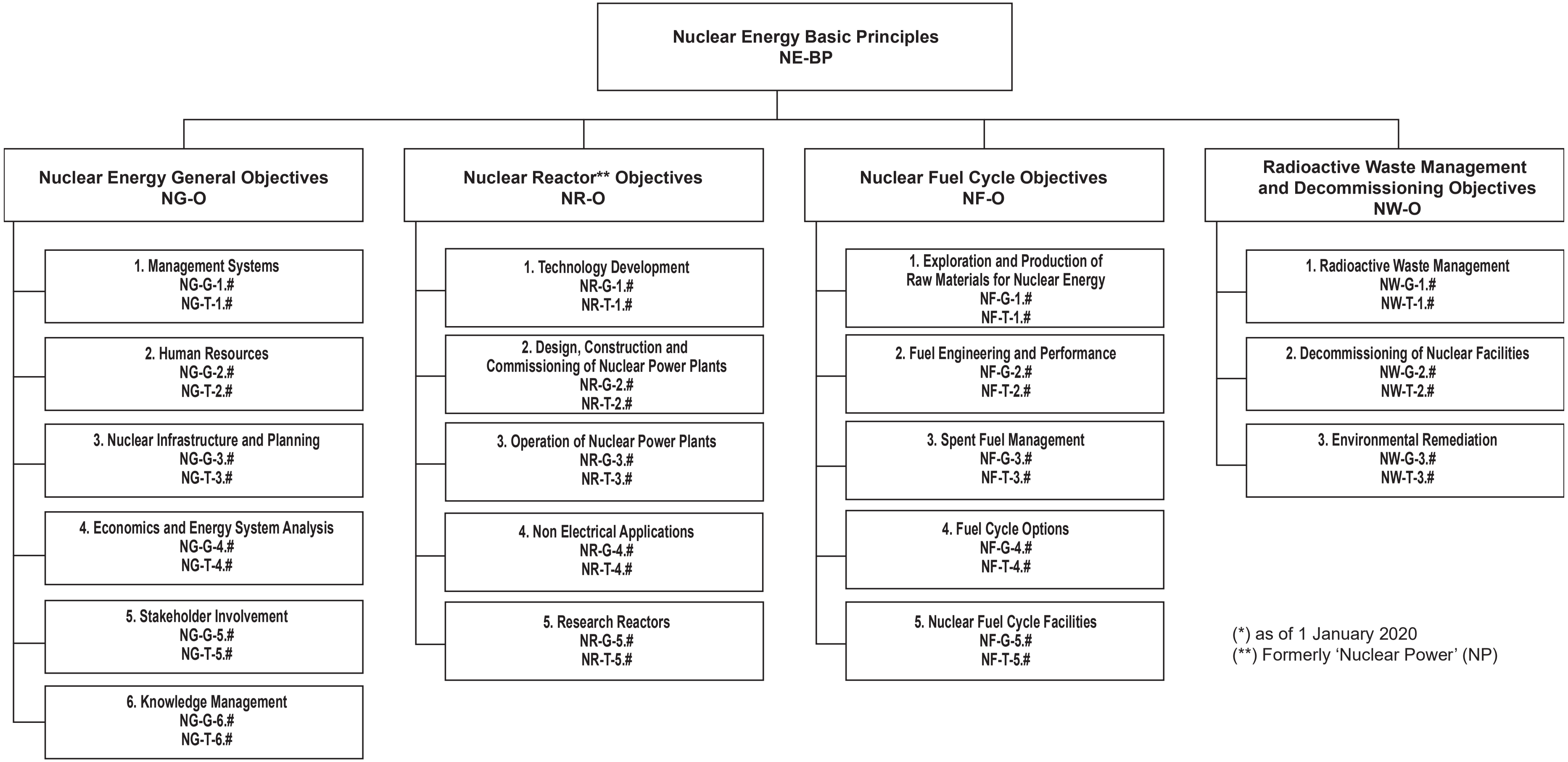

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