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Data Analysis and Collection for Costing of Research Reactor Decommissioning

Report of the DACCORD Collaborative Project

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DATA ANALYSIS AND COLLECTION FOR COSTING OF RESEARCH REACTOR DECOMMISSIONING

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REPORT OF THE DACCORD COLLABORATIVE PROJECT

INTERNATIONAL ATOMIC ENERGY AGENCY
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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
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For further information on this publication, please contact:

Waste Technology Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

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FOREWORD

In 2007, the IAEA established the International Decommissioning Network (IDN) to enhance the sharing of knowledge and experience among Member States. Supporting greater cooperation and coordination improves Member State capability to develop decommissioning plans and to undertake decommissioning activities. The 2011 annual meeting of the IDN noted the lack of detailed published data on the cost of decommissioning research reactors and other small nuclear facilities. Although there are currently several hundred such facilities that are permanently shut down and are either in a preparatory phase for decommissioning or in an active dismantling phase, the limited data available tend to provide overall costs only, without any breakdown of the main elements. A collaborative project for collecting and analysing decommissioning costs for research reactors was proposed to address this deficiency.

Launched in 2012, the Data Analysis and Collection for Costing of Research Reactor Decommissioning (DACCORD) project provides representative input and benchmarking data required for the costing of research reactor decommissioning at preliminary planning stages. These data are important for plant managers and policy makers involved in decisions on how to proceed with decommissioning. The final cost for decommissioning can vary considerably on account of the large number of different types of research reactor, construction complexity, different planned end states, events during operation that affect decommissioning, and differing capabilities concerning spent fuel and radioactive waste management. Three main working groups undertook this work and addressed TRIGA research reactors, pool-in-tank research reactors and open pool research reactors.

The IAEA is grateful to K. Moshonas Cole (Canada) for chairing the coordinating working group. The IAEA officers responsible for this publication were P.J. O'Sullivan of the Division of Nuclear Fuel Cycle and Waste Technology and V. Ljubenov of the Division of Radiation, Transport and Waste Safety.

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1. INTRODUCTION

1.1. BACKGROUND

The DACCORD project (Data Analysis and Collection for Costing of Research Reactor Decommissioning) was launched in 2012 to address a need to support Member States with the development of preliminary cost estimates for research reactor decommissioning. The project sought to address this challenge by identifying benchmarking data, developing reference cases, increasing overall experience, and sharing of knowledge among working group members.

The lack of published data has made it very difficult to benchmark estimated costs against international practice. This lack of information hampers: (1) the activities of organizations responsible for the development of decommissioning plans, and (2) governmental authorities and other bodies that are responsible for reviewing cost estimates. In the case of research reactors, the limited data that are available tend to provide overall costs only, without any breakdown of the main cost elements. The DACCORD project was undertaken to address this deficiency.

In recent years, the IAEA has undertaken, unilaterally or in partnership with other international organizations, a number of initiatives aimed at improving the comparability of decommissioning cost estimates [1-3]. In particular, a revised standardized structure for the presentation of estimates, the “International Structure for Decommissioning Costing” (ISDC) [4], was developed in 2012 in collaboration with the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) and the European Commission (EC). Consistent use of the ISDC facilitates direct comparison of detailed cost elements. Taking account of the ISDC, the IAEA subsequently developed in 2013 a software tool, CERREX (Cost Estimation for Research Reactors in Excel) to be used for estimating costs for research reactor decommissioning [1, 3]. This software code is suitable for use on a wide range of facilities and structures the resulting cost estimate according to ISDC formats. It was intended as a tool that would not require significant training or cost estimating experience; however, feedback indicated that significant support was required to enable its effective use.

To improve the accessibility of CERREX, the DACCORD project initiated a process of input and output data collection and analysis. The expectation was to develop and make available a number of reference cases and to provide insights to enhance the use of CERREX. The results were used to increase accessibility and usability of CERREX by individuals with limited experience of decommissioning cost estimating. Furthermore, the collection of data and experience has supported improvement of the CERREX methodology and information structure.

All detailed cost cases considered in the DACCORD project are presented as CERREX-D files (CERREX Version D, 2015, enhanced to support the objectives of the DACCORD project) to ensure uniformity of the presented data and generally to facilitate the analysis of the available information.

1.2. OBJECTIVES

The main objective of the DACCORD project is to assist Member States in preparing preliminary cost estimates for the decommissioning of their research reactors. This objective is realized by collecting, selecting and analysing data from a range of completed and ongoing decommissioning projects, to build up representative information and data to inform users of CERREX and to establish benchmarks. The objective is to enable Member States with little or no decommissioning expertise to estimate the overall cost of decommissioning during the early planning stages by facilitating the preparation of preliminary cost estimates using CERREX.

An improved representative data was developed through the collection and analysis of available data given by participants with experience in decommissioning, costing and/or detailed knowledge of research reactor installations.

Due to the large number of different types of research reactors, their construction complexity, different planned end states, events during operation that may have an impact on decommissioning (e.g. leakages during operation), a potential lack of decommissioning background and experience, differing capabilities concerning waste management and spent fuel management, the costing cases may be very different for individual facilities.

1.3. SCOPE

The collection of input data and the development of reference cases during the project reflects the experience and interest of the working group participants and, as such, the DACCORD project focused on the open pool research reactors (including TRIGA-type reactors), and WWR pool-in-tank research reactors of Soviet-era design. Some data are presented for other reactors types in the annexes (Annex V), though these have generally not been the subject of detailed analysis.

Each research reactor decommissioning case reflects a country-specific legal and regulatory framework, country- and site-specific waste management infrastructure, a decommissioning strategy and end state, and country-specific unit costs of media, energy, services, tools and equipment and labour. Accordingly, and in light of significant diversity of research reactor applications in IAEA Member States, the results obtained in this project may only be regarded as indicative of the situation applying for any specific reactor.

1.4. TYPES OF RESEARCH REACTOR

Research reactor facilities are used for a variety of purposes, including training, radioisotope production, and irradiation of materials for research or safety purposes and industrial processing of material. Many universities and government institutes use these facilities for conducting basic research on material behaviour. There are many different types of reactors, and the range of power ratings varies from several watts up to hundreds of megawatts. The complexity varies from relatively simple constructions of critical assemblies to a complexity comparable with power reactors.

The typical period of operation of research reactors and critical assemblies is of the order of 40 years, with typical decommissioning times of 3-5 years for research reactors and about one year for critical assemblies. Some research reactors have been in operation for 50 years or more.

The construction of research reactors varies widely. Relatively simple constructions of critical assemblies may be located within a large laboratory room. Medium size research reactors have a compact construction (mostly embedded in a concrete monolithic structure) located within a single building with a reactor hall and some additional rooms for auxiliary systems. The research reactors at the highest power range have construction features similar to power reactors: a reactor building with a reactor hall, many additional cells for primary, secondary and auxiliary systems and several additional buildings including ones for treatment of operational wastes. Different methods can 0be used to classify research reactors, e.g. power level, utilization and the type of moderator used.

Research reactors may be classified according to the following main types: Open pool reactors, of which TRIGA (Training, Research, Isotopes, General Atomics, supplied by General Atomics, USA) and SLOWPOKE are specific types. Tank reactors including WWR pool-in-tank reactors (Water-Water Reactors of Soviet design). Argonaut (Argonne Nuclear Assembly for University Training) reactors. Homogeneous liquid reactors. Fast reactors. Graphite reactors and others, including critical assemblies and homogeneous solid reactors.

- **Open pool reactors** (including TRIGA and SLOWPOKE reactors) are characterized by a reactor core submerged in a pool of water that usually provides cooling, moderation and shielding. The reactor may also be equipped with a specific moderator or reflector (e.g. graphite or beryllium). The continuous rated power varies from 0 $W_{(th)}$ to over 10 $MW_{(th)}$. The core is either suspended from a bridge or supported from the floor of the pool. Activation of the pool floors and walls is usually low (although power dependent) as a result of the shielding effect of the water. The irradiation facilities of these reactors can include channels penetrating the walls of the pool, devices suspended from the top of the reactor pool or experimental rigs resting on the pool floor. Pool reactors utilize a wide variety of fuels, including metal plate, oxide and a homogeneous mix of partially enriched uranium in zirconium hydroxide, as in TRIGA reactors. Low powered reactors may rely on natural convection for cooling whilst those of higher power ratings generally have a forced convection for operational cooling. The tank of water may provide cooling in the event of loss of coolant flow and during routine shutdowns. The reactor pool is often significantly extended beyond the core region requirements, and this pool area is used for storage of activated materials including spent fuel following its removal from the reactor core.
- **Tank reactors** (including WWR pool-in-tank reactors) have the core located within a closed tank, which is generally made of aluminium or steel. The tank is typically surrounded by the cylindrical structure of a graphite or water reflector, an iron or lead thermal shield and a concrete biological shield. Many of these reactors are in the power range of tens of megawatts. The cooling systems are mainly of the closed circuit type. The complexity of primary and auxiliary systems of reactors in the highest power ranges is similar to power reactors. The irradiation facilities of these reactors are channels penetrating the vertical and horizontal surrounding walls of the biological shield; these channels sometimes also penetrate the walls of the reactor tank. Such facilities are often connected to large and complex experimental equipment and test loops. The auxiliary systems of some tank reactors, e.g. heavy water reactors, may require special treatment and storage facilities for the heavy water and the need for an inert cover gas.

- **Argonaut reactors** are water-cooled, graphite moderated, thermal neutron, heterogeneous tank-type reactors. The core lattice consists of a cube of graphite containing rows of material testing reactor type fuel elements located in aluminium tanks containing cooling water. An internal graphite moderator has access holes for experimental purposes. The reactor is shielded by concrete, and has an integral water tank and graphite thermal column for use in a variety of experiments. Commercial versions were initially rated at 10 kW(th) and later upgraded to power levels of about 300 kW(th). Argonaut reactors are small research reactors intended primarily for teaching of reactor theory and nuclear physics. Argonauts are constructed in two configurations of biological shield, either fixed massive concrete shield or modular block shield. Usually the rabbit systems are used to insert samples into the reactor core to irradiation positions. Twenty-eight Argonaut reactors were constructed, three of which are still in operation and one is in final shutdown mode.
- **Homogeneous liquid reactors** are characterized by a homogeneous liquid mix of fuel and moderator (which also serves as a heat transfer medium) connected through a heat exchanger to an external coolant. Because of this, the fuel moves through the core and a piping system during operation; this may create a serious decontamination challenge during the decommissioning process. Usually, additional gas purification (with a recombiner) is installed which may be highly contaminated.
- **Fast reactors** are characterized by the lack of a moderator. The fuel is mainly plutonium oxide or uranium oxide. The only fluid passing through the core is the liquid metal coolant, which is generally sodium, sodium–potassium or mercury. These coolants, which have high reaction rates with water, may impose some difficulties for decommissioning. Less activation of the structural materials is expected relative to thermal reactors, owing to the lower percentage of thermal neutrons in the core.
- **Graphite reactors** incorporate graphite blocks to serve as the moderator, as well as being the major structural component of the reactor core. The fuel rods are inserted among or within the graphite blocks, and the coolant, if required, is generally gas (usually air or carbon dioxide), but may sometimes be water.

1.5. STRUCTURE OF THE REPORT

Section 1 (this section) presents the background, objectives, and scope of the DACCORD project.

Section 2 presents the method of working and the role of the CERREX-D code for the data collection.

Section 3 discusses and compares the actual or estimated costs, inventories and labour power utilization for the reactors considered in the project.

The fourth, fifth and sixth sections provide a detailed analysis of cost and associated cost drivers organized according to different types of research reactors (TRIGA open pool reactors, WWR pool-in-tank reactors, and other open pool reactors).

The final section (section 7) provides overall conclusions on the benchmarking of costs, workforce and inventory information, discusses lessons learned from the use of CERREX, and provides recommendations.

The report contains four appendices, which provides detailed information on the reactors analysed and on the results of the study. Appendix I provides an overview and analysis of unit factors and work difficulty factors; the remaining appendices provide detailed descriptions of the reactors studied: TRIGA (Appendix II); WWR-type (Appendix III) and Open Pool-type (Appendix IV).

Detailed cost-relevant data for the analysed cases are provided as annexes in a CD-ROM accompanying the main report, together with descriptions of some other reactors considered in outline during the study though these were not though these were not the subject of detailed analysis.

2. METHOD OF WORKING

2.1. OVERALL PROJECT APPROACH

This project was executed over the course of three years by a team of Member State representatives, the number of which varied from 20-30 at any time. Member States have participated through the provision of data or through direct participation in working meetings and on deliverables during the project. Project guidance and consistency was provided by the project's Coordinating Working Group (CWG) comprising of a chair, experts and the working group chairs.

The main work was undertaken by three working groups comprising representatives from different IAEA Member States and addressed the following issues. (1) TRIGA-type open pool reactors; (2) WWR pool-in-tank reactors and (3) other generic open-pool reactors (not including TRIGA types). Each working group undertook a cost estimate for several reactors of the relevant type, with some of the cases relating to projects that are already completed and with the remainder to projects that are at the planning stage, i.e. the reactors are still in operation or have been recently shut down.

The participants provided information to the extent possible used to develop a cost estimate in CERREX-D. This included, but was not limited to, inventory, labour cost, waste management approach. In some cases, actual decommissioning cost data was available. In all cases, a complete cost file using CERREX-D was prepared. For those cases where the decommissioning work had already been completed, unit factors were selected such that the calculated cost using CERREX-D corresponded to the actual cost, thus facilitating the calculation of the achieved unit factors relating to the project in question.

2.2. GENERAL METHODOLOGY FOR DECOMMISSIONING COST ESTIMATION

Decommissioning costing involves a number of discrete sequential activities:

2.2.1. Development of an inventory database

The inventory database has three main components: (i) inventory of systems, (ii) inventory of structures and (iii) radiological parameters. The systems and structures inventories normally locate the inventory item in the building structure: floor, room and equipment structure and provide parameters such as mass, surfaces, volumes, categories of systems and structures, and materials. The radiological parameters refer to contamination of inner and outer surfaces, activation of construction materials and dose rates (differentiated by radionuclide content).

2.2.2. Database of unit factors

This database provides unit factors for performing individual decommissioning activities, such as workforce unit factors, secondary waste production unit factors, consumable unit factors (e.g. electricity, gas and water), working group composition and associated parameters for particular tasks (e.g. skills, labour unit cost factors and exposure parameters).

2.2.3. Definition and selection of decommissioning options

Decommissioning options are based on existing or planned decommissioning infrastructure and the selected decommissioning strategy. The associated cost calculation should cover all relevant possibilities being considered: immediate or deferred decommissioning options and the envisaged end states, combined with various scenarios for waste treatment. Costs are calculated based on the decommissioning inventory database and the extent of decommissioning activities anticipated for each selected option.

2.2.4. Cost calculation for selected options

The basic elements needed to initiate a cost estimate include a well-developed decommissioning plan; a detailed material analysis; a description of the required working steps and a proposed time schedule. Different quality cost estimates are derived for decommissioning projects, based on the level of detail of this required input information [1]:

1. Order of magnitude estimate: One without detailed engineering data, where an estimate is prepared using scale-up or -down factors and approximate ratios. It is likely that the overall scope of the project has not been well defined. The level of accuracy expected is −30% to +50%.

2. Budgetary estimate: One based on the use of flowsheets, layouts and equipment details, where the scope has been defined, but the detailed engineering has not been performed. The level of accuracy expected is −15% to +30%.

3. Definitive estimate: One where the details of the project have been prepared and its scope and depth are well defined. Engineering data would include plot plans and elevations, piping and instrumentation diagrams, one-line electrical diagrams and structural drawings. The level of accuracy expected is −5% to +15%.

The management of unknowns remains a major challenge of all decommissioning projects. At the estimate stage, it is appropriate to include provisions for uncertainties. This is separate from a contingency cost, which should also be provided, to account for costs that are expected but not well defined. This is also typical in costing of construction work.

2.3. USE OF CERREX-D FOR DECOMMISSIONING COST ESTIMATION

The CERREX-D software code is based directly on the cost calculation structure ISDC (International Structure for Decommissioning Costing) described in [4] and is implemented in Microsoft Excel. The main principles for implementing the ISDC methodology in the CERREX-D code are:

- Inventory and waste-related information is implemented 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).

- Implementation of unit factor information for the inventory-dependent and waste management activities, together with work difficulty factors to reflect any constraints due to anticipated local working conditions.

- Identification of the cost elements (calculation items), including 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).

CERREX-D 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 unit factors associated with these decommissioning and waste management categories. A detailed analysis of the unit factors used in the costing cases presented in this report is provided in Appendix I.

The default unit factors incorporate all relevant preparatory and finishing activities associated with each activity. It should be noted that, in general, unit factors may be country-, reactor-type and even facility-specific. It is therefore usually necessary to modify the default unit factors in the code in order to achieve a reasonable level of accuracy in the cost calculation.

The unit factor information collected as part of this project will allow users to benchmark their unit factors against those being used for a range of research reactor decommissioning cost calculations.

3. OVERALL BENCHMARKING OF DECOMMISSIONING COSTS

3.1. TOP LEVEL BENCHMARKING

To provide context to the detailed data collection and analysis presented in the following sections of this report, global decommissioning costs from completed decommissioning projects were compiled from various sources for approximately 50 research reactors of the commonly built types, including a small number of critical assemblies – see Fig. 1. The original cost data is adjusted for inflation in order to provide equivalent cost information for the reference year for this project, 2013.

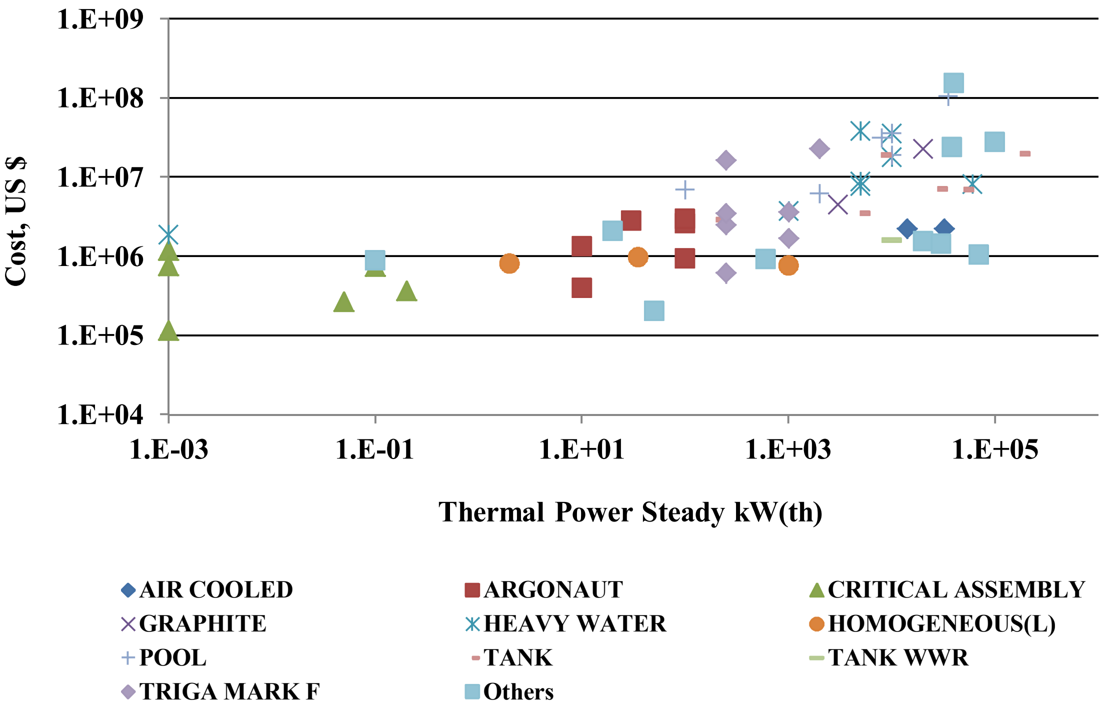


FIG. 1. Actual decommissioning cost of selected reactors vs. thermal power, based on data compiled by IAEA [5].

The data suggest a relation between the full decommissioning cost and the rated thermal power for research reactors, particularly those with a power rating of greater than 1 kW(th). It is possible that there exist threshold levels below which costs are unlikely to fall for very low or zero power reactors. From the limited dataset considered here this threshold value may be of the order of one hundred thousand US \$. The cost of dismantling research reactors of power ratings greater than 1 $kW_{(th)}$ will generally be greater than US \$1million (2013 price levels) provided all major cost elements are included, including waste disposal costs. At power levels of 1 $MW_{(th)}$ or more the cost can range from US \$1-10 million (2013 price levels). For power reactors rated at 10 $MW_{(th)}$ or more the cost may range from US \$10-100 million (2013 price levels); the highest–cost reactor included above is the Siloé reactor 35 $MW_{(th)}$ in Grenoble, France, recently decommissioned at a total cost of \$168 million (2013 price levels).

Although there exists a general tendency for costs to increase with increasing thermal power, the limited data available show that decommissioning costs at any given power level can vary widely, with increased variability at higher power levels.

Variations in decommissioning cost for the research reactors of the same or similar thermal power are caused by differences in reactor type and design, decommissioning project scope, country-specific unit workforce costs, and other reactor or project factors. These factors are analysed in more detail in the later sections of this report.

It should be borne in mind that the project decommissioning costs presented in Fig. 1, which are based on published data (converted to 2013 price levels), have not been normalized according to a common interpretation of project scope. Accordingly, some estimates are focused largely on dismantling costs, with other normally significant costs being largely ignored, e.g. waste management costs may not include disposal costs or licensing-related costs may have been excluded. For this reason, the presented data points only provide an indication of the relationship between overall costs and power levels, and of possible cost ranges at a given power level. In light of this, these data should not be used for cost estimation purposes without having a detailed understanding of the precise project scope that is applicable.

It should be noted that many research reactors remain in a state of permanently shut down for a significant period prior to active decommissioning. Costs incurred during this period, though not included as decommissioning costs, may nonetheless be significant. These costs are mainly due to the cost of personnel required to maintain the facility in a safe state pending the start of decommissioning.

3.2. COST COMPARISONS BASED ON DACCORD DATA

3.2.1. Overall Level 0 Comparisons

One of the objectives of DACCORD was to collect overall decommissioning cost data, including actual reported costs and calculated estimates, and to compare these according to reactor thermal power and the complexity introduced by operating history and radiological hazards. Table 1 below summarizes the range of results obtained for the 14 costing cases analysed in detail over the course of the project.

3.2.2. Total Cost and Workforce Comparisons and Observations

Figures 2 and 3 below provide a graphical illustration of the total cost and total worker hours respectively as a function of reactor power. These graphs are based on the data collected during the project. The values of completed decommissioning projects are shown in yellow to differentiate them from the estimates. Actual costs presented in Fig. 1 (converted to equivalent 2013 US $) indicate a large variation in total cost from US $1-100 million in the thermal power range of interest of 1–10 $MW_{(th)}$. The reactors in the sample set assessed in the DACCORD project in that power range show a total cost range of US $2.5–24 million (in equivalent 2013 US $).

TABLE 1. SUMMARY RESULTS FOR COSTING CASES ANALYSED

Reactor power output	Property analysed	Radiological Complexity		
		Limited operation	Standard operation	Accidents / Leakage
1 $MW_{(th)}$ and above	Cost, US $ (thousand)	Not analysed	2500-23500	Not analysed
	Workforce, Labour.h (thousand)	Not analysed	50-255	Not analysed
	Inventory, (t)	Not analysed	75-7700	Not analysed
100 kW to 1000 kW	Cost, US $ (thousand)	Not analysed	Not available	3380
	Workforce, Labour.h (thousand)	Not analysed	Not available	81
	Inventory, (t)	Not analysed	Not available	4325
100 kW and below	Cost, US $ (thousand)	Not analysed	8500	Not analysed
	Workforce, Labour.h (thousand)	Not analysed	40	Not analysed
	Inventory, (t)	Not analysed	120	Not analysed

The data shown on Fig. 2 generally shows higher total costs (at a particular power value) for completed decommissioning projects as compared to those projects for which costs are estimates relating to future decommissioning. Nonetheless, there is insufficient data to suggest that there is a general tendency to underestimate research reactor decommissioning costs, e.g. the completed decommissioning cases may have involved case-specific factors that are not generally applicable.

When assessing the workforce hours, it is noteworthy that lower workforce hours are reported for completed decommissioning projects than are estimated for the planned projects. There are many factors affecting the total cost estimate including waste management strategy, schedule, and selected end state among others. One significant factor that appears to be affecting the comparison of actuals vs. estimates in our case is the labour cost unit factors. When comparing the six completed cases in Figs. 2 and 3, with the estimated cases, the completed cases are in global regions with higher labour costs. This has a definite impact the total cost estimate and indicates that the estimates are likely of the correct order of magnitude.

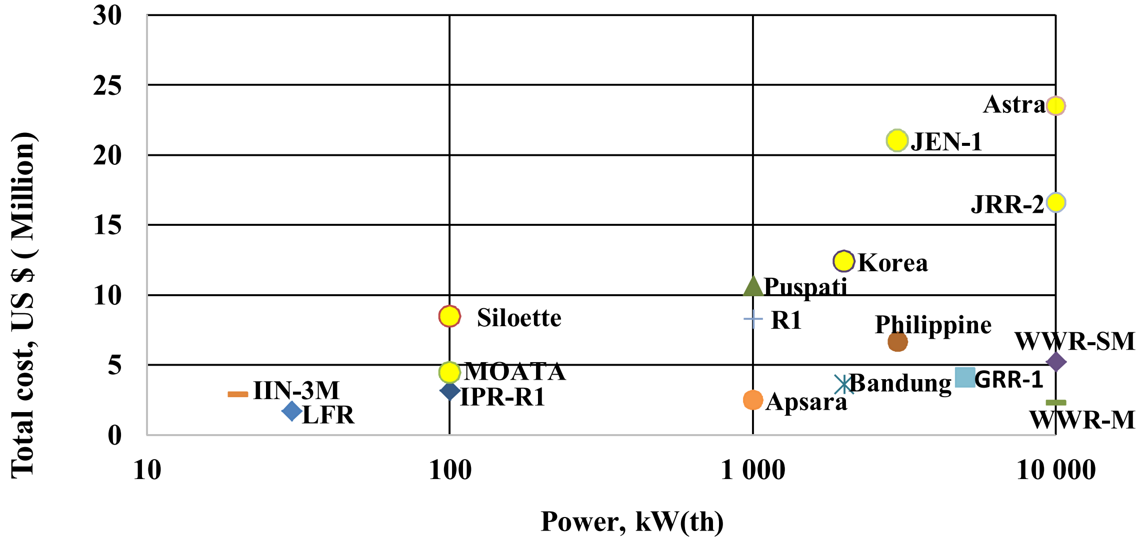


FIG. 2. Decommissioning cost of selected reactors vs. thermal power based on the DACCORD data.

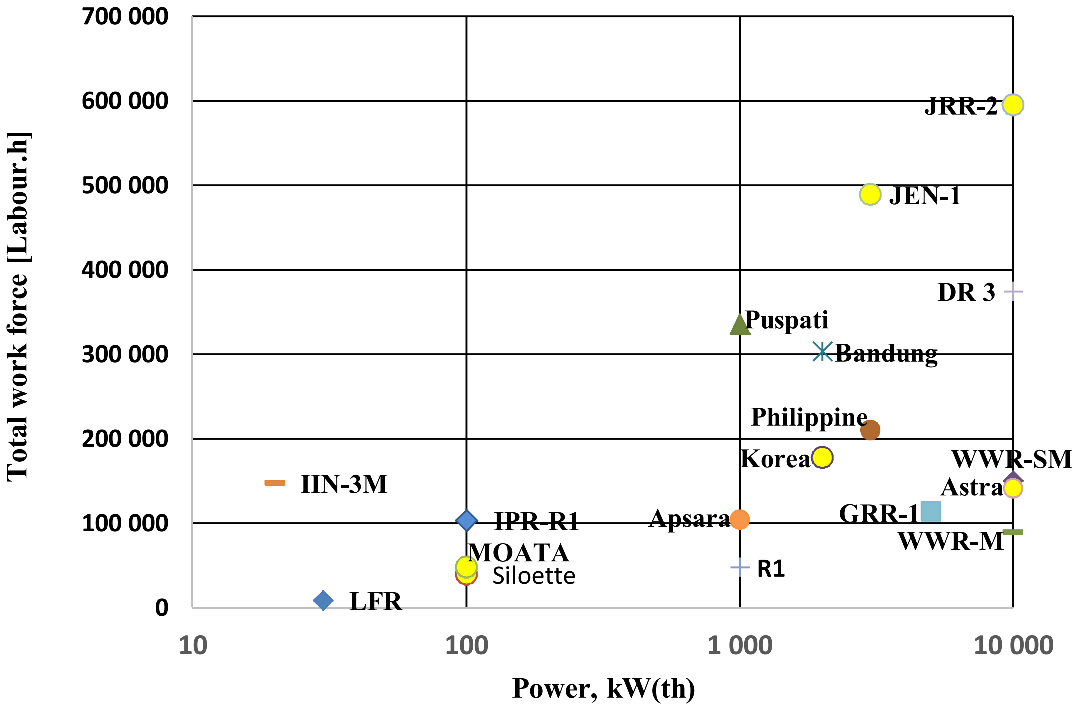


FIG. 3. Total workforce of selected reactors vs. thermal power, based on the DACCORD data.

3.2.3. ISDC Principal Activity comparisons

To identify the activities that make significant contributions to the total cost, the collected data were assessed to determine which ISDC Level 1 (L1) cost categories have the greatest contribution to the total cost. ISDC defines eleven Principal Activities (i.e. Level 1 activities), as follows:

01 – Pre-decommissioning actions

02 – Facility shutdown activities

03 – Additional activities for safe enclosure and entombment

04 – Dismantling activities within the controlled area

05 – Waste processing, storage and disposal

06 – Site infrastructure and operation

07 – Conventional dismantling, demolition and site restoration

08 – Project management, engineering and support

09 – Research and development

10 – Fuel and nuclear material

11 – Miscellaneous expenditures

Figure 4 below shows the ‘full decommissioning’ cases assessed during the DACCORD project, i.e. those cases for which the majority of activities for the entire facility undergoing decommissioning were included in the total cost. In some instances, research reactor decommissioning activities have focused only on the dismantling of specific systems and therefore these are not shown here.

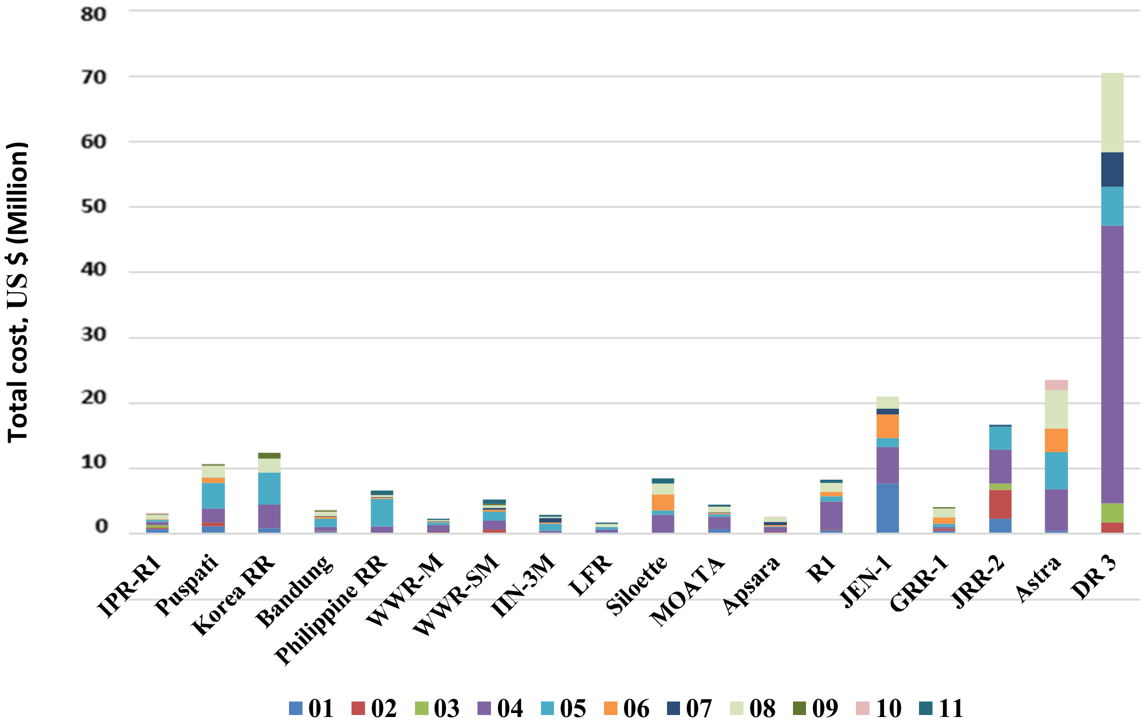


FIG. 4. Total decommissioning costs partitioned according to ISDC L1Principal Activities2013 US $.

Table 2 shows the percentage contribution to the total cost of each ISDC Level 1 Principal Activity. Significant variances are observed among the cases studied, though it is clear that in the majority of cases, Principal Activity 04 (Dismantling) and Principal Activity 05 (Waste Management) are the dominant contributors. The next most significant contributions are from Principal Activity 08 (Project Management) and Principal Activity 01 (Preliminary Activities).

Averaged data for each reactor type, with standard deviations (average% | standard deviation%) is shown in Table 3. For the ISDC Principal Activities with large contributions and with significant standard deviations, provide the greatest scope for optimizing the total cost of decommissioning. It is evident for instance that the majority of the cost for TRIGA type reactors relates to ISDC Item 05, Waste Processing and the standard deviation is also significant, at 20%. The particularities of approaches to waste management results in important differences in cost and this is further explored in the specific analysis for this reactor type in Section 4. In contrast, though the second most significant cost item is ISDC Principal Activity 04 (Dismantling in the Controlled Area), the standard deviation is only 5%, which warrants review but is not expected to provide as large a cost driver as the waste management activities.

TABLE 2. PERCENT OF TOTAL BY ISDC LEVEL 1 CATEGORIES

ISDC No.	IPR-R1	Puspati	of Korea RR	Bandung	Philippine RR	WWR-M	WWR-SM	IIN-3M	Siloëtte	MOATA	Apsara	R1	JEN-1	JRR-2	Astra
01	25	11	7	10	0	7	4	5	1	17	6	6	37	14	2
02	5	6	0	3	1	4	9	1	1	0	5	2	0	27	0
03	12	0	0	0	0	2	0	0	0	0	0	0	0	6	0
04	18	20	29	16	16	47	26	9	32	41	32	52	26	31	27
05	7	37	39	34	64	14	25	39	8	10	2	10	7	21	24
06	3	7	0	9	2	5	7	4	30	4	10	7	17	0	15
07	1	0	0	4	2	3	5	27	0	2	20	0	4	1	0
08	21	18	17	16	5	9	8	5	19	21	25	17	9	0	25
09	2	1	7	6	0	0	4	0	0	1	0	0	0	0	0
10	6	0	0	1	0	0	0	0	0	0	4	0	0	0	7
11	0	0	0	0	10	9	12	10	9	5	-3	5	0	0	0

TABLE 3. AVERAGE PERCENT OF TOTAL FOR EACH ISDC L1 CATEGORY BY REACTOR TYPE AND THE STANDARD DEVIATION %)

ISDC No.	ISPC activity	TRIGA Ave%|SD%	WWR Ave%|SD%	Open Pool Ave%|SD%
01	Pre-decommissioning actions	11 | 9	5 | 2	11 | 15
02	Facility shutdown activities	3 | 2	7 | 4	3 | 3
03	Additional activities for safe enclosure or entombment	2 | 5	1 | 2	0 | 0
04	Dismantling activities within the controlled area	20 | 5	37 |15	25 | 10
05	Waste processing, storage and disposal	36 |20	19 | 7	10 | 8
06	Site infrastructure and operation	4 | 4	6 | 1	19 | 8
07	Conventional dismantling and demolition and site restoration	1 |2	4 | 1	5 |9
08	Project management, engineering and support	16 |6	9 | 0	23 | 9
09	Research and development	3 | 3	2 | 3	1 | 1
10	Fuel and nuclear material	1 | 3	0 | 0	2 | 3
11	Miscellaneous expenditures	2 | 4	10 | 2	1 | 5

In summary, the key cost drivers are related to activities related to waste management, dismantling in the controlled area, pre-decommissioning activities and project management. In the specific case of open pool reactors, decisions and approaches related to site infrastructure are also reviewed and discussed further in Section 6.

4. TRIGA REACTOR TYPE: ANALYSIS OF ESTIMATED COSTS AND KEY COST DRIVERS

4.1. INTRODUCTION AND FACILITIES CONSIDERED

4.1.1. Introduction

General Atomics (GA) developed the TRIGA reactor in the early 1950s. It was unveiled publicly for the first time at the First Geneva Conference on Peaceful Uses of Atomic Energy in 1955. TRIGA reactors are small research reactors intended to be inherently safe, operationally flexible, relatively inexpensive, and allowing a large variety of experiments and using low enriched uranium. During subsequent decades, approximately 60 TRIGA reactors were constructed around the world. Three basic TRIGA models have been produced: (1) Mark-I, comprising an underground pool without beam tubes, (2) Mark-II, comprising an above-ground tank with several beam tubes, and (3) Mark-III, comprising an above-ground oval tank with movable core.

The TRIGA reactors for which decommissioning costs are analysed in this section using CERREX-D software are shown in Table 4. KRR-2 (Republic of Korea) cost data relate to a completed decommissioning project; the data provided for the other reactors are estimated costs.

TABLE 4. LIST OF ANALYSED TRIGA REACTORS

Name	Reactor type	Operator (location, country)	Power, $MW_{(th)}$	Start-up	Current status
IPR-R1	TRIGA-Mark-I Pool Type	CDTN (Belo Horizonte, Brazil)	0.100	1960.11	Operational
TRR2000	TRIGA-Mark-II Pool Type	BATAN (Bandung, Indonesia)	2.00	1964.10	Operational (Temporary shutdown)
KRR-2	TRIGA-Mark-III Pool Type	KAERI (Seoul, Republic of Korea)	2.00	1972.4	Decommissioned
RTP	TRIGA-Mark-II Pool Type	Malaysian Nuclear Energy (Bangi, Malaysia)	1.00	1982.6	Operational
PRR-1	Converted TRIGA	PNRI (Manila, Philippines)	3.00	1963.8	Shutdown

Detailed descriptions of the above cases are provided in Appendix-II. Important specificities related to costing the decommissioning of each of these cases are:

- Mark-I, IPR-R1, Brazil: as described in Section 4.1.3;
- MARK-II, TRR 2000, Indonesia: waste management costs are included;
- MARK-III, KRR-2, Republic of Korea: a large R&D programme was implemented and actual cost data are provided;
- MARK-II, RTP, Malaysia: conventional D&D activities have already been performed and are not included in the estimate; and
- Converted TRIGA, PRR-1, Philippines, the biological shielding will not be demolished.

4.1.2. Description of the ‘Model’ case

Input parameters for the model case are described in Annex I (I-4 to I-10). This model costing case may be used as a reference case for TRIGA Mark II cost estimates. The main decommissioning activities for the model TRIGA reactor are shown in Fig. 5; the associated decommissioning schedule reactor is shown in Fig. 6.

A typical sequence of dismantling activities for the main components is as follows:

1. Removal of the heat exchanger;
2. Removal of the reactor core assembly;
3. Removal of the graphite reflector;
4. Removal of the rotary specimen rack;
5. Removal of the reactor core;
6. Removal of the graphite blocks;
7. Cutting the aluminium container of thermal column;
8. Dismantling the four beam ports and steel shadow;
9. Cutting and dismantling the reactor tank liners (aluminium plus concrete plus carbon steel);
10. Decontamination of the biological shielding concrete surface;
11. Demolishing the biological shielding concrete.

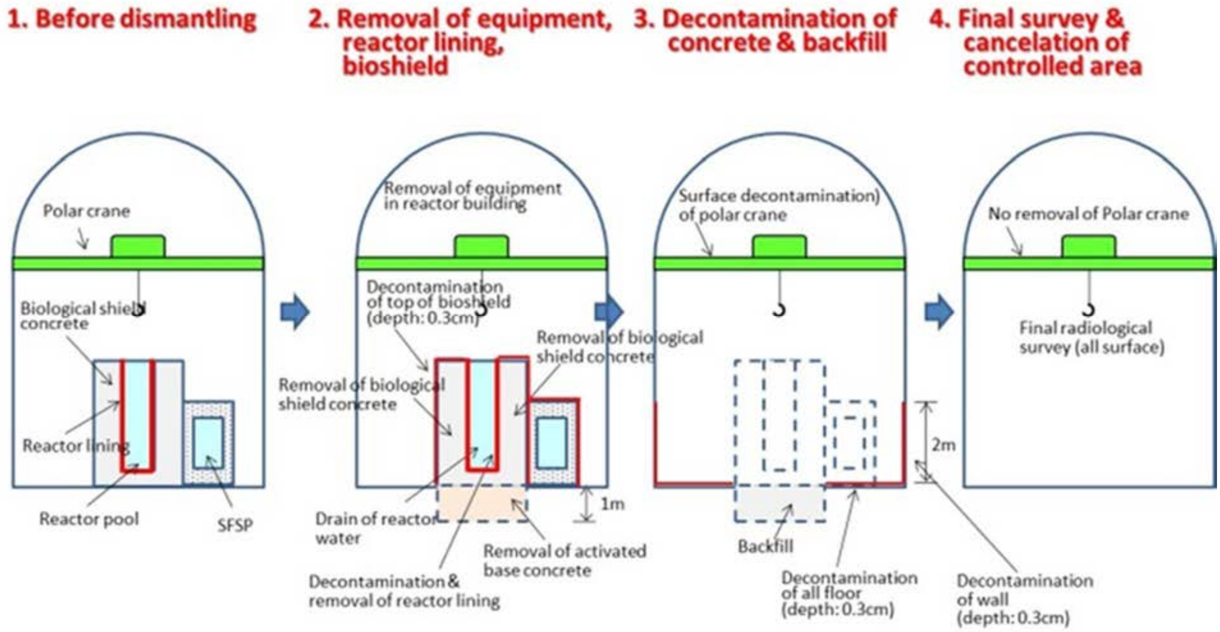
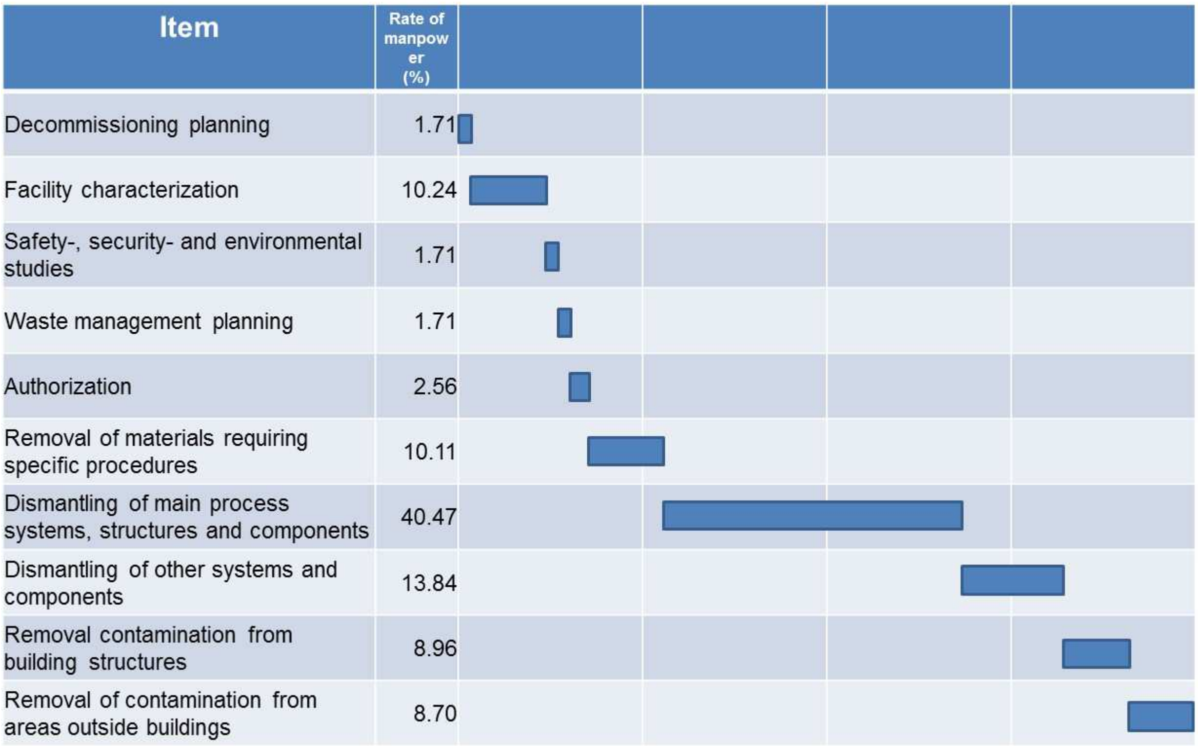


FIG. 5. Scheme of Model TRIGA Mark-II reactor including a description of decommissioning approaches.



Item	Rate of manpower (%)
Decommissioning planning	1.71
Facility characterization	10.24
Safety-, security- and environmental studies	1.71
Waste management planning	1.71
Authorization	2.56
Removal of materials requiring specific procedures	10.11
Dismantling of main process systems, structures and components	40.47
Dismantling of other systems and components	13.84
Removal contamination from building structures	8.96
Removal of contamination from areas outside buildings	8.70

FIG. 6. Decommissioning schedule of KRR-2 TRIGA reactor.

Concerning the waste management approach, dismantled material is either stored in 200L drums (in the case of radioactive waste), or transported for industrial disposal (non-radioactive waste).

The following assumptions are common to each of the analysed TRIGA reactors:

- The decommissioning strategy is immediate dismantling after standard shutdown, with the end-point being the reuse of the reactor area for other, non-nuclear, purposes and the site being released from regulatory control;
- The systems subject to decommissioning include: reactor building including ventilation system, heat exchangers, and reactor cooling systems; the overhead crane is retained;
- Pre-decommissioning activities are performed before reactor shutdown, with a duration of 2 years;
- The decontamination depth is 3mm for all floors in a reactor building, and 3mm for walls up to 2m high from the floor;
- 20% of the concrete biological shield is activated, 80% is non-activated, and there is also surface contamination. The concrete biological shield is removed completely down to 1m beneath the base of the concrete reactor pool;
- All components are segmented on-site, the waste is transported in containers;
- Full waste management system is included in the decommissioning project. All radioactive waste is conditioned;
- A final radiological survey is performed on all inner surfaces of the reactor building. Active buildings are refurbished;
- Staffing: Management of activities is performed by contractor and supervised, and approved by the licensee management group. Contractors are used partially for critical ISDC 04 activities. Operational staff is also used during decommissioning for the

project management and conventional D&D. R&D activities are performed by own personnel;

- Spent fuel management is out of the decommissioning project scope. No related projects, taxes, and insurances are included. No assets are considered.

4.1.3. TRIGA Reactors Design and Layout

4.1.3.1. *TRIGA Mark-I Reactor*

The below-ground TRIGA Mark I reactor (Fig. 7) is extremely simple in physical construction. It has a graphite-reflected core capable of operating at up to 2 000 kW(th)in steady state and pulsing routinely and reproducibly with reactivity insertions up to 3.2% δk/k. The reactor core rests at the bottom of an aluminium tank. Surrounding earth and demineralized water provide the necessary radial and vertical shielding. No special containment building is required and installation in an existing building is often feasible. The TRIGA Mark-I can be installed in a circular pool or in a large, oblong pool to provide improved access to the reactor core for experimental purposes. Core cooling is achieved through natural convection, eliminating the need for an expensive and restrictive forced cooling system.

The main technical attributes of the TRIGA Mark-I reactor are:

- 100 kW(th) to 2 000 kW(th) steady state power level;
- Up to 6 400 000 kW(th) pulsing power level;
- 8.0×10^{13} n/cm^2 s maximum thermal flux (<0.21 eV) at 2 000 kW(th);
- 9.6×10^{13} n/cm^2 s maximum fast flux (10 keV) at 2 000 kW(th);
- $UZrH_{1.6}$ fuel elements using uranium enriched to 20%.

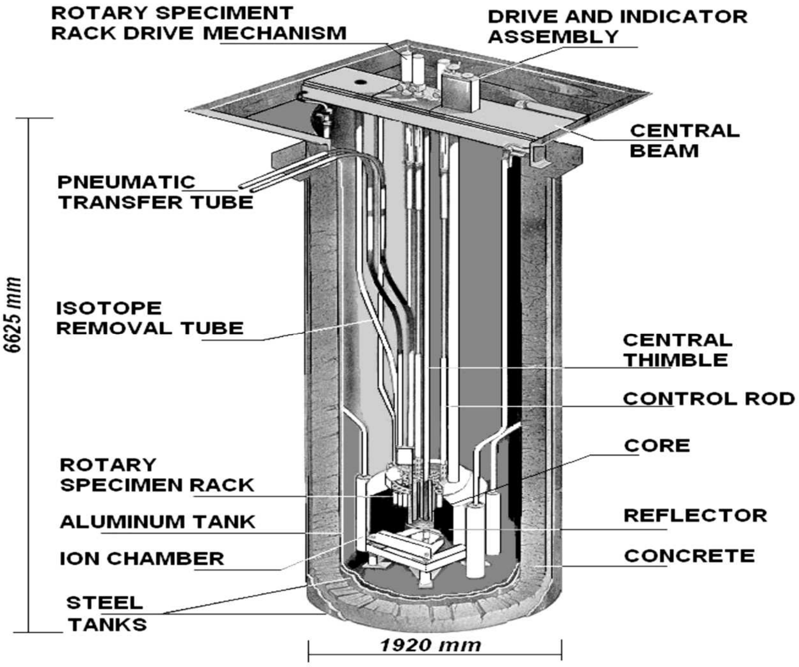


FIG. 7. TRIGA Mark-I reactor.

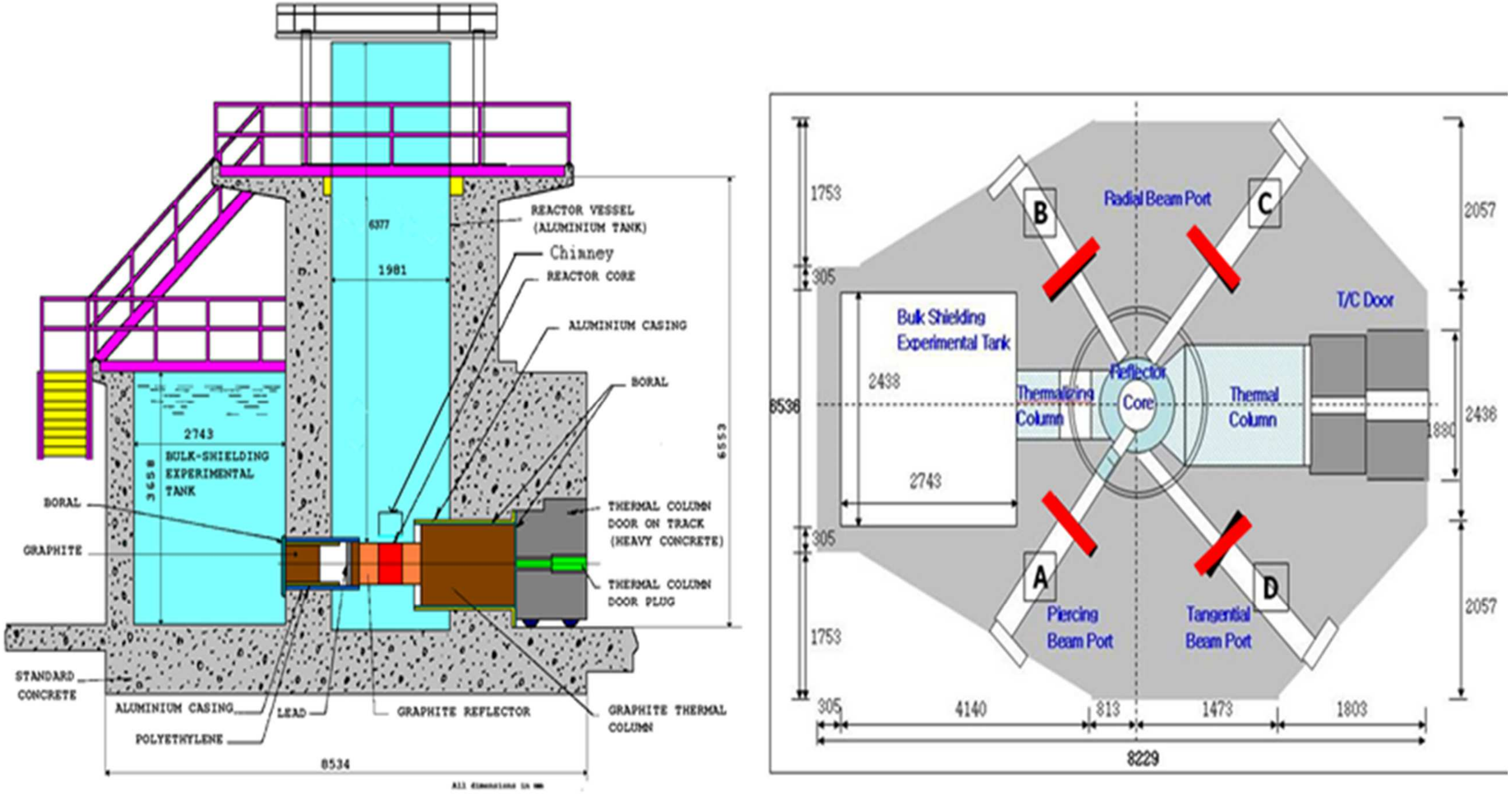
4.1.3.2. *TRIGA Mark-II Reactor*

The TRIGA Mark-II, which provides experimental capabilities greater than the TRIGA Mark-I, is an above-ground fixed-core research reactor (Figs. 8 a, 8 b), with a graphite reflector. Its core, identical to that of the TRIGA Mark-I, is located in a pool surrounded by a concrete shield structure which is above the reactor room floor. The pool water provides natural convection cooling. The TRIGA Mark-II reactor comprises:

- *A graphite thermal column* (1.2m×1.2m ×1.65m) extending from the reflector through the concrete structure, provides a source of well thermalized neutrons suitable for physical research or biological irradiation. A movable high-density concrete door with a removable 20cm concrete plug shields the outer face of the column.
- *Four horizontal beam ports* (15cm diameter) extending through the concrete shield to the face of the reflector, facilitating accessibility of core radiation, or the insertion of specimens for irradiation. Two of the beam tubes extend radially to the reflector, the third penetrates the reflector to the edge of the core, and the fourth one is at a tangent to the core.

The main technical attributes of the TRIGA Mark-II reactor are:

- 250 kW(th) to 2 000 kW(th) steady state power level with natural convection cooling (3 000 kW(th) with forced cooling);
- Up to 6 400 000 kW(th) pulsing power level;
- 8.0×10^{13} n/cm^2 s maximum thermal flux (<0.21 eV) at 2 000 kW(th);
- 9.6×10^{13} n/cm^2 s maximum fast flux (>10 keV) at 2,000 kW(th);
- $UZrH_{1.6}$ fuel elements using uranium enriched to 20%.



a) b)

FIG. 8. a) TRIGA Mark-II reactor – vertical section; b) TRIGA Mark-II reactor – horizontal section.

4.1.3.3. *TRIGA Mark-III Reactor*

The TRIGA Mark-III reactor, the most adaptable of the standard TRIGA series, is available in either above- or below-ground configurations. Its water-reflected movable core greatly increases the reactor's flexibility. The core can be moved to one end of the pool for experiments in an adjacent dry, walk-in, exposure room; or to the opposite end for experiments involving the thermal column and beam ports. The ability to move the radioactive core away from the experimental facilities greatly eases the setting-up of experiments.

The reactor tank is approximately 7.5m long and 7.5m deep, with a maximum width of 3m at the centre. Since it has natural convection cooling up to 2 000 kW(th), the reactor can be operated elsewhere in the pool. The TRIGA Mark-III reactor includes following:

- *Two thermal columns with internal void.* A graphite thermal column (1.2 m x 1.2m x 3m) extends from the periphery of the reactor core through the concrete shield structure. A Hohlraum space (0.9m x0.9m x1.05m) is provided in this horizontal thermal column with a vertical thermal column directly above. Four ports through the concrete shielding allow access to the two thermal columns;
- *Four horizontal beam ports* (15cm diameter) penetrate the concrete shield and the reactor pool water to the edge of the core, and two 20cm diameter through-beam ports intersect in the thermal column adjacent to the core;
- *Walk-in exposure room* (3m wide, 3.6m long, 2.9m high) provides significant space for experimental requirements. Access to the room is provided by several 15cm diameter conduits and a motor-driven concrete door.

General data for the TRIGA Mark-III reactor (Fig. 9) are as follows:

- 1 000 kW(th) to 2 000 kW(th) steady state power level with natural convection cooling (3 000 kW(th) with forced cooling);
- Up to 6 400 000 kW(th) pulsing power level;
- 6.6×10^{13} n/cm^2 s maximum thermal flux (<0.21 eV) at 2 000 kW(th);
- 6.2×10^{13} n/cm^2 s maximum fast flux (>10 keV) at 2 000 kW(th);
- $UZrH_{1.6}$ fuel elements using uranium enriched to 20%.

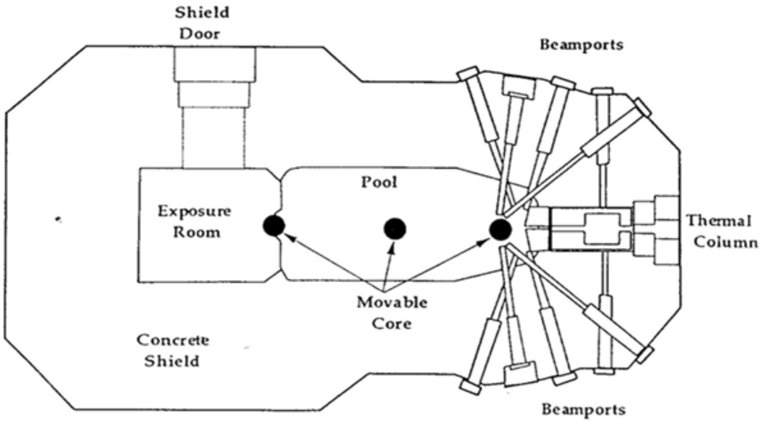


FIG. 9. TRIGA Mark-III reactor.

4.2. ANALYSIS OF AVAILABLE CASES

4.2.1. Analysis of the assumptions, boundary conditions, and comparison of input parameters

Input inventory and waste parameters and unit factors are listed in Appendix I (I-4 – I-10) for each costing case. The dismantling sequence is described in Fig. 5.

4.2.2. Analysis at the ISDC Level 0 costing categories

The following figures present an analysis of the available TRIGA reactor cases according to total cost, workforce, total inventory, radioactive waste and thermal power.

The Fig. 10 presents the total cost of analysed TRIGA reactors vs. thermal power. The high level of total costs for KRR-2 reactor is due to: several R&D activities performed during decommissioning, a higher inventory estimation and the higher labour rates in Republic of Korea. The relatively high costs for RTP reactor are assigned to a higher work force to perform the decommissioning project and the higher labour rates in Malaysia. The relatively low total costs for TRR2000 are based on the fact that D&D activities are planned to be performed by contractors with low labour rates. The PRR-1 reactor decommissioning costs are based on relatively low labour rates and the dismantling scope considering the remaining of reactor concrete bio-shield.

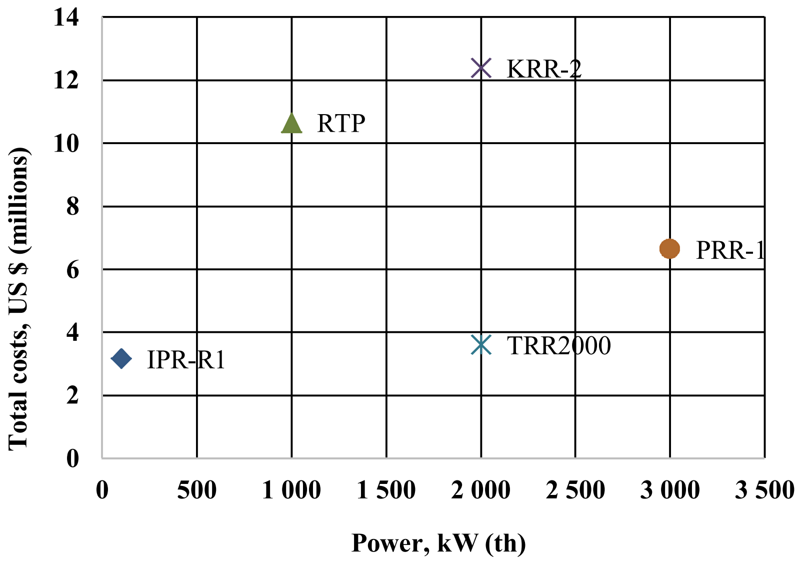


FIG. 10. Total cost of analysed TRIGA reactors vs thermal power.

Figure 11 shows total cost vs inventory. Considering the similar inventories of the reactors TRR2000, PRR-1 and RTP, the differences in the total cost are largely caused by the differences in the labour rates of the countries were the decommissioning activities will be performed. Some new decommissioning technologies were developed and applied in the case of KRR-2. This was to reduce the impact of a higher inventory on the total costs.

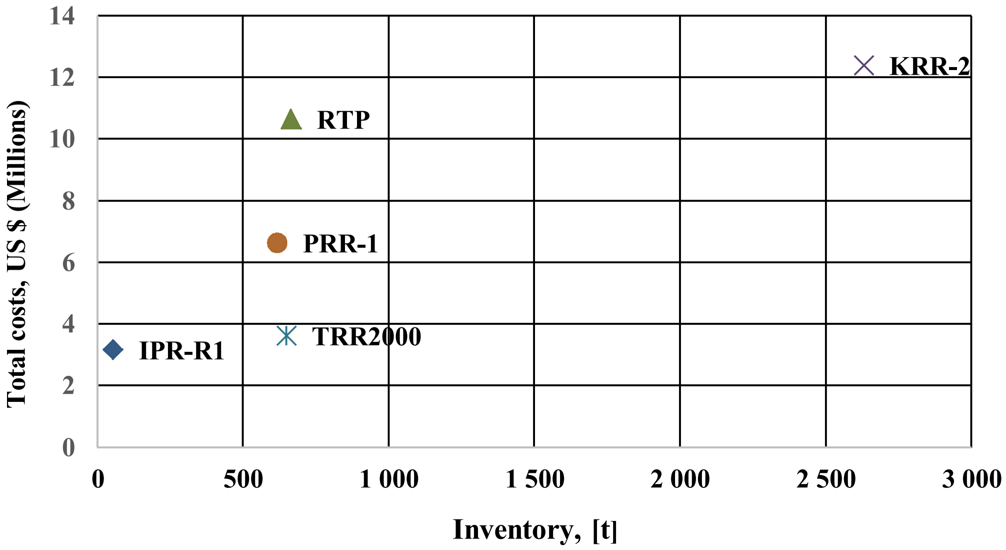


FIG. 11. Total Costs vs Inventory.

Figure 12 presents the total mass inventory vs. thermal power. The larger KRR-2 reactor inventory is due to the dismantling of several additional facilities used for isotope production (study rooms 1, 2 and 3, instrument room, hot lab 1 and 2, weighing room, preparation room 1 and 2, underground pit). The relatively lower inventory applicable to the PRR-1 reactor is due to its short period of operation and the planned retention of the bio-shield.

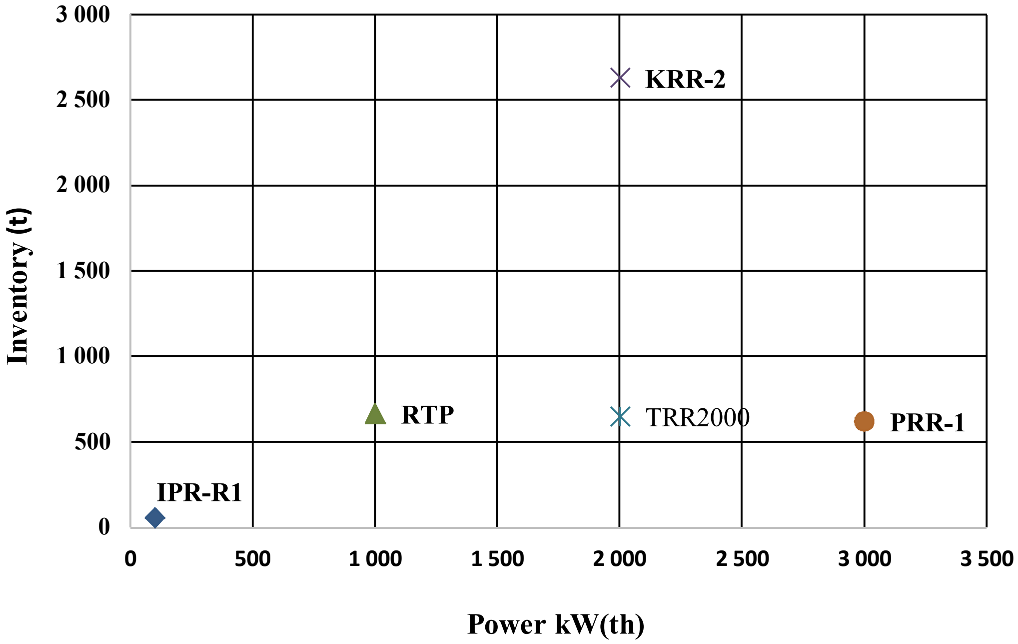


FIG. 12. Total Mass Inventory vs Thermal Power.

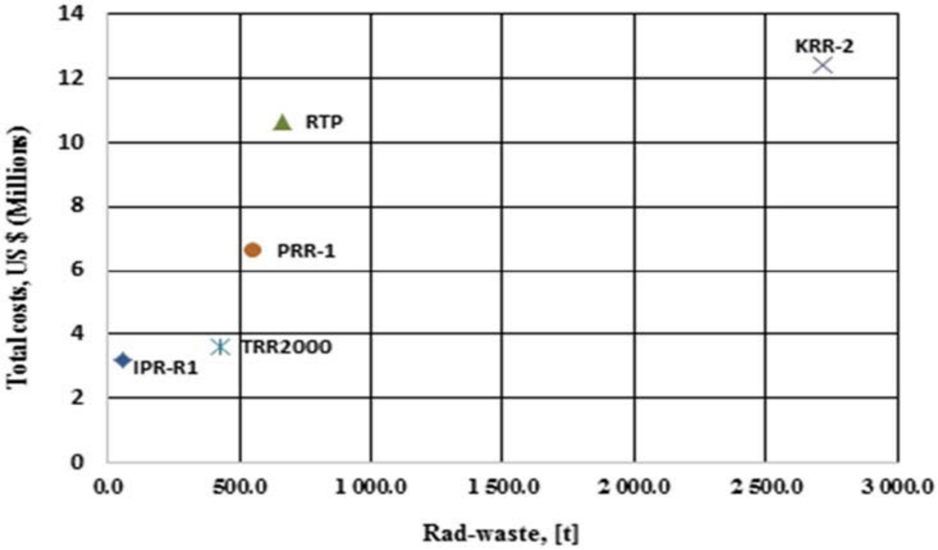


FIG. 13. Total Costs vs Radioactive Waste.

Regardless, the higher inventory and radioactive waste observed for the KRR-2 reactor on Figs. 12-13. Figure 14 shows a lower value for the total workforce for this decommissioning project. This reflects the application of a number of new decommissioning technologies, which were developed to counteract the impact of the higher inventories.

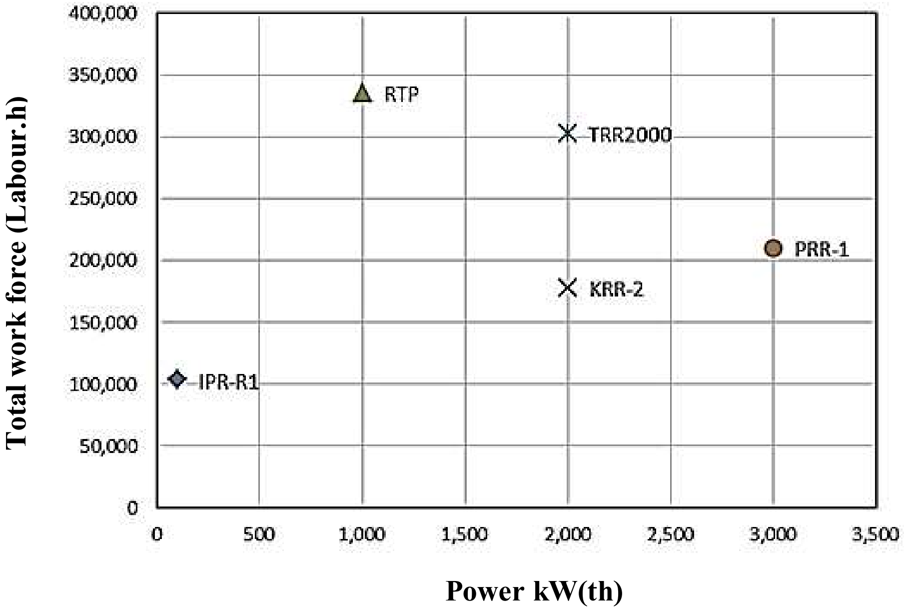


FIG. 14. Total Workforce vs Thermal Power.

Table 5 presents the summary costing matrix with the values of total costs, workforces and inventories observed for the assessed TRIGA reactors decommissioning costing cases using CERREX software.

TABLE 5. SUMMARY RANGES OF VALUES OBSERVED FOR THE ASSESSED TRIGA REACTORS

Reactor power output	Property	Limited operation	Standard operation	Accidents Leakages
1 $MW_{(th)}$ and above	Cost, US $ (thousand)	Not available	3-12	Not available
	Workforce, Labour.h (thousand)	Not available	178-336	Not available
	Inventory, (t)	Not available	617-2630	Not available
100 kW to 1000 kW	Cost, US $ (thousand)	Not available	3	Not available
	Workforce, Labour.h (thousand)	Not available	103	Not available
	Inventory, (t)	Not available	54	Not available
100 kW and below	Cost, US $ (thousand)	Not available	Not available	Not available
	Workforce, Labour.h (thousand)	Not available	Not available	Not available
	Inventory, (t)	Not available	Not available	Not available

4.2.3. Analysis of ISDC Level 1 Principal Activities

For comparison, the total costs corresponding to the ISDC Level 1 costing categories are presented in Table 6 for the five assessed costing cases for TRIGA reactors.

TABLE 6. SUMMARY TRIGA COMPARISON OF TOTAL COSTS FOR ISDC L1 COSTING CATEGORIES

ISDC No.	ISDC activity	Costs by Research Reactor (US $ Million)					
		IPR-R1	TRR2000	KRR-2	RTP	PRR-1	Mean Value
01	Pre-decommissioning actions	0.78	0.38	0.88	1.13	0.004	0.63
02	Facility shutdown activities	0.15	0.10	-	0.62	0.08	0.24
03	Additional activities for safe enclosure	0.39	-	-	-	-	0.39
04	Dismantling activities in the controlled area	0.57	0.57	3.59	2.13	1.04	1.58
05	Waste processing. storage and disposal	0.23	1.24	4.89	3.91	4.27	2.91
06	Site infrastructure and operation	0.11	0.32	-	0.77	0.12	0.33
07	Conventional D&D and site restoration	0.02	0.15	-	0.04	0.13	0.09
08	Project management. engineering and support	0.68	0.59	2.16	1.90	0.33	1.13
09	Research and development	0.05	0.23	0.88	0.16	0.01	0.27
10	Fuel and nuclear material	0.20	0.03	-	0.01	0.005	0.06
11	Miscellaneous expenditures	-	-	-	-	0.65	0.65
	Total Cost	3.18	3.63	12.40	10.66	6.64	7.30

ISDC L1 Cost Distributions and ISDC L1 Workforce Distributions are shown below in Figs. 15 and16.

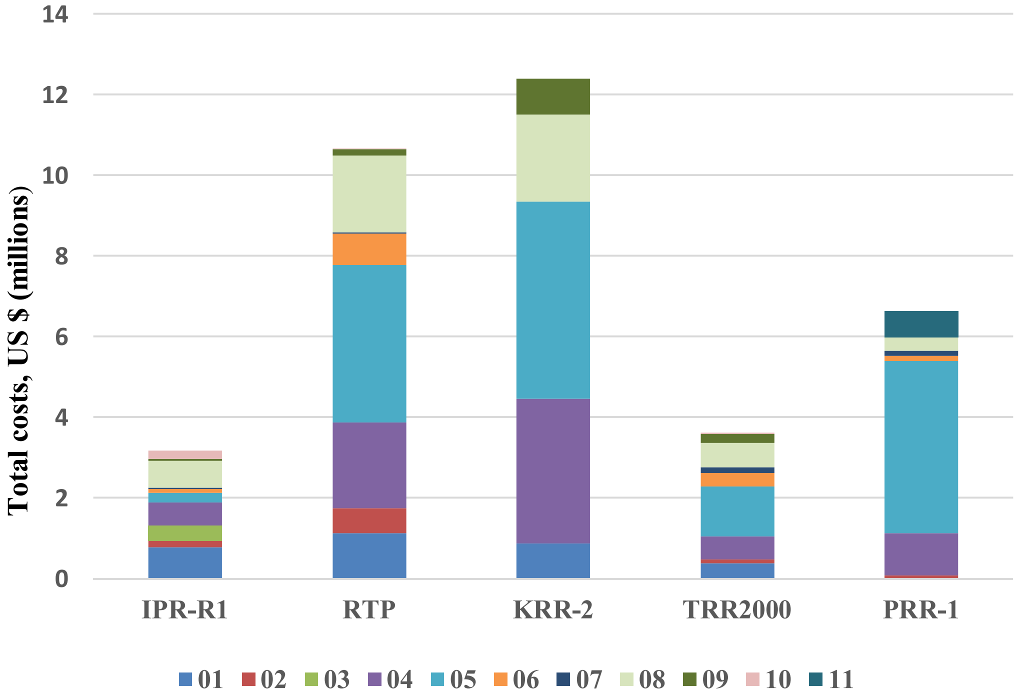


FIG. 15. ISDC L1 Cost Distribution.

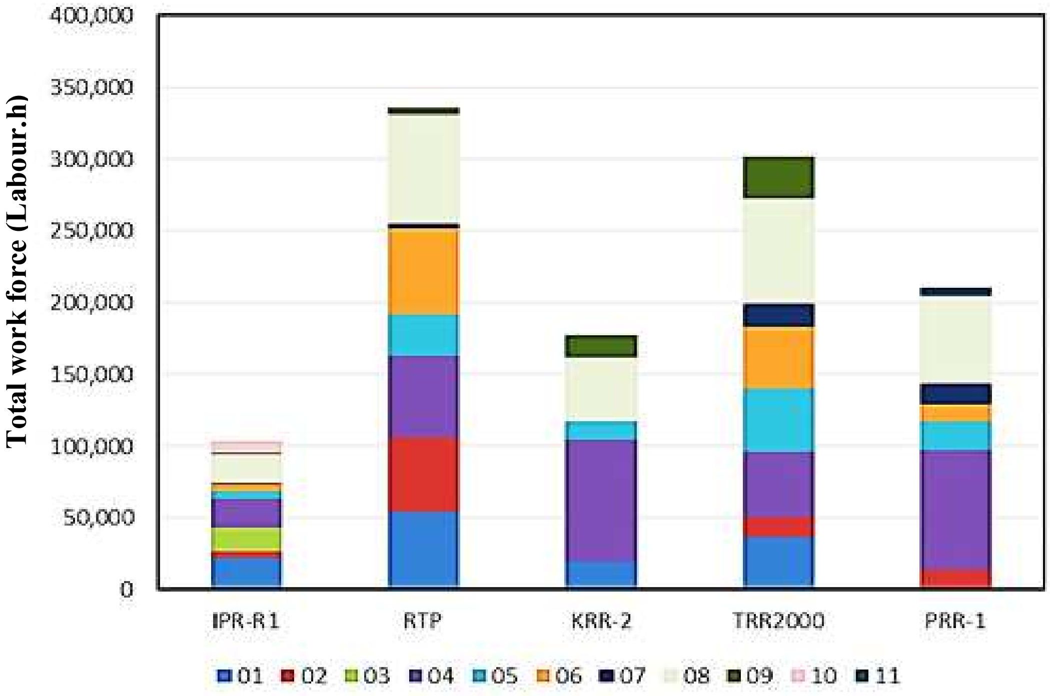


FIG. 16. ISDC L1 Workforce Distribution.

4.2.4. Conclusions and key cost contributors

According to the assessed costing cases, the four main cost-relevant activities are associated with the following Level 1 ISDC principal activities as shown in table 7.

TABLE 7. AVERAGE PERCENTAGE OF TOTAL COST OF ISDC 01, 04, 05 AND 08

ISDC Number	ISDC Activities	Average Percentage of Total Cost	Standard Deviation
01	Pre-decommissioning actions	11	9
04	Dismantling activities within the controlled area	20	5
05	Waste processing, storage and disposal	36	20
08	Project management, engineering and support	16	6

From above assessed data, it is evident that waste processing, storage and disposal are responsible for more than one-third of total decommissioning costs and also have high variability between different costing cases.

Considering Level 2 ISDC costing categories, the relative percentage for the main cost-relevant ISDC activities are presented in tables 8 and 9.

TABLE 8. MAXIMUM PERCENTAGE OF L2 ISDC 05 COST

ISDC Number	L2 ISDC Activities	IPR-R1	RTP	KRR-2	TRR 2000	PRR-1
05.0100	Waste management system	22	16	4	10	4
05.0400-0600	Management of historical/legacy wastes[1])	4				
05.0800-1100	Management of decommissioning radioactive wastes[2])	42 (Max)	68 (Max)	86 (Max)	65 (Max)	95 (Max)
05.1200	Management of decommissioning exempt waste and material	22	15	11	22	0
05.1300	Management of decommissioning waste generated outside controlled areas...	11	0		4	1

[1]) Historical/legacy wastes include historical/legacy low level waste (05.0400), very low level waste (05.0500), and exempt waste and materials (05.0600).

[2]) Decommissioning radioactive wastes include decommissioning intermediate level waste (05.0800), low level waste (05.0900), very low level waste (05.1000), very short lived waste (05.1100), and exempt waste and materials (05.1200).

TABLE 9. MAXIMUM PERCENTAGE OF L2 ISDC 04 COST

ISDC Number	ISDC Activities	IPR-R1	RTP	KRR-2	TRR 2000	PRR-1
04.0200	Preparations and support for dismantling	22 (Max)	3		15	2
04.0500	Dismantling of main process systems, structures and components	11	62 (Max)	50 (Max)	34 (Max)	9
04.0900	Final radioactivity survey for release of buildings	4	0		11	48 (Max)

An assessment of the behaviour of the main cost drivers is provided below.

- Labour costs: direct proportional impact on the cost estimates;
- Radioactive waste: direct proportional impact on the cost estimates;
- Inventory: direct proportional impact on the cost estimates but some deviations/outliers can be expected;
- Reactor design (type) model: no clear correlation with the total costs;
- Decommissioning and dismantling strategy and end state: indirect correlation with the total cost due to the direct impact on the adopted dismantling approaches (conventional dismantling, remote dismantling, remaining of reactor bioshield as momentum or historical purposes) and on the need for R&D activities during the project.

Note: ISDC hierarchical detail level: the complexity of the estimation promotes the robustness of the assessment and can result in the identification of additional costs.

4.3. PARAMETRIC ANALYSIS

4.3.1. Parametric analysis for costing case

Five input parameters (Labour rate, Inventory (total), Duration (ISDC 06&08), Waste Management Unit Factor (WMUF), Decommissioning Unit Factor (DCUF) were selected for parametric analysis using actual costs of KRR-2 decommissioning. Total decommissioning costs were recalculated in the case of a 30% increase and decrease of the input parameter value.

Figure 17a shows results of parametric analysis for the KRR-2 costing case. The result showed the greatest level of sensitivity of the total decommissioning cost to labour rate, inventory (total) and the WMUF.

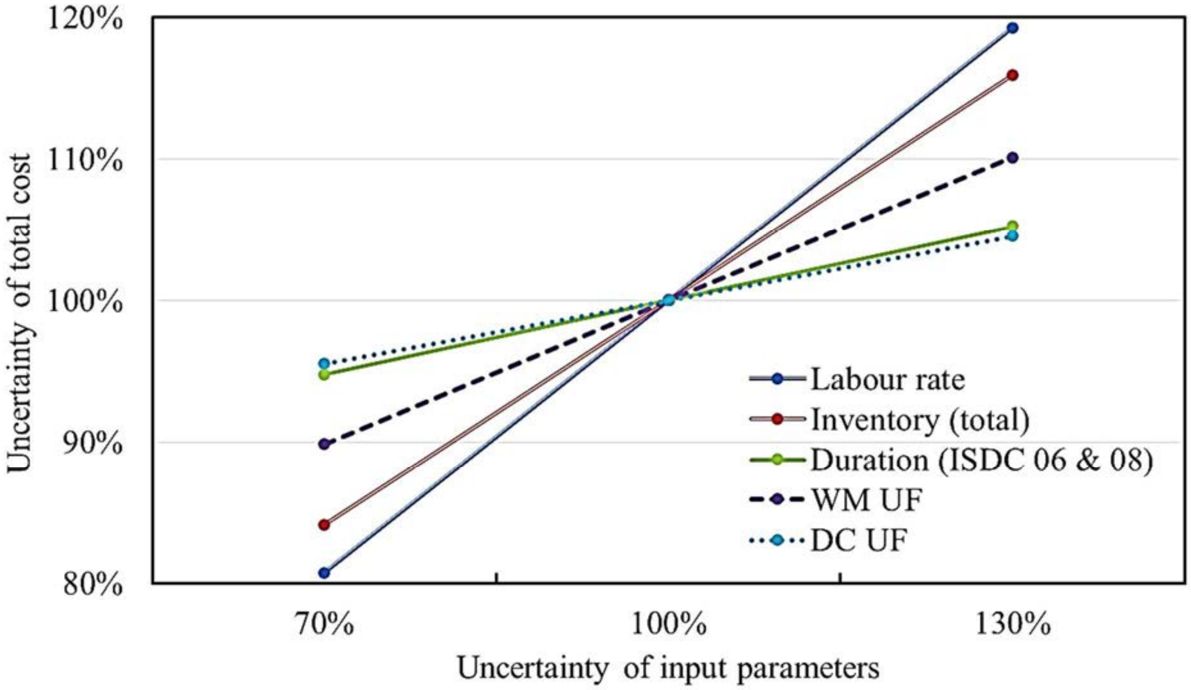


FIG. 17a. Parametric analysis for KRR-2 costing case.

4.3.2. Histograms of uncertainty of total cost at high sensitive parameter

Figure 17b shows histograms of uncertainty of total decommissioning cost of each TRIGA reactors corresponding to a 30% increase in the value the most sensitive input parameters: labour rate, total inventory and the waste management UF. Sensitivity of the total decommissioning cost to different input parameters was highest in the case of labour rate in all cases expect for the Philippines reactor. The trend of uncertainty in the total decommissioning costs for the KRR-2, Bandung, and Malaysian reactors were similar. For the Philippines reactor, sensitivity of total decommissioning cost to different input parameters was highest in the case of total inventory.

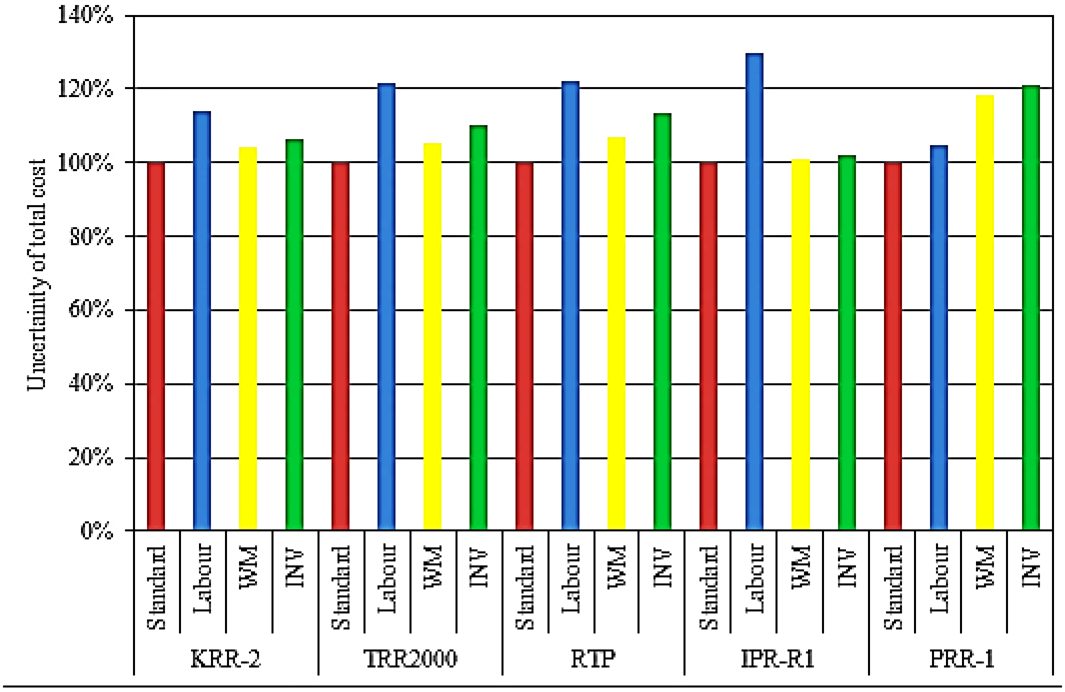


FIG. 17 b. Histograms of uncertainty of total decommissioning cost at high sensitive parameter.

Labour: Labour rate, INV: inventory (total), WM: WMUF

4.3.3. Conclusion

The parametric analysis undertaken for the five assessed research reactors suggests that the total cost is most sensitive to the assumed labour rate, with the total inventory generally being the second most important input parameter.

5. POOL IN TANK WWR REACTOR TYPE: ANALYSIS OF ESTIMATED COSTS AND KEY COST DRIVERS

5.1. INTRODUCTION AND FACILITIES CONSIDERED

5.1.1. Introduction

The WWR (Water-Water Reactor) reactor type represents one of the later developments of water-moderated, water-cooled research reactors in the former Soviet Union. The WWR is a pool-in-tank type heterogeneous reactor, where the distilled light water provides cooling, moderation and shielding [6]. These reactors were built mainly in Central and Eastern European countries from the mid-1950s to the beginning of the 1960s [7]. Such reactors from Hungary and Ukraine are shown in table 10. Some of the reactors were later refurbished and continue to operate while others have been permanently shut down, either being considered for decommissioning or are currently undergoing decommissioning. Reactors of this type have a simple construction convenient for conducting experiments, relatively low construction and operational cost, with a good standard of safety and reliability.

TABLE 10. SOVIET-DESIGNED RESEARCH REACTORS OF WWR TYPE IN HUNGARY AND UKRAINE

Reactor	Operator (location, country)	Power, $MW_{(th)}$	Start-up	Current status
BRR (WWR-SM10)	Atomic Energy Research Institute (Budapest, Hungary)	10	1959	operational, estimated shutdown 2023
WWR-M	Institute for Nuclear Research (Kiev, Ukraine)	10	1960	operational

Two of the above reactors, WWR-M (Kiev, Ukraine) and WWR-SM10 (WWER-SM, Budapest, Hungary) are considered in this report. Both reactors were constructed according to the standard design and have been in operation for more than 50 years. Neither reactor has experienced any significant incidents or accidents, or events with hazardous impact on the staff, public or the environment during their operation. Design and operational documentation has been preserved and information on the technical and radiological status of both reactors is readily available. For both reactors the strategy of immediate dismantling with a planned end state of facility release from regulatory control has been adopted. Initial decommissioning planning was performed, and further planning is ongoing [8-12].

5.1.2. Reactor Design and Layout

The WWR-M and WWR-SM reactor's schematic of the cross-section, layout of the systems and assumed dismantling sequence for each reactor is discussed in Appendix III.

The main reactor elements (systems) are:

- reactor vessel (tank) containing the core;
- control rod system and system for control of the reactor's parameters;
- cooling circuits (primary and secondary);

- water cleaning system for the primary circuit;
- radiation protection system (biological shielding);
- emergency cooling system;
- temporary storage for spent nuclear fuel (cooling pond);
- special sewerage system (collection, storage and treatment of liquid radioactive waste);
- special ventilation and filtration systems for normal operations and in the case of accidents;
- power supply system for normal operations and back-up in the case of failure;
- radiation control and protection system;
- radioactive waste management system;
- fire-control system;
- security system.

5.2. ANALYSIS OF AVAILABLE CASES

As in the previous section, this section presents an analysis of the relationship between total inventory, radioactive waste, total cost and workforce . As only two very similar reactors with the same upgraded thermal power of 10 $MW_{(th)}$ are being compared, it is not possible to establish a general relationship with thermal power.

5.2.1. Analysis of the assumptions, boundary conditions, and comparison of input parameters

Several decommissioning projects, which are already completed or in progress, indicate that technical capabilities are readily available to facilitate the safe and timely dismantling of this type of reactor. Cost estimations for decommissioning the reactors nonetheless show relatively large differences. The differences are related to a number of different factors, including:

- boundary conditions and the decommissioning strategy selected;
- cost items taken into account;
- origin of the cost estimate;
- methodology applied;
- the approach to including contingency.

In this section, a comparison has been made between two decommissioning projects in neighbouring countries for research reactors of the same type and with similar operational histories. The overall approach to cost estimation is similar and both projects exclude the costs of handling of fuel and nuclear material, as this is considered to be removed during the shutdown and post-operational period by the operation staff. Despite the similarities, there are large differences in the assumed decommissioning schedule for the two projects, with project durations of one and three years for the WWER-M and WWER-SM reactors, respectively.

Both cost estimations have been evaluated and the differences and similarities have been analysed. This comparative analysis aims to explain why differences exist and what the consequences are for the two cases.

Labour cost comparison

Salary levels for different workforce categories are shown in table II-6 of Annex II. The 'mean weighted' salary, which includes all salary-related costs averaged for all workforce categories, is shown in the same table. These values are equal to US $ 10.0 and 11.9 /hour for WWR-M and WWR-SM, respectively.

Inventory comparison

The absolute mass values (technological and building part) of inventories used for the two estimates are shown in Fig. 18. There is good agreement between the two cases, with the difference in total inventory being less than 2% of the total, i.e. 52 tonnes.

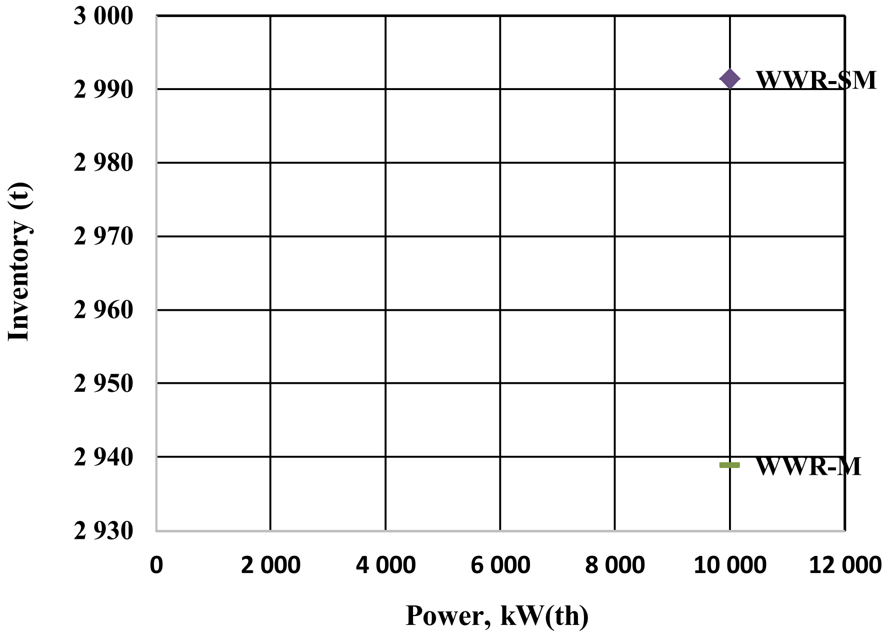


FIG. 18. Sum of mass inventory vs thermal power.

There is a large variation in the physical inventory data for the technological systems of the two reactors. In the case of some technological systems (piping, valves, tanks and heat exchangers, etc.) the difference is in the order of 50 %. The total mass of technological systems of the WWR-SM is 156 tonnes more than of the WWR-M, the greatest contributor to this being the quantity of the steel linings. The quantity of the massive reinforced concrete (the demolition of which is one of the most expensive items) is identical in both cases, being 2 500 tonnes. It is not planned to undertake full circuit decontamination in either case, and none of the following items are anticipated to be present: thermal insulation, items for remote dismantling, massive lead shielding, other shielding, miscellaneous items, and contaminated soil.

The waste inventory data of the facilities is shown in the table II-4.2 of Annex II. This table presents information on the waste masses from decommissioning. In both cases the quantity of the historical/legacy wastes are zero. The total mass of the waste is almost two times higher in the case of the WWR-SM (see Fig. 19.), there being also a large difference in its dispersion.

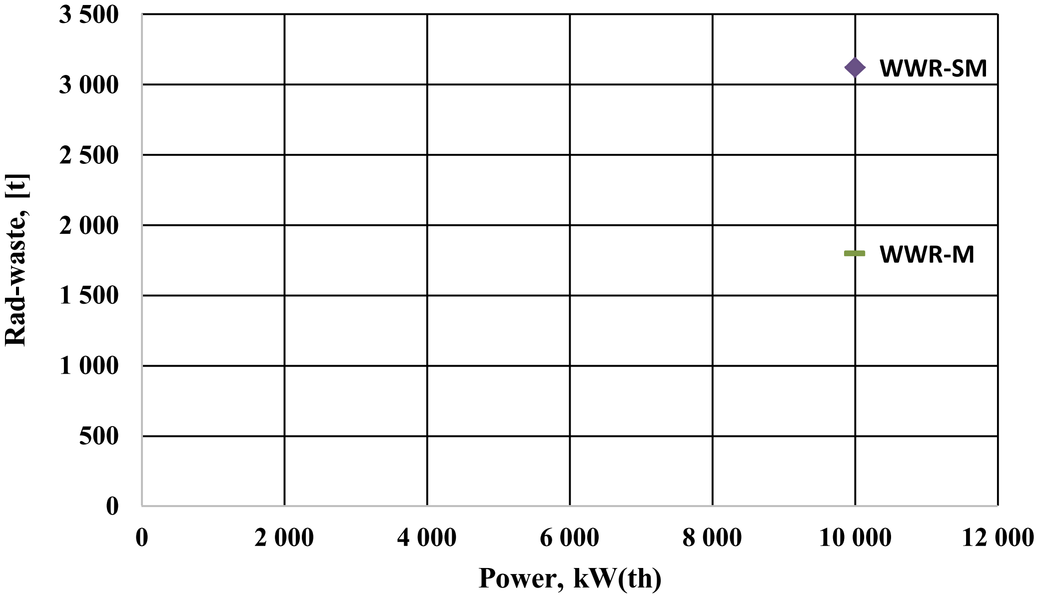


FIG. 19. Radioactive waste vs power.

Unit factor comparison

The unit factor values for inventory items are shown in Table II-5.1 of Annex II. There are only minor differences, being related to different decommissioning strategies for individual components (or available operational experience in some cases) for the two reactors.

Work difficulty factor comparison

The work difficulty factors applied for different ISDC items are shown on Table II-10 of Annex II. There are numerous differences both in terms of the relative magnitudes of the factors and their absolute values: all work difficulty factors applied in the case of WWR-M reactor were equal to 10%, while for WWR-SM reactor some of these factors were equal to 15% and the remainder to 20%.

A detailed comparison of the unit and difficulty factors with all (14) reactors considered in the DACCORD project is provided in Appendix 1.

5.2.2. Analysis of ISDC Level 0 Principal Activities

The calculated decommissioning costs for both reactors are shown in Fig. 20 and in Table II-1 of Appendix II. The total costs differ by a factor of 2.25 (2.3 million US $ for WWR-M reactor and 5.3 million US $ for the WWR-SM reactor).

More detailed analysis of the decommissioning cost performed for ISDC Level 1 activities is presented in Section 5.2.3.

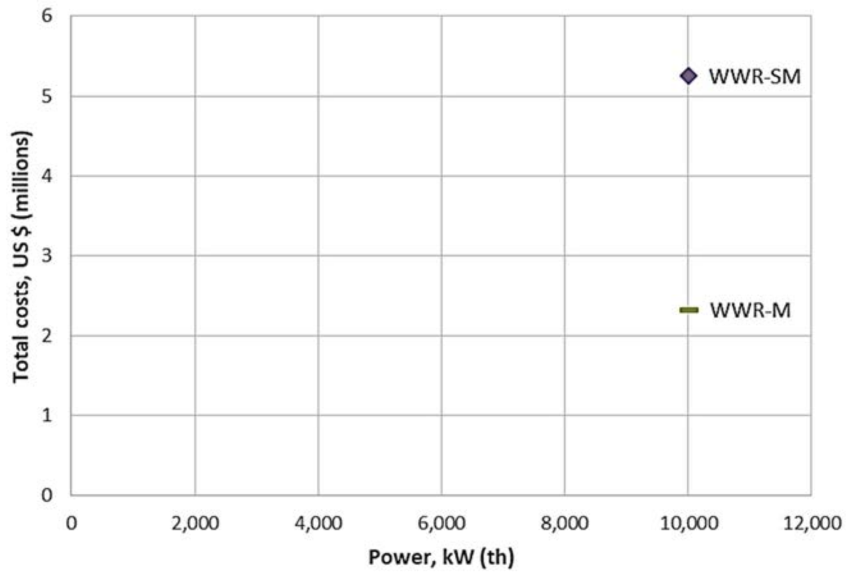


FIG. 20. Total cost of analysed WWER reactors vs thermal power.

The assumed total workforce required for the two cases differs by a factor of 1.7 (89 687 labour-hours for WWR-M and 150 343 labour-hours for WWR-SM), see Fig. 21.

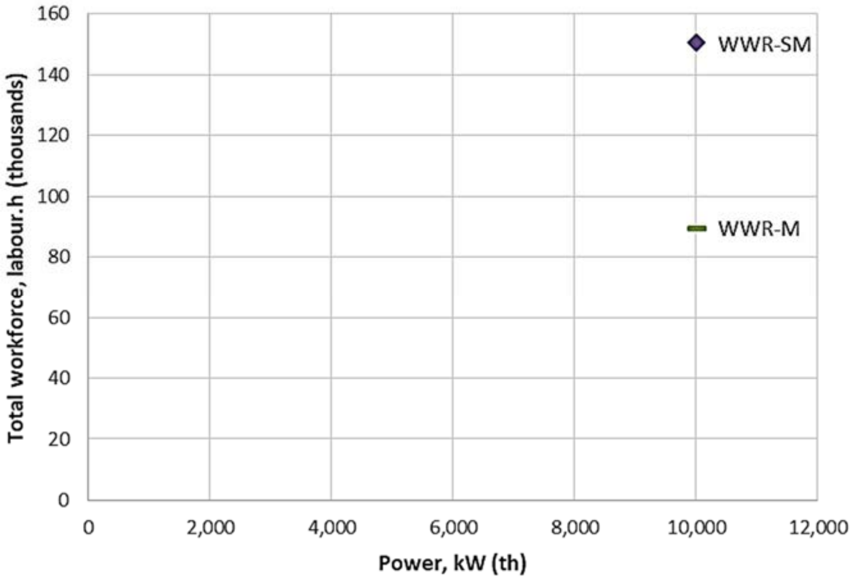


FIG. 21. Total workforce vs. thermal power.

The relationship of the total decommissioning cost vs. inventory and radioactive waste is shown in Figs. 22 and 23.

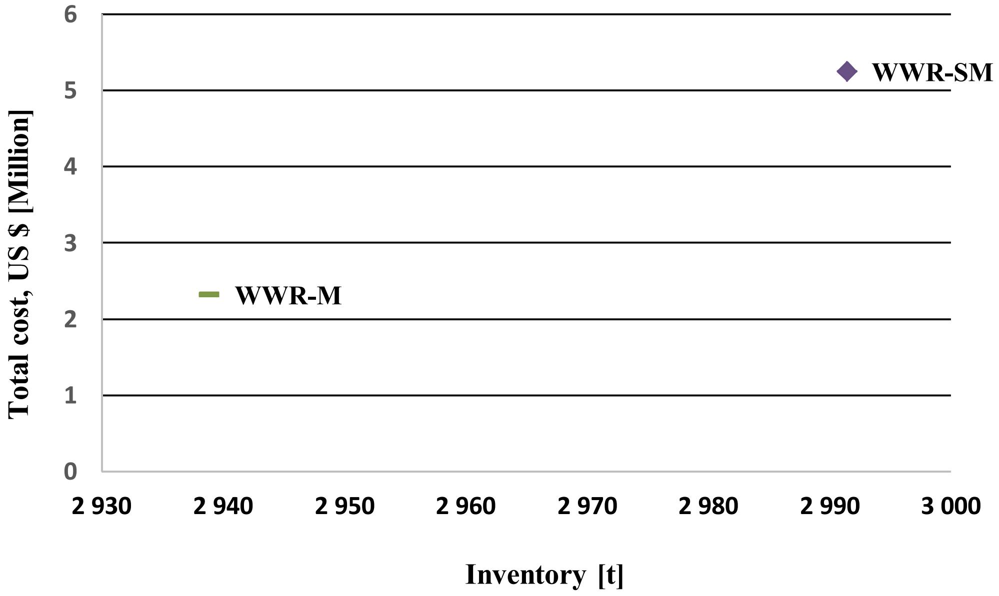


FIG. 22. Total cost vs. inventory.

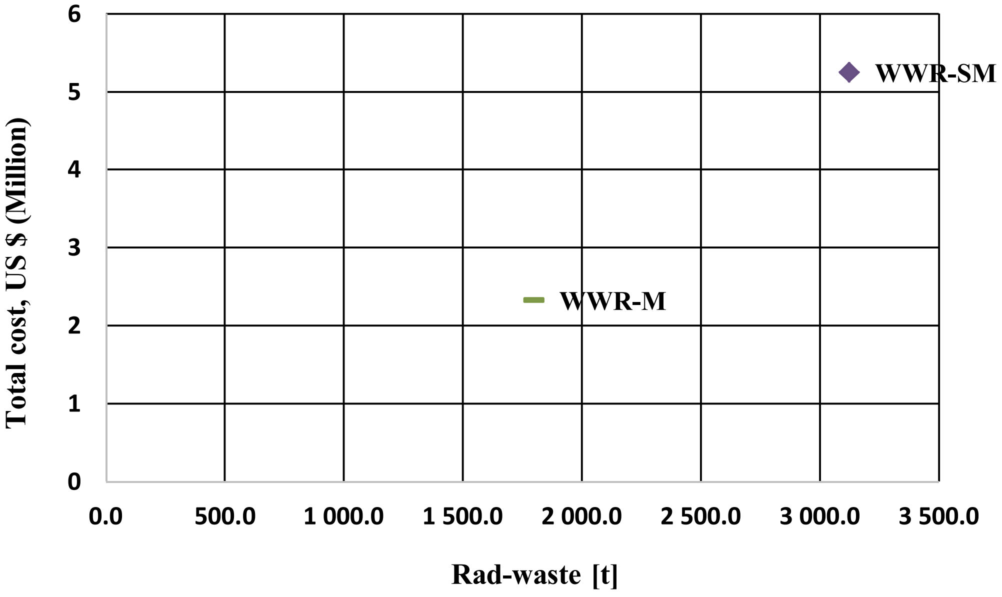


FIG. 23. Total cost vs. Radioactive Waste.

5.2.3. Analysis of ISDC Level 1 activities

The comparison of results for both estimates at ISDC Level 1 is presented in Fig. 24. It should be noted that, in the case of the WWR-M reactor, only the cost of radioactive waste pre-treatment at the reactor site (0.3 million US $) was included in Principal Activity 05 (‘Waste processing, storage and disposal’), without transportation and disposal cost. Whereas for the WWR-SM reactor, the radioactive waste disposal cost (1.3 million US $) was included into this Principal Activity. This difference in approach introduces an important difference in the cost comparisons.

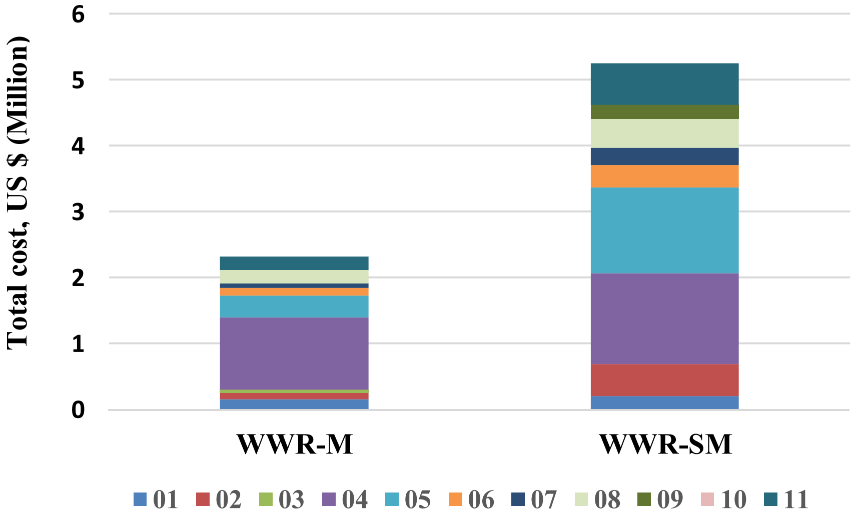


FIG. 24. ISDC L1 cost distribution in US $.

Another significant difference concerns the contingencies of 0.15 million US $ for the WWR-M reactor, and 0.9 million US $ for the WWR-SM reactor, as shown on Fig. 25. Setting aside the cost of Principal Activity 05 and the contingency from the total cost, the remaining costs differ by only 65% (1.85 million US $ for the WWR-M reactor and 3.0 million US $ for the WWR-SM reactor).

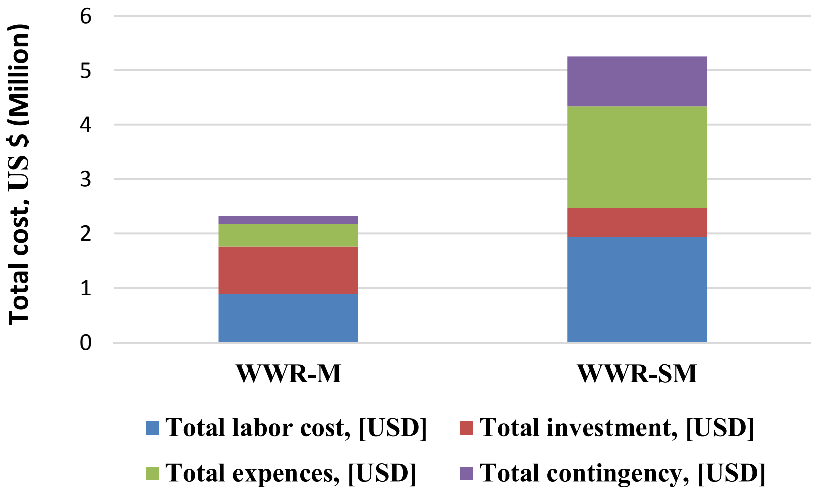


FIG. 25. Total cost breakdown by cost categories in US $.

The distribution of required workforce according to ISDC Principal Activities is shown on Fig. 26. With the exception of Principal Activity 05 (as mentioned above), close agreement may be observed, especially in the case of Principal Activity 04 (Dismantling activity in the controlled area) where the difference between the two cases is only 8%.

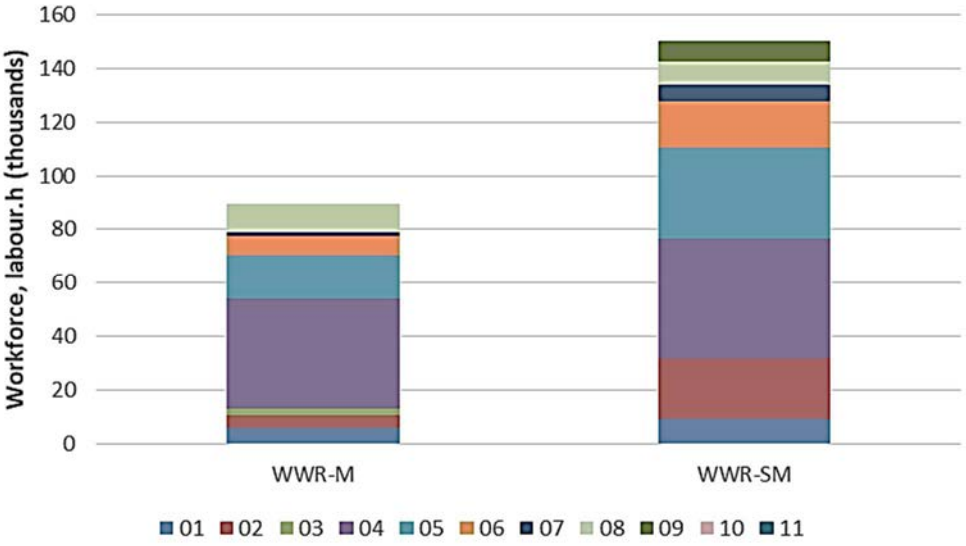


FIG. 26. ISDC L1 Workforce distribution [Labour.h].

5.2.4. Conclusions and key cost contributors

The cost estimations for two research reactors of the same type were compared and analysed, showing a factor of 2.25 difference in the calculated total cost. This difference is caused mainly by the scope of planned decommissioning work considered in the estimation. In particular, the radioactive waste disposal costs are not included in the WWR-M reactor case, whereas for the WWR-SM reactor this item represents a significant part of the total cost.

The second reason of difference is concerned with contingency estimation. Although the contingency is equal to 6.4% and 17.3% of the total costs for the WWR-M and WWR-SM reactors, respectively, in absolute terms the contingencies differ by one order of magnitude.

The third reason is a difference in estimated values of the work duration for similar activities included in the two cases, which results in a difference of the total workforce and salary costs.

The fourth reason of difference arises from the different scope of work inherent to the decommissioning projects, although the difference is less significant than those mentioned above and the differences in various ISDC activities tend to compensate each other.

The labour cost is the dominant cost driver (near 40% for both reactors), as may be seen in Fig. 25. The second most significant cost driver is different in the two cases, i.e. being expenses for WWR-M (~36%) and investment cost for WWR-SM (~37%). If investment and expenses costs are considered together, these comprise 55% and 46% for the WWR-M and WWR-SM, respectively.

As expected, the main cost-relevant activities for the total cost are Principal Activities 04 (Dismantling within the controlled area) and 05 (Waste processing, storage and disposal). The sum for these two activities is 61% and 50% (total costs) and 64% and 52% (workforce), for the WWR-M and WWR-SM, respectively.

Principal Activities 01 (Pre-decommissioning actions) and 08 (Project management, engineering and support) amount to 13% and 15% (of total costs) and 18% and 12% (workforce), for the WWR-M and WWR-SM, respectively.

The dominant cost contributor for dismantling is the vessel removal, primary circuit component (PCC) dismantling and the biological shield demolition (Activity Group 04.500); which account for 85% and 72% of dismantling costs for WWR-M and WWR-SM, respectively.

5.3. PARAMETERIC ANALYSIS

A parametric analysis was undertaken to understand the sensitivity of decommissioning costs to various decommissioning parameters. Generally, this involves a large number of calculations, there being tens of different input parameters. For the two WWER reactors, as in the other two workgroups (paragraphs 4.3 and 6.3), a simplified sensitivity analysis was performed for five sets of important input parameters:

- labour rate;
- inventory (total);
- duration (ISDC 06 & 08);
- waste management unit factors, and
- decommissioning unit factors.

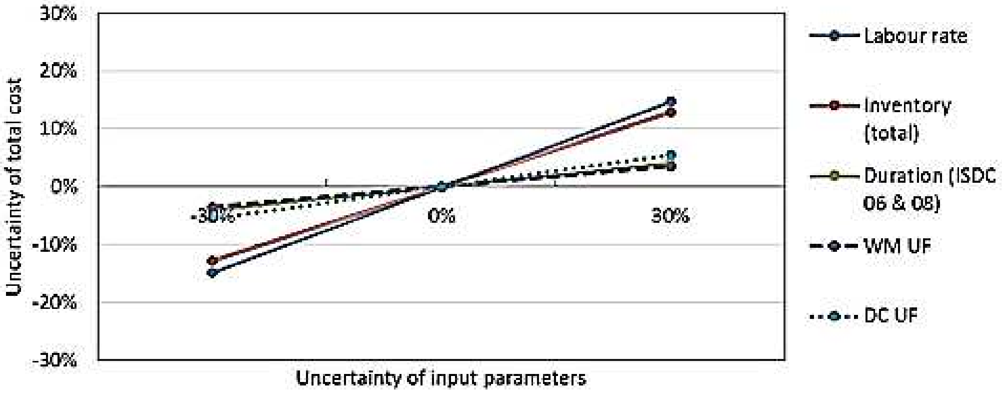


FIG. 27. Parametric analysis of WWER-SM costing case.

During calculation of the total decommissioning cost the parameter values have been modified by +/- 30 %. The results of the analysis for the WWER-SM costing case are presented on Fig. 27, which indicates that for this reactor the three most sensitive parameters are:

- Labour rate;
- Inventory (total);
- Decommissioning unit factors.

The comparison of the five most sensitive parameters for both reactors is shown in Fig. 28 for the case when the assumed parameter value was increased by 30%. This figure shows that the total cost is highly sensitive to the assumed labour rate. The total inventory with its value of 12.9% is the second most sensitive parameter. The other assessed parameters show lower levels of sensitivity.

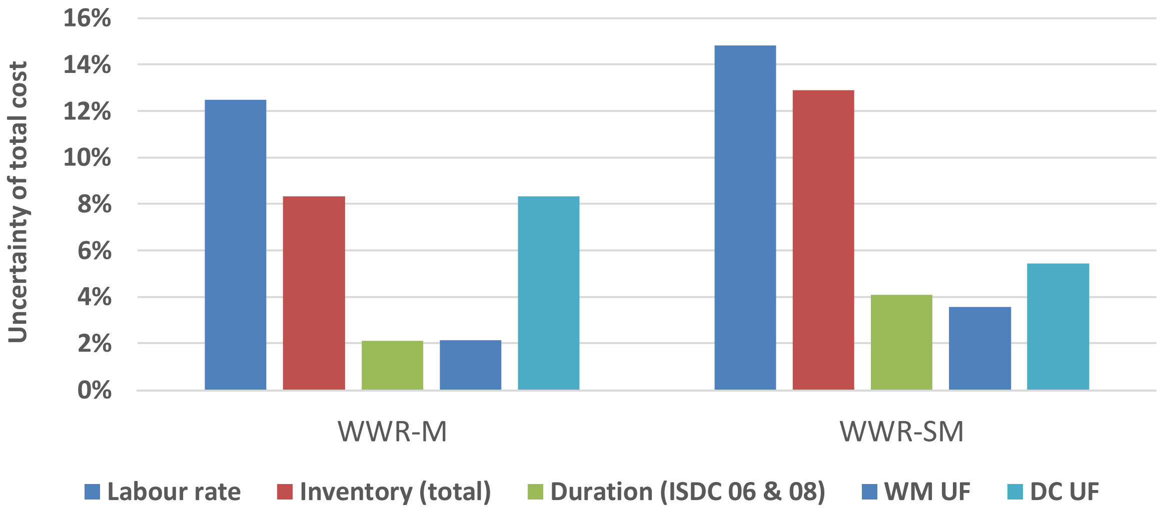


FIG. 28. Parametric analysis of WWER type research reactors. Uncertainty of input parameters has been taken as +30%.

In the WWER-M reactor case the labour rate is also the most sensitive parameter, followed by total inventory and the decommissioning unit factors each resulting in an increase in total costs in the order of 8%. Project duration (ISDC 06&08) and waste management unit factors are less sensitive, resulting in differences in the order of 2%.

6. OPEN POOL REACTOR TYPE: ANALYSIS OF ESTIMATED COSTS AND KEY COST DRIVERS

6.1. INTRODUCTION AND FACILITIES CONSIDERED

6.1.1. Introduction

The reactors analysed in this group are listed in Table 11. Decommissioning of some of these reactors has been completed or in progress; whereas for the remaining cases a preliminary/advanced decommissioning plan and cost estimate is available and this was used to prepare a CERREX-D file for cost estimation.

TABLE 11. LIST OF REACTORS ANALYSED IN SECTION 6

Reactor	Operator, location, country	Power MW$_{(th)}$	Operational period		Current Status
			from	until	
Astra	Austrian Research Centres (ARCS), Seibersdorf, Austria	10	1960	1999	Decommissioning is completed.
DR2	Risø National Laboratory, Denmark	5	1958	1975	Decommissioning is completed.
GRR-1	National Centre for Scientific Research, Athens, Greece	5	1961	2004	Extended shutdown.
JEN-1	CIEMAT, Madrid, Spain	3	1958	1987	Decommissioning is completed.
Apsara	Bhabha Atomic Research Centre (BARC), Bombay, India	1	1956	2009	Partial decommissioning completed.
Tammuz-2	Ministry of Science and Technology (MoST), Baghdad, Iraq	0.5	1980	1990	Major accident, Decommissioning is on-going.
Siloëtte	CEA, Grenoble, France	0.1	1964	2002	Decommissioning is completed.

Detailed description of the above reactors is provided in Appendix IV. Other examples of open pool reactors, as well as pool-in-tank reactors, homogenous reactors with a liquid core and Argonaut reactors are shown in Annex V. These reactors have not been analysed due to limited availability of cost-relevant data.

6.2. ANALYSIS OF AVAILABLE CASES

6.2.1. Analysis of the assumptions, boundary conditions, and comparison of input parameters

Input inventory information and waste parameters and unit factors are provided in Annex III (III-4 – III-10) for each costing case. Additional information concerning the CERREX calculation cases is presented in Annex VI. The decommissioning projects discussed here include some that address the full range of ISDC Principal Activities and others that address only some of these.

For the ASTRA, JEN-1, DR-2 and Siloëtte research reactors, published data have been used for the cost calculation; this has required the development of appropriate costing models to facilitate the translation of the published data to the ISDC format.

The data used for the TAMMUZ-2, Apsara and GRR-1 cost calculation are part estimated data and part actual data.

6.2.2. Analysis for the ISDC Level 0 costing categories

Basic characteristics of costing cases

- Astra—removal and disposition of the fuel elements; full dismantling of the reactor including the biological shield; treatment and future disposal of waste; clearance of the reactor building for unrestricted reuse; high labour rate [13];
- DR-2—ISDC 04 activities, i.e. removal of the reactor and biological shield and technological systems in the reactor building; high labour rate [14];
- Siloëtte—full dismantling, an example of the effect of on-site parallel decommissioning activities on ISDC 06 and ISDC 08; waste has been stored; high labour rate [15];
- JEN-1—dismantling of systems and components in the reactor building; removal of activated concrete; demolition of the pool structure and the underground tanks; buildings restoration; final radiological survey; waste has been stored; medium labour rate; example of the effect of on-site parallel activities on ISDC 06 and ISDC 08;the costing model has been developed from the original decommissioning programme of several nuclear installations on the site [16];
- GRR-1—full dismantling simulated; concrete of the pool remained and cleared; waste has been stored; lower labour rate [17];
- Apsara—removal of the fuel elements; full dismantling simulated including the reactor pool and reactor building; waste has been stored; lower labour rate;
- Tammuz—dismantling of structures remained after a bomb attack; waste has been stored; lower labour rate; ISDC 04, 05 and 07 considered;

Except for the ASTRA case, waste management in all cases is relatively simple, involving neither conditioning nor final disposal costs. In the case of the ASTRA reactor, waste management costs include also future waste management including disposal.

The following figures present analysis of all available reactor cases of section 6, according to the relevant parameters as total costs, workforce, total inventory and thermal power. Figure 29 presents the total decommissioning cost of analysed reactors vs thermal power.

From the discussion already presented in section 3.1 a proportional relationship may normally be expected between total reactor power and decommissioning cost. Deviation from this relationship may be due to factors such as significant divergence in project scope or labour cost unit factor. Varying scopes of considered decommissioning projects and different labour cost (by factor up to 7) are the main reasons for large spread of total costs presented below.

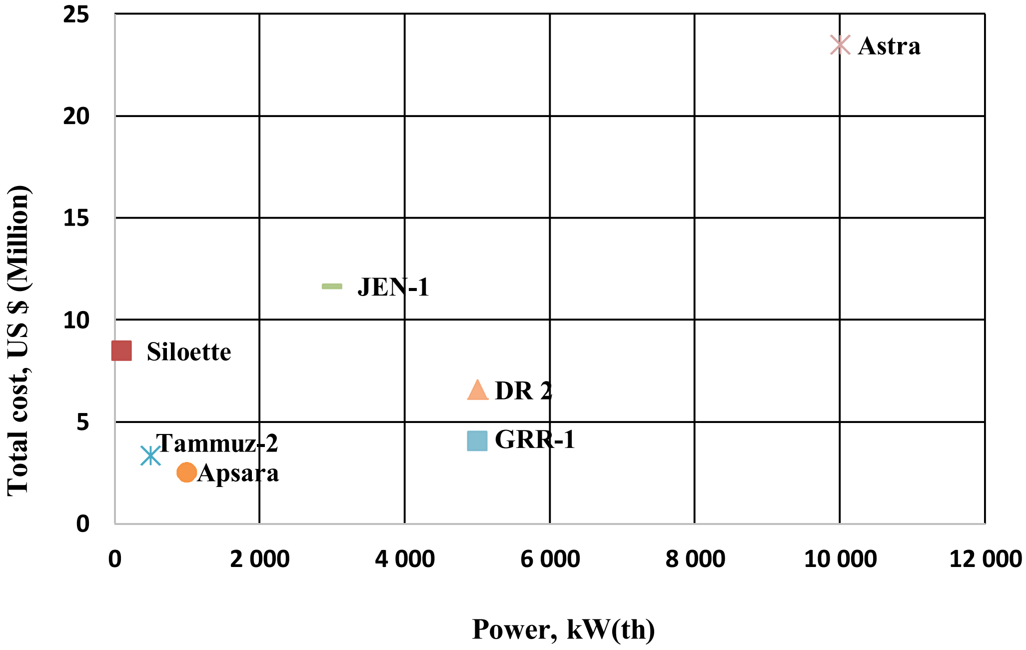


FIG. 29. Total decommissioning cost of analysed reactors vs thermal power.

Some basic observations on comparison of total costs and thermal power of the reactors analysed

- Astra reactor has the highest total cost, the main reasons being:
  - It is the largest reactor in terms of power;
  - Most ISDC activities are included in the costing case;
  - The waste management cost includes final disposal;
  - High labour rate is an important contributor to the total cost.
- For the JEN-1 reactor, the project scope includes other surrounding facilities and, for this reason, its power rating is not directly related to total cost. Preparatory activities, ISDC 01 (Pre-decommissioning actions), which are related to the preparation of a multi-facility decommissioning project, are dominant in this case;
- For the Siloëtte reactor, which is the lowest in power compared to the other assessed reactors, costs associated with ISDC 06 (Site infrastructure and operation) and ISDC 08 (Project management, engineering and support), are not directly related to power, however, those represent approximately 50% of total costs, so the total cost is more than expected. Moreover, the high labour rate increases the overall cost;
- Although DR-2 and GRR-1 reactors have the same thermal power, the lower labour rate applicable to the latter results in lower total costs in comparison to the former. For DR-2, ISDC 04 (Dismantling activities within the controlled area) is the dominant activity, while in GRR-1 costing model includes most of the ISDC activities;
- The Apsara reactor has the lowest total cost because it is a small reactor in terms of power (except for the special case of the Tammuz reactor, destroyed as a result of bombardment);
- Tammuz reactor is the lowest in power but its dominant activities (which are site restoration activities and waste management) affect the cost keeping it higher.

The above analysis is compatible with the general conclusion from Fig. 1, indicating a proportional relationship between thermal power and total cost, provided the specific features of the assessed costing cases ae taken into account, i.e. in the case of similar labour rates, assumptions and conditions for decommissioning cases. It needs to be borne in mind however that labour cost varies significantly in different countries and this will impact directly the total cost of decommissioning (See Labour cost unit factors, Annex III-6)

The ASTRA case can be considered as the representative case for higher power rate (25 million US $). The GRR-1 case (when using the labour rate 50 US $/h) can be used to represent middle power rate with the total cost approx. 13.6 million US $, the Apsara case (when using the labour rate 50 US $/h) to represent lower power rate with the total cost approx. 7.8 mil US $. The Siloëtte case is a specific case reflecting the situation when several nuclear installations are decommissioned at one site simultaneously.

Figure 30 shows Total Workforce vs Power:

- the higher workforce data for the JEN-1 reactor is a reflection of the multi-facility character of the decommissioning project;
- even though DR-2 and GRR-1 reactors have the same power, only ISDC 04 (dismantling) activities are included for the DR-2 reactor;
- there appears to be a strong relationship between total workforce and power for the other cases considered.

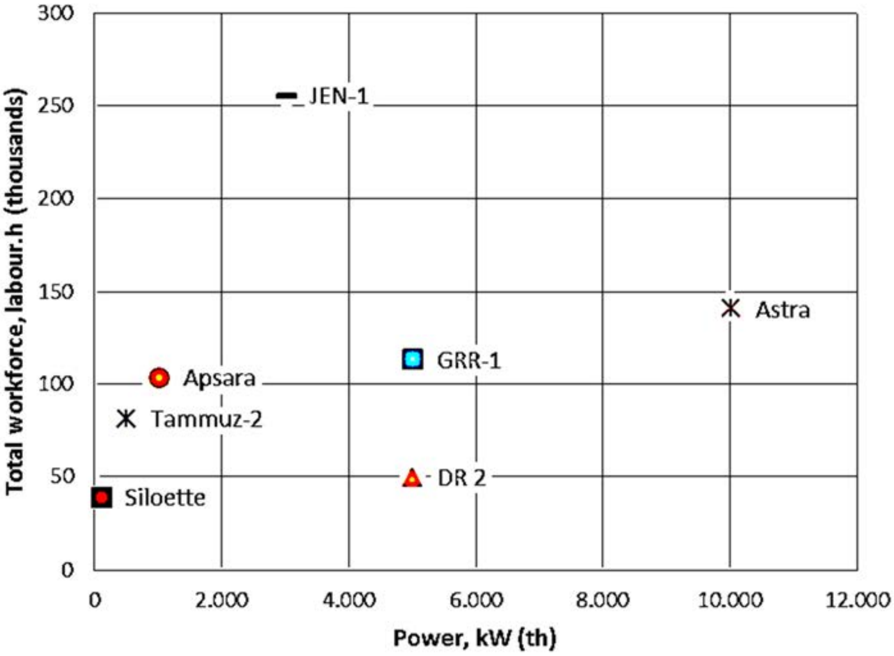


FIG. 30. Total Workforce vs Power.

Figures 31 and 32 show the total inventory vs thermal power, and the total costs vs. the total inventory, respectively. For the Apsara reactor, the total concrete quantity also includes concrete from other than the biological shield. For Tammuz, other site inventory items are included. The high total costs for ASTRA, shown in Fig. 32, result from the high labour rate and the higher inventory of the biological shield.

The total quantity of radioactive waste originating from the biological shield in the Siloëtte and the GRR-1 cases is less than for the other assessed cases; this is because in reactors with larger pools the bioshield has very low activation due to water shielding. The impact of the biological shield leads to the main difference in compared inventories.

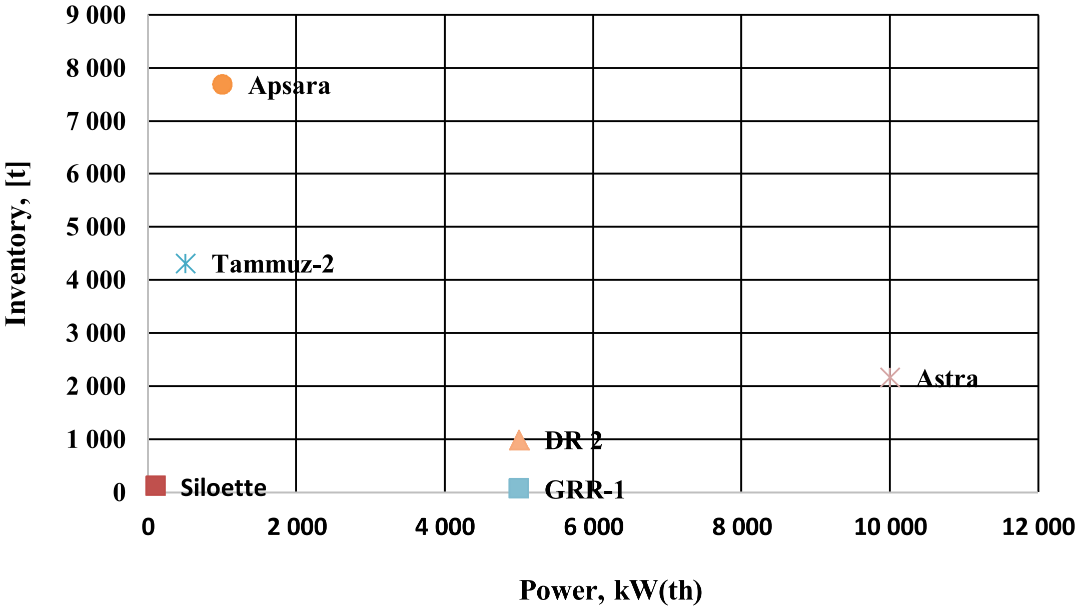


FIG. 31. Sum of Mass Inventory vs Thermal Power.

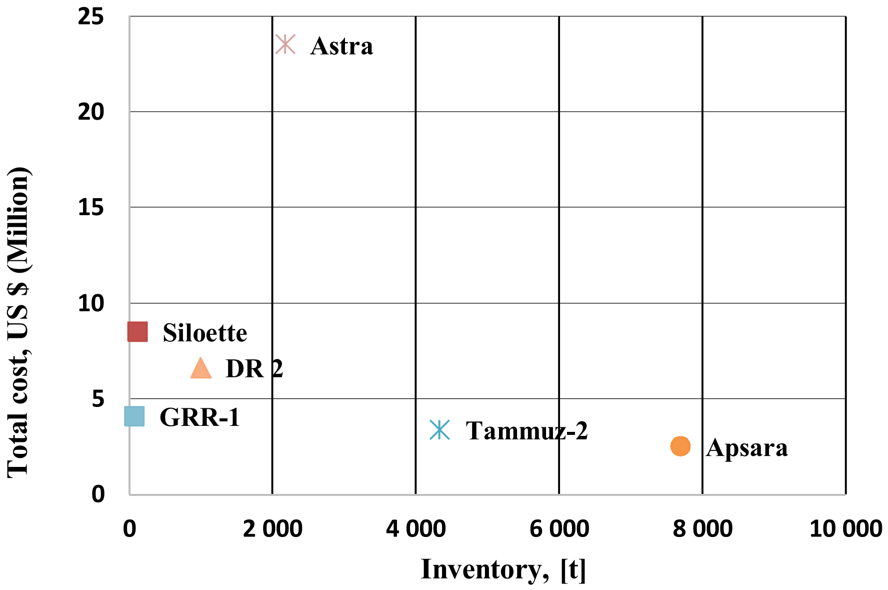


FIG. 32. Total costs vs Mass Inventory.

Figure 33 shows the total radioactive waste mass vs. thermal power. Similar issues apply as in the case of Figs. 31 and 32. Some of the Apsara inventory results in non-radioactive waste. Radioactive waste quantities consist mainly of activated biological concrete shields; the Siloëtte and the GRR-1 cases, as discussed above, do not include the total volume of the biological shield.

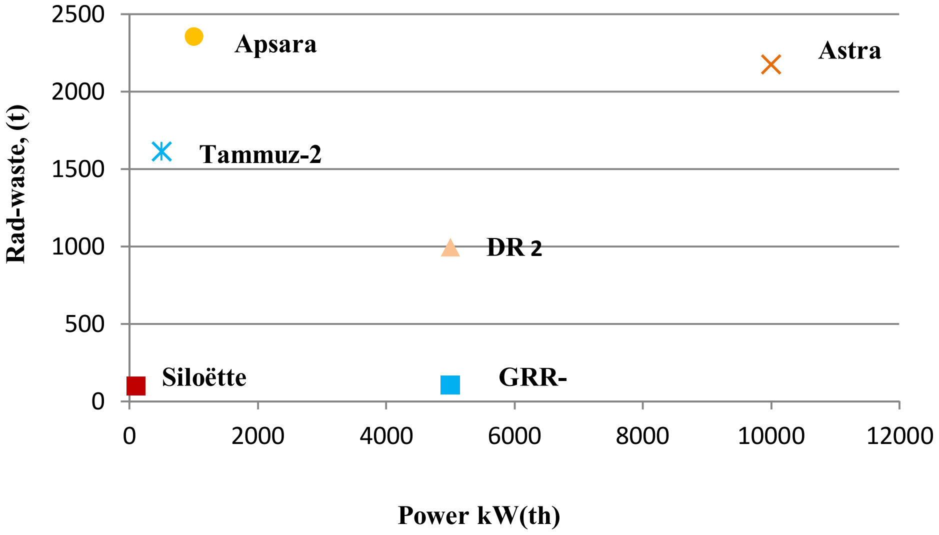


FIG. 33. Radioactive Waste vs Power.

6.2.3. Analysis at the ISDC Level 1

Table 12 shows the total costs for ISDC level 1 costing categories for the analysed open pool type reactors. The ISDC L1 Cost Distribution is also shown in Figure 34.

Recent analysis of costs for decommissioning of NPPs [18] suggests that the majority of NPP decommissioning costs may be assigned to three major cost groupings, each of which typically represent 25-30% of the total cost:

- Dismantling/site restoration (including demolition) costs, i.e. ISDC 04 and ISDC 07;
- Waste management costs, i.e. ISDC 05;
- Project management, engineering support and site operation, i.e. ISDC 06 and ISDC 08.

The most significant differences between the decommissioning of research reactors and NPPs are the inventories and extent of decommissioning activities. Although research reactor inventories are generally much smaller than those of NPPs, all typical decommissioning activities are nonetheless still implemented, which may result in an increase of unit factors of some specific activities, e.g. dismantling of reactor cores.

TABLE 12. TOTAL COSTS IN US $ FOR ISDC LEVEL 1 COSTING CATEGORIES FOR THE ANALYSED OPEN POOL TYPE REACTORS

ISDC	ISDC Name	Astra 10 MW$_{(th)}$	DR2 5MW$_{(th)}$	GRR-1 5 MW$_{(th)}$	JEN-1 3 MW$_{(th)}$	Apsara 1 MW$_{(th)}$	Tammuz-2 0,5 MW$_{(th)}$	Siloëtte 0,1 MW$_{(th)}$
01	Pre-decommissioning actions	494.900	-	456.287	3.954.362	143.621	-	124.399
02	Facility shutdown activities	-	-	307.873	-	119.482	-	56.535
03	Additional activities for safe enclosure or entombment	-	-	-	-	-	-	-
04	Dismantling activities within the controlled area	6.311.381	6.610.87	331.595	3.722.609	805.998	79.191	2.752.02
05	Waste processing, storage and disposal	5.655.247	-	470.328	693.923	60.000	1.484.920	643.852
06	Site infrastructure and operation	3.619.297	-	985.600	1.857.427	240.217	-	2.507.46
07	Conventional dismantling and demolition and site restoration	-	-	-	420.221	493.474	1.816.649	-
08	Project management, engineering and support	5.898.558	-	1.388.073	1.019.345	639.470	-	1.644.95
09	Research and development	-	-	130.694	-	-	-	-
10	Fuel and nuclear material	1.544.335	-	-	-	88.615	-	-
11	Miscellaneous expenditures	-	-	-	-	-78.799	-	768.453
	TOTAL COST US $	23.523.717	6.610.87	4.070.451	11.667.886	2.512.078	3.380.760	8.497.68

Unit factors for standard activities, i.e. decommissioning categories, may be similar to those applying to the decommissioning of NPPs. It should also be borne in mind that many preparatory and finishing activities, especially for decommissioning activities within the controlled area related to decontamination and dismantling, do not depend significantly on the inventory.

The percentages of total cost related to Principal Activities ISDC 04 and 07, ISDC 05 and ISDC 06 and 08 are presented in Tables 13 to 15.

TABLE 13. COMPARISON OF ISDC 04 AND 07 OUT OF TOTAL COSTS FOR ISDC L1 COSTING CATEGORIES

ISDC	ISDC Name	Astra	GRR-1	JEN-1	Apsara	Tammuz-2	Siloëtte
		10 $MW_{(th)}$	5 $MW_{(th)}$	3 $MW_{(th)}$	1 $MW_{(th)}$	0,5 $MW_{(th)}$	0,1 $MW_{(th)}$
04	Dismantling activities within the controlled area	6.311.381	331.595	3.722.609	805.998	79.191	2.752.028
07	Conventional dismantling and demolition and site restoration	-	-	420.221	493.474	1.816.649	-
	TOTAL ISDC (04 + 07)	6.311.381	331.595	4.142.830	1.299.472	1.895.841	2.752.028
	TOTAL COST US $	23.523.717	4.070.451	11.667.886	2.512.078	3.380.760	8.497.687
	ISDC (04 + 07)/TOTAL COST %	26,8	8,1	35,5	51,7	56,1	32,4

The dismantling/ site restoration activities (ISDC 04 and ISDC 07) are the dominant cost group for Apsara and Tammuz-2, reflecting the specific scope of those projects. For the GRR-1 case, ISDC 04 and ISDC 07 costs are unusually low, reflecting the absence of the concrete biological shield from the total inventory.

Although the management of decommissioning waste (ISDC 05) may include the cost of waste treatment, conditioning and disposal, many of the decommissioning projects considered here only include the cost associated with the initial sorting of decommissioning waste, clearance of exempt waste and storage of the remaining radioactive waste. The ISDC 05 costs for Tammuz-2 are high due to the specific scope of that project. The cost of full waste management is shown in the case of the ASTRA reactor; the other cases are based on less comprehensive waste management systems.

TABLE 14. COMPARISON OF ISDC 05 OUT OF TOTAL COSTS FOR ISDC L1 COSTING CATEGORIES

ISDC	ISDC Name	Astra	GRR-1	JEN-1	Apsara	Tammuz-2	Siloëtte
		10 $MW_{(th)}$	5 $MW_{(th)}$	3 $MW_{(th)}$	1 $MW_{(th)}$	0,5 $MW_{(th)}$	0,1 $MW_{(th)}$
05	Waste processing, storage and disposal	5.655.247	470.328	693.923	60.000	1.484.920	643.852
	TOTAL ISDC 05	5.655.247	470.328	693.923	60.000	1.484.920	643.852
	TOTAL COST US $	23.523.717	4.070.451	11.667.886	2.512.078	3.380.760	8.497.687
	ISDC 05/TOTAL COST%	24,0	11,6	5,9	2,4	43,9	7,6

The costs associated with ISDC Principal Activities 06 and 08 (project management, engineering support and site operations) are not directly related to inventories, i.e. these tend to be period dependent. The main cost drivers are the cost of staff and the duration of the project.

TABLE 15. COMPARISON OF ISDC 06 AND 08 OUT OF TOTAL COSTS FOR ISDC L1 COSTING CATEGORIES

ISDC	ISDC Name	Astra	GRR-1	JEN-1	Apsara	Siloëtte
		10 MW(th)	5 MW(th)	3 MW(th)	1 MW(th)	0,1 MW(th)
06	Site infrastructure and operation	3.619.297	985.600	1.857.427	240.217	2.507.468
08	Project management, engineering and support	5.898.558	1.388.073	1.019.345	639.470	1.644.951
	TOTAL ISDC (06 + 08)	9.517.855	2.373.673	2.876.771	879.687	4.152.419
	TOTAL COST US $	23.523.717	4.070.451	11.667.886	2.512.078	8.497.687
	ISDC 06 + 08/TOTAL COST%	40,5	58,3	24,7	35,0	48,9

The costs associated with the remaining Principal Activities, i.e. ISDC 01, 02, 03, 09, 10 and 11, are relatively high than average in the case of GRR-1 (22%) and JEN-1 (34%). ISDC 01 activities are the dominant cost group for the Spanish reactor, reflecting the specific situation applying to that project, i.e. several nuclear installations were under simultaneous decommissioning resulting in increased complexity.

ISDC Level 1 cost and workforce distributions are shown on Figures 34 and 35, respectively.

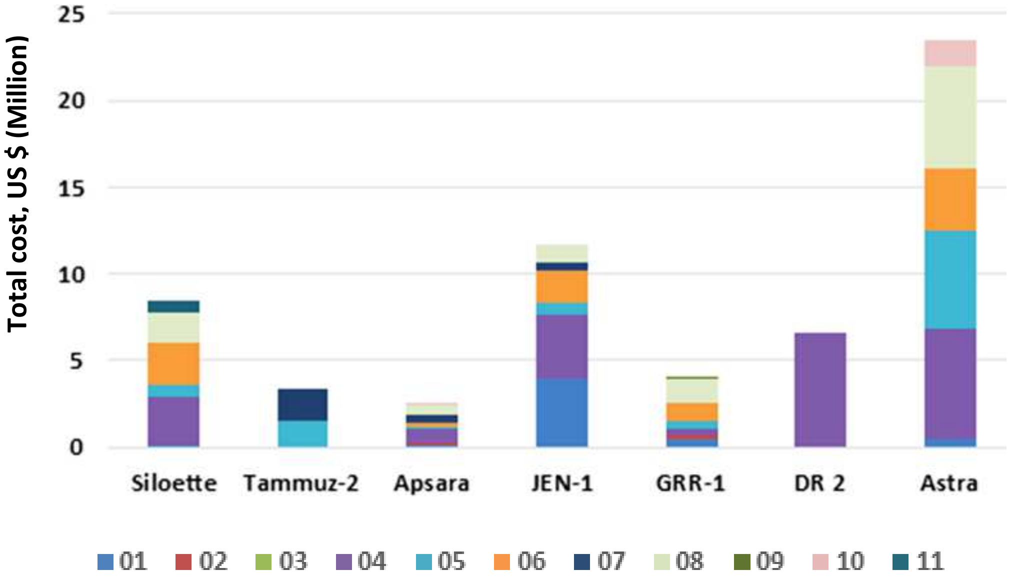


FIG. 34. Total cost distribution by ISDC L1 Cost Distribution in US$.

In summary:

- Costs for ISDC Principal Activity 04 are broadly equivalent for ASTRA, DR2, JEN-1 and Siloëtte, where the labour rate is also comparable. Lower costs are evident for the reactors where labour rates are lower: Apsara (which has a similar inventory), GRR-1 (a smaller inventory); and Tammuz-2 (very small inventory due to the bombardment experienced by that reactor).
- In the case of waste management (ISDC Principal Activity 05), ASTRA includes all waste management costs, whereas the other cases do not include all costs (especially disposal costs); the DR2 case does not include the cost of waste management.
- ISDC 06 and ISDC 08 represent important cost elements in all cases, except for DR2, which includes only ISDC 04 activities, and Tammuz-2, which only considers ISDC 04, 05 and 07 activities.
- In the case of Tammuz-2 reactor, the dominant cost elements are waste management costs, ISDC 05, and site restoration costs, ISDC 07, which correspond to specifics of the project.

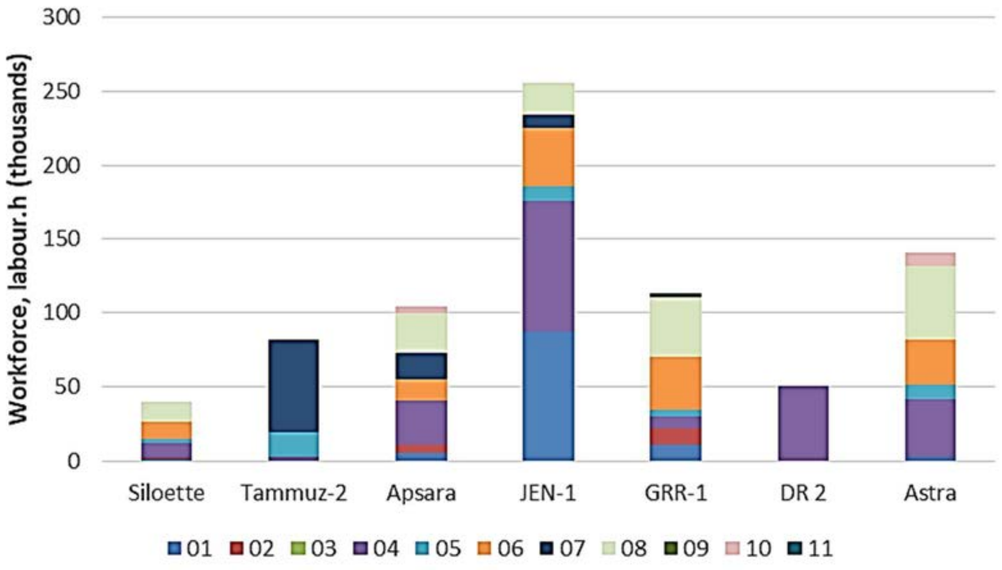


FIG. 35. ISDC L1 Workforce Distribution (Labour.h).

The analysis suggests a broad correlation between workforce costs and the power rating of the reactor, with the exception of: DR2 where only ISDC 04 activities are included; Siloëtte, where the inventory is relatively small in relation to its size; and JEN-1, due to the impact of multiple decommissioning projects being undertaken simultaneously. In the latter case, the available data were not sufficient to enable the site wide decommissioning costs to be allocated properly to individual projects, such that the cost allocated to the decommissioning of JEN-1 may be overestimated.

Waste management workforce corresponds to the extent of waste management included in each of the costing cases. It should be noted, in the ASTRA case, that the workforce shown for waste management does not correlate with the waste management costs shown in Figure 34; this is because future waste management costs (for disposal etc.) are shown in money terms only, not as labour hours [8].

ISDC 06 and ISDC 08 workforce represent the duration and the associated labour rate for each of the assessed cases.

For more detailed analysis, the ISDC 04 (Dismantling activities within the controlled area), is shown in Figs. 36 and 37 (cost and workforce, respectively).

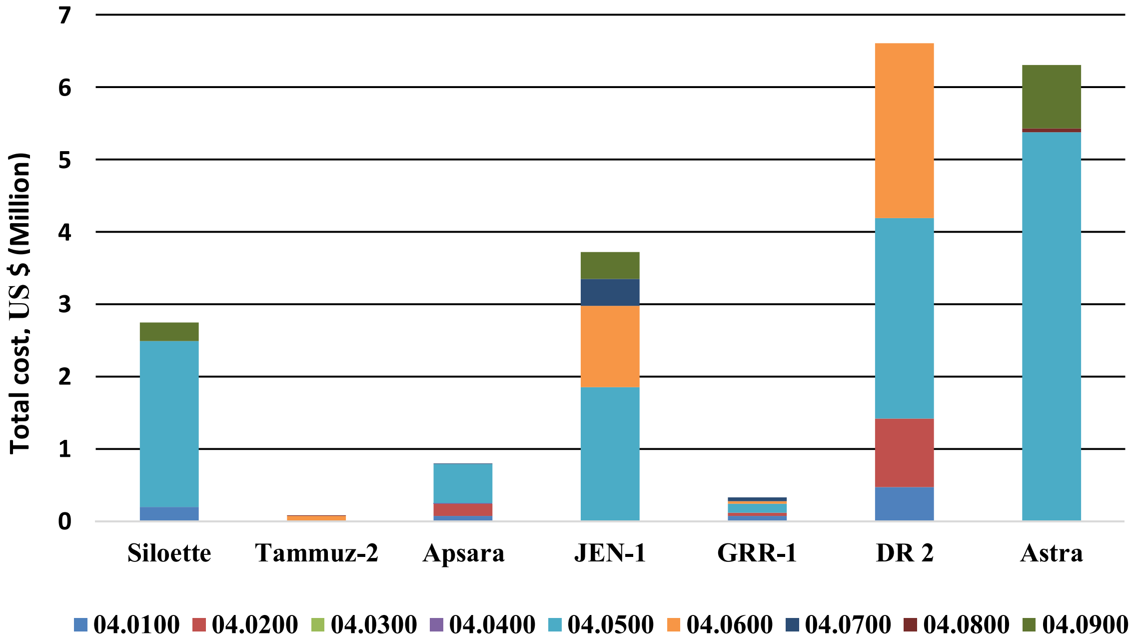


FIG. 36. ISDC 04 Cost Distribution in US $.

As can be seen from the Fig. 36, ISDC 04.0500 (Dismantling of main process systems, structures and components) and 04.0600 (Dismantling of other systems and components) represent the dominant dismantling (ISDC 04) costs. The distinction between activities 04.0500 and 04.0600 may sometimes be ambiguous due to allocation of inventory items to 04.0500 or 04.0600. Therefore, it is reasonable to consider these two items together, at least at a first approximation. Preparation of the infrastructure 04.0200 (Preparations and support for dismantling) may be important in some cases. ISDC 04.0900 (Final radioactivity survey for release of buildings) is significant in cases where the clearance of reactor building is included.

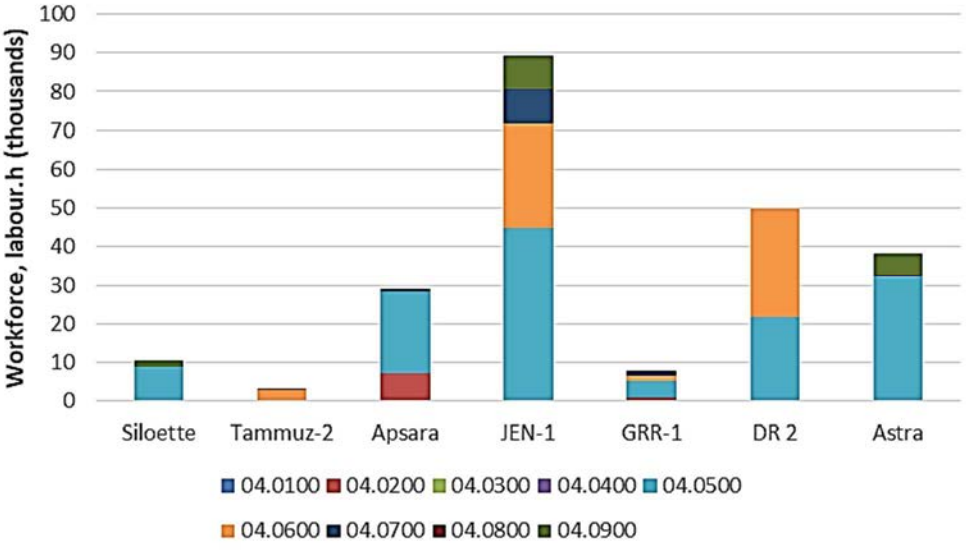


FIG. 37. ISDC 04 Workforce Distribution [Labour.h].

The workforce figures for ISDC Principal Activity 04 show a broad correlation with reactor power and the associated inventory, with low workforce figures being applicable to those cases with relatively small inventories: GRR-1, Tammuz-2 and Siloëtte, for the reasons discussed above. Note that the JEN-1 data may be overestimated, as discussed above in relation to Fig. 35.

6.2.4. Conclusions and key cost contributors

It is worth noting that there are many differences in decommissioning cases analysed within this reactor group, which have an important impact on the total costs:

- Specific design of these reactors and related inventories;
- Scope of decommissioning project;
- History of operation of the different reactors (burnup relative to the maximum power);
- End state of decommissioning project;
- Extent of radioactive waste management activities, waste management strategy;
- National regulatory framework;
- Level of experience and expertise in decommissioning;
- Labour rate.

Generally, the activities associated with the most significant cost contributions are: Principal Activity 04 (Dismantling activities in the controlled area), Principal Activity 05 (Waste processing, storage and disposal), Principal Activity 06 (Site infrastructure and operation), and Principal Activity 08 (Project management, engineering and support). The most important activities within Activity 04 are 04.0500 (Dismantling of main process systems structures and components) and 04.0600 (Dismantling of other systems and components). It should be borne in mind that the specific cost contributors for an individual project will depend strongly on the scope of that project.

6.3. PARAMETRIC ANALYSIS

The general considerations and practical procedure used for performing the parametric analysis are presented in section 4.4.3. The results of the analysis for open pool reactors are shown in Figs. 38 to 41.

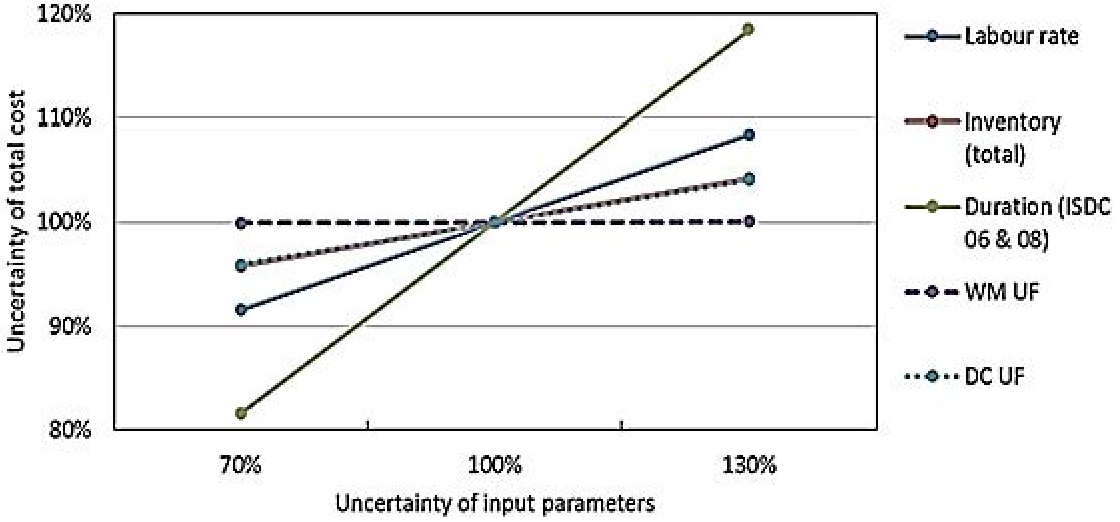


FIG. 38. Parametric analysis of Siloëtte costing case.

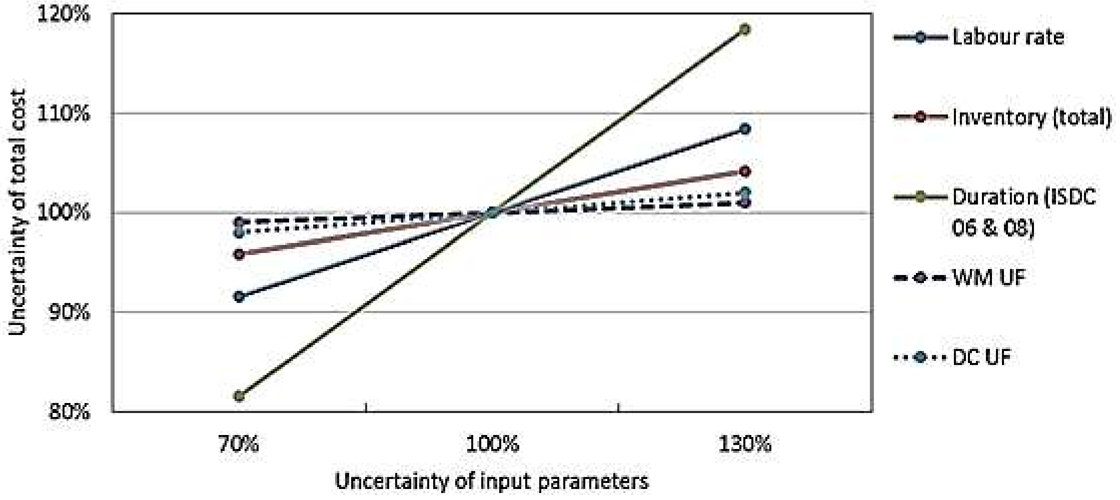


FIG. 39. Parametric analysis of Apsara costing case.

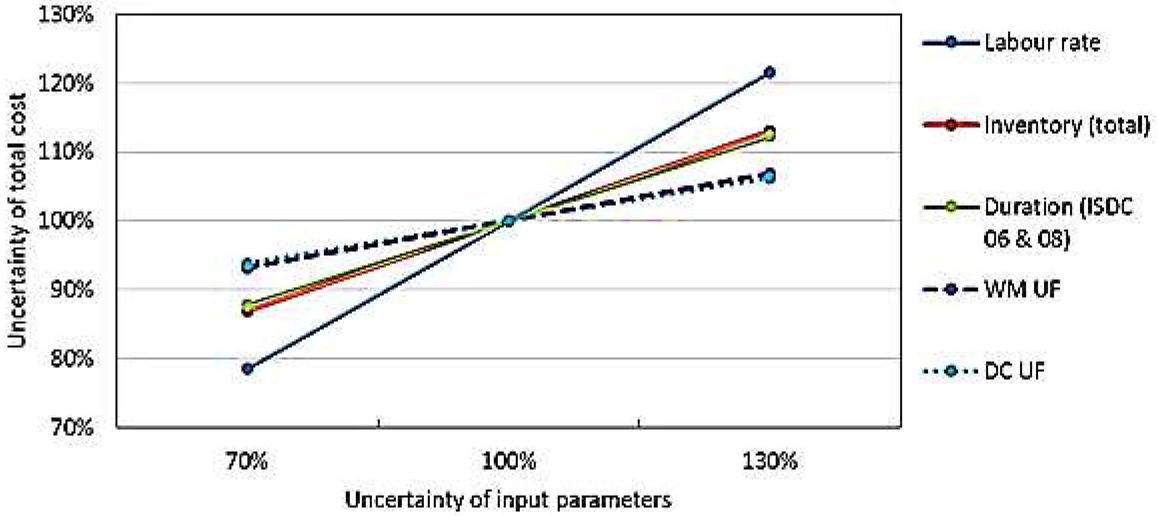


FIG. 40. Parametric analysis of Astra costing case.

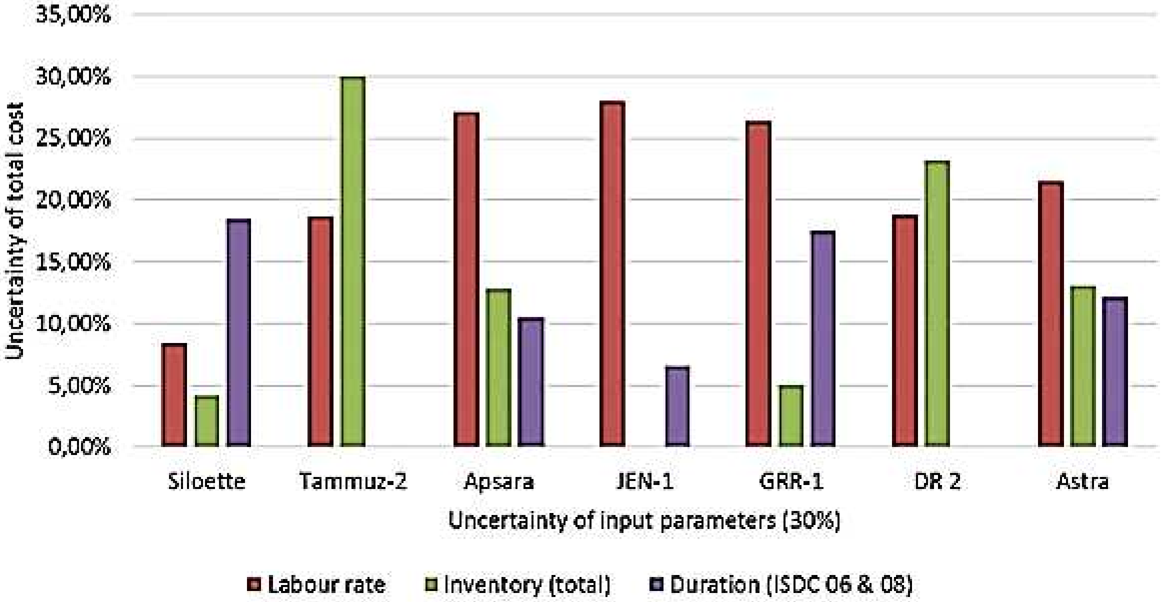


FIG. 41. Parametric analysis of open pool type research reactors. Uncertainty of input parameters is +30%.

The following conclusions are evident from the parametric analysis:

- Each case might behave differently in terms of parametric analysis;
- Uncertainty of waste management unit factors has a bigger impact on total cost uncertainty in the Astra case, which includes full waste management (treatment, conditioning and disposal) for ILW, LLW and VLLW types of radioactive waste;

- Uncertainty of the decommissioning unit factors has a greater impact on total cost uncertainty in the Siloëtte and Astra cases;
- Uncertainty of labour rate shows the largest impact on total cost uncertainty for all cases excluding Siloëtte and Tammuz-2 and DR 2 cases;
- Uncertainty of inventory is the most important factors for the Tammuz-2 and DR 2 cases;
- Uncertainty of the duration of ISDC 06 and 08 items has the biggest impact on total cost for Siloëtte, reflecting the dominance of period-dependent costs (due to the low inventory) and the high labour rates applicable in this case;
- Tammuz-2 and DR 2 (ISDC 04) only include inventory dependent activities, resulting in inventory being the most sensitive input parameter in estimating total cost

In order to reduce uncertainty of total cost, efforts mostly should be foccused on reducing uncertainty of those input parameters which have the biggest impact on total cost uncertainty.

OVERALL CONCLUSIONS

The cost of decommissioning a research reactor depends on many different factors including the reactor type, its age and operational history, the final status of the facility, the level of previous decommissioning experience of the reactor owner, the general labour and equipment costs in the country of location, together with the national infrastructure for management of spent fuel and radioactive waste. Associated with the work-power cost is the issue of whether the dismantling work will be undertaken by personnel previously involved in the operation of the reactor or by specialist contractors, which in turn will have a significant impact on the overall project duration due to the time needed for operating personnel to be retrained to perform decommissioning roles.

The above combination of factors makes it very difficult to predict the cost of decommissioning in the absence of a detailed analysis of the specific reactor in question and of associated facilities such as hot cells and laboratories, including having a good understanding of the physical and radiological inventory, the detailed decommissioning strategy and associated timeframe for different phases of activity, and the strategy for management of the resulting materials and waste. This complexity also means that decommissioning costs vary over a wide range, even for reactors with a similar power rating and having a broadly similar design.

An analysis of the above issues was undertaken during the course of the DACCORD project, based on existing data previously collected by the IAEA on total cost (calculated or actual), as well as datasets collected for 14 research reactors, which were analysed in detail. The detailed dataset includes reactors already decommissioned as well as several reactors that are shutdown but not yet decommissioned and some reactors still in operation, whose decommissioning is still at the planning stage. The objectives of the project were twofold: (1) to establish benchmarking data for decommissioning costs of research reactors and (2) to determine representative data for use in the CERREX-D cost estimation software developed during the course of the project. The intent was that the first objective should enable Member States with little or no decommissioning expertise to estimate the overall cost of decommissioning during the early planning stages; whereas the second objective would facilitate the preparation of preliminary cost estimates for the decommissioning of research reactors using CERREX by using data typical to the reactor type being analysed.

It should also be borne in mind that a significant period of time (sometimes tens of years) may elapse between the shutdown of the reactor and the commencement of active dismantling. Activities undertaken during this period, e.g. to ensure the reactor and any remaining fuel remain in a safe state, will also incur costs. These costs are generally not reflected in the decommissioning cost, except when the reactor is put into a safe enclosure state awaiting final decommissioning. The cost implications of delayed dismantling are related to ongoing surveillance and maintenance of the facility, possible changes to the technology used for dismantling in the event that dose levels are reduced and changes in waste management processes. These issues require careful consideration; they are outside the scope of this project.

6.4. GENERAL CONSIDERATIONS ON COLLECTED DATA

The data collected on total costs do suggest a possible relation between the global decommissioning cost and the rated thermal power for reactors, particularly those with a power rating of greater than 1 $kW_{(th)}$, though with increasing variability of costs at higher power levels. Even for zero power or very low power reactors it is unlikely that decommissioning costs will be less than US $100 000. The cost of dismantling research reactors of power ratings greater than 1 $kW_{(th)}$will generally be greater than US $1 million (2013 price levels) provided all major cost elements are considered, including waste disposal costs. At power levels of 1 $MW_{(th)}$ or more the cost can range from US $1-10 million (2013 price levels). For power reactors rated at 10 $MW_{(th)}$ or more the cost may range from US $10-100 million (2013 price levels); the highest–cost reactor included in this project is the Siloe reactor (35 $MW_{(th)}$) in Grenoble, France, recently decommissioned at a total cost of US $168 million (2013 price levels). It is important to bear in mind that site-specific factors, such as exceptional costs associated with demonstrating that site release criteria have been achieved or costs associated with location on multi-facility sites, may result in the costs being outside these ranges.

The parametric analysis undertaken as part of this project suggests that the input parameters to which a decommissioning cost estimate is most sensitive include: the material inventory (taken to include clearance of buildings), the unit labour cost for the relevant disciplines involved, the duration of the project and the strategy adopted for management of materials and waste. The material inventory is a key cost driver for research reactor decommissioning, giving rise to activity-dependent costs. This has a significant impact on work-power needs (i.e. the total number of labour-hours that are necessary to implement the full decommissioning project) as it determines the scope of the major decommissioning activities such as decontamination, dismantling, and material and waste management. Research reactor inventories vary broadly from critical assembly facilities to reactors that are comparable in size and complexity to nuclear power plants.

Project duration is also an important cost driver, giving rise to period–dependent costs that are also work-power dominated. Work-power requirements associated with project management and site infrastructure and support activities, including engineering support, will typically result in costs of a similar order of magnitude to those for dismantling activities undertaken in the controlled area. Many of the latter costs will occur throughout the lifetime of the project whereas the former will be limited to when the relevant dismantling activities are taking place.

Given the overall importance of work-power costs, the labour rates for the different disciplines involved in decommissioning represent a key cost driver, being a major determinant both of activity-related and period-related costs for research reactor decommissioning. Labour rates vary significantly across the world and it is evident that in countries where these are relatively very high there is a strong tendency to reduce the overall project duration, and thus decrease the workforce needed, through applying more efficient decommissioning strategies.

Many of the decommissioning cases considered in this project assume that waste will be placed in long-term storage and no allowance is made in the estimate for the eventual disposal cost. It is evident that inclusion of the disposal cost will generally increase the overall waste management costs by a significant amount. This is therefore an important cost driver.

The decommissioning activities which typically contribute most to the overall cost are: the dismantling activities in the controlled area (ISDC Principal Activity 04); waste management activities (Principal Activity 05); project management, engineering and support (Principal Activity 08) and site infrastructure costs (Principal Activity 06). These activities together result in 70-80% of the total decommissioning cost, in roughly equal proportions between: (1) dismantling, (2) waste management and (3) project management, engineering support and site infrastructure costs. Licensing-related activities (Principal Activity 1) generally account for about 10% of total costs. It needs to be borne in mind that significant variations in the relative costs of the main contributing activities were evident. Detailed results for the limited dataset considered in this project were:

- Pre-decommissioning actions (Activity 01): 5-11% (of total cost)
- Dismantling activities in the controlled area (Activity 04): 20-37%
- Waste management (Activity 05): 10-36%
- Project management, support and site-related cost (Activity 06 & 08): 15-42%

As well as undertaking an analysis of the project activities, which result in the greatest overall costs, an analysis of the relative contributions of different cost categories, i.e. labour, investment and expenses, was carried out. Significant variations are also evident in the relative importance of labour costs, investment/equipment costs and expenses, though, as a general rule, labour is likely to account for 50-60% of the total cost. The relative importance of investment costs and expenses will depend on the accounting conventions used in the relevant Member State (and on the contracting strategy employed).

6.5. EXPERIENCE FROM USE OF THE CERREX-D SOFTWARE

The experience gained from the use of CERREX-D in this project suggests that this is an effective tool for preliminary costing for non-complex nuclear facilities with relatively small inventories, enabling greater understanding of the main contributors to costs and thereby facilitating the cost estimation for individual cases. The default decommissioning categories incorporated in the software and the related unit factors appear generally to be sufficient for the main inventory items relevant to research reactor decommissioning. For specific situations in which remote dismantling technologies may be required, e.g. dismantling of reactor core components or situations involving non-standard preparation and finishing activities, additional decommissioning categories need to be developed for that specific case. Some of the costing cases considered in this project involved the use of such categories together with appropriate unit cost factors.

The waste management categories used in CERREX are based on the current IAEA classification of radioactive waste (GSG-1). The unit factors for waste management vary very significantly according to the waste management approach considered in specific decommissioning project. The default unit factors used in CERREX-D represent the full cost of waste management including conditioning and disposal. Most of the costing cases assessed in this project only included the costs of storage of the waste, generally on the site, but not including the cost of final disposal. Based on the experience of the contributors to this project, unit cost factors are lower by factor of approximately 5 to 10 when disposal costs are excluded. The partitioning schemes developed for evaluation of waste streams may be used as templates for further work with CERREX-D.

In undertaking a cost estimate for decommissioning it is important that the assumptions, exclusions and boundary conditions relating to the decommissioning project are clearly and unambiguously described and recorded, as these are important determinants of differences between different cases. These may be related to the legal and regulatory framework, clearance limits, waste acceptance criteria, waste management infrastructure, decommissioning strategy, project scope and the planned end state.

Other aspects which need careful attention in developing a decommissioning cost estimate include:

- Input data for period dependent activities and collateral costs.
- Selection of the decommissioning categories for reactor-related inventory items. The applicability of default unit factors for decommissioning categories requires careful consideration for each specific case, together with selection of work difficulty factors.
- Selection of waste management categories and associated unit factors.

6.6. OPEN ISSUES CONCERNING THE USE OF CERREX

CERREX has a number of shortcomings compared to costing analysis undertaken with more sophisticated costing tools:

- The duration of different period-dependent activities or project phases cannot be distinguished, i.e. a single duration of all project management and site support activities must be assumed.
- The inventory database does not include radiological data and partitioning of inventory quantities into waste classes needs to be done manually.
- Only single-point deterministic cost estimates may be made; the use of probabilistic methods in order to perform decommissioning cost risk assessment.
- The variation with time of decommissioning parameters (e.g. work-power, overall costs, is not possible with the current version of the CERREX software.

APPENDIX I. UNIT FACTORS AND WORK DIFFICULTY FACTORS

The methodology used to develop cost estimate for nuclear facilities follows the basic approach presented in the DOE's Decommissioning Handbook [19] and the AIF/NESP-036 'Guidelines for producing commercial nuclear power plant decommissioning cost estimates [20] study report [21].

I.1. OVERVIEW OF UNIT FACTORS

Based on Refs. [20, 22-23] this sub-section gives a short overview of the decommissioning cost calculations and the use of the unit factors.

I.1.1. Guidelines for Producing Commercial Nuclear Power Plant Decommissioning Cost Estimate

These very detailed guidelines were prepared in a response to the nuclear industry need to facilitate the preparation of cost estimates to decommission nuclear power reactors of the pressurized water reactor (PWR) or boiling water reactor (BWR) types. While the examples, references and terminology directly apply to PWRs and BWRs, much of the estimation approach is applicable to other types of reactors or fuel cycle facilities [20].

The guidelines classify the types of costs into three categories: (1) period dependent costs, (2) activity-dependent costs, (3) collateral and special item costs.

- Period–dependent costs are proportional to the duration of individual activities or of the entire project. They arise from project management, administration, routine maintenance, radiological, environmental and industrial safety and security activities.
- Activity–dependent costs are directly related to the extent of 'hands-on' work involved in decommissioning (activities related to inventory, performed manually or remote controlled). They include activities such as decontamination, removal of components, and packaging, shipping and disposal of waste. Costs arise from labour, materials, energy, equipment and services.
- Collateral costs and costs for special items are those which cannot be assigned to a certain work activity or to a period–dependent activity, e.g. if equipment is used to support many activities, the purchase or the rent of this equipment may belong to this category.

The 'unit factor approach' to costing, as described above, provides an activity detailed cost estimate by breaking down the decommissioning programme into a series of discrete and measurable work activities. The preparation of cost estimates using such an approach relies on a development of unit factors for each repetitive event such as cutting pipes, segmenting vessels, demolishing concrete, transporting and disposing of wastes, etc. The factors were prepared on a productivity unit basis (labour hours per unit mass or volume of specific material etc.) to perform activities under ideal conditions.

The costs of repetitive activities may be estimated using the following formula [22]:

$$\text{Activity Cost} = \text{inventory quantity X unit cost factor}$$

The inventory of each type of component is developed from the site-specific information for the facility.

Due to the transfer from ideal to real working conditions, the work difficulty factors (WDF) are applied (by multiplying to increase the performance time) to account for the productivity losses associated with working in a difficult or hazardous environment (e.g. work in heights, in confined space, in protective clothes, with respirators).

I.1.2. CERREX-D software

Costing methodology implemented into the CERREX-D software is based on the ISDC and implements directly the unit factor approach [23]. In order to use the CERREX-D software effectively, a set of decommissioning categories was developed to cover typical decommissioning activities and relevant representative inventory items, typical for research reactors.

Decommissioning categories (D&D and waste management categories) in cost estimates represent key parameters for calculation of cost for inventory dependent and waste management activities which are considered as a sub-group of inventory dependent activities.

D&D categories

There are 30 pre-defined D&D categories in the CERREX-D software, that the users can use for the cost calculation, and there are additional 20 possibilities to be defined by user, if needed.

The list of the pre-defined D&D categories are shown in Table 16. In the CERREX-D software the inventory dependent D&D categories are referred with the acronym INV. A detailed description of each above listed categories are given in Ref. [23].

TABLE 16. LIST OF D&D CATEGORIES

No. of the category	Name of the category	Unit
INV1	Removal of operational solid waste & materials	[t]
INV2	Removal of operational liquid waste & sludge	[t]
INV3	Manual chemical decontamination	[m^2]
INV4	Mechanical & thermal decontamination	[m^2]
INV5	Decontamination of closed circuits	[syst]
INV6	Dismantling of general equipment	[t]
INV7	Dismantling of massive & thick wall equipment	[t]
INV8	Dismantling of piping and valves	[t]
INV9	Dismantling of tanks, heat exchangers	[t]
INV10	Dismantling of steel linings	[t]
INV11	Dismantling of ventilation & thin wall equipment	[t]
INV12	Dismantling of cranes and lifting devices	[t]
INV13	Dismantling of cables & cable trays	[t]

No. of the category	Name of the category	Unit
INV14	Dismantling of general switchboards, el. cabinets	[t]
INV15	Dismantling of graphite elements	[t]
INV16	Dismantling of embedded elements	[t]
INV17	Dismantling of thermal insulation of systems	[t]
INV18	Dismantling of asbestos & hazardous materials	[t]
INV19	Dismantling of equipment using remote dismantling techniques	[t]
INV20	Dismantling of doors, gates, hatches, etc.	[t]
INV21	Dismantling of massive lead shielding	[t]
INV22	Dismantling of lead shielding bricks & plates	[t]
INV23	Dismantling of other shielding	[t]
INV24	Dismantling of glow boxes	[t]
INV25	Dismantling of remaining types of equipment	[t]
INV26	Removal of contaminated soil	[t]
INV27	Removal of massive reinforced concrete	[t]
INV28	Demolition of standard civil materials	[t]
INV29	Final remediation of the site	[m^2]
INV30	Final radiological monitoring of building surfaces	[m^2]

Waste management categories

There are 16 pre-defined waste management categories (11 for the waste management of the decommissioning waste and 5 for the retrieval of the legacy waste) in the CERREX-D software, and there are additional 41 possibilities to be defined by user, if needed.

The list of the pre-defined waste management categories are shown in the Tables 17 and 18. In the CERREX-D software the waste management categories are referred with the acronyms WM and RLW. A detailed description of the categories are given in Ref. [23].

TABLE 17. LIST OF WASTE MANAGEMENT CATEGORIES

No. of the category	Name of the category	Unit
WM1	Processing of the HLW	[t]
WM2	Processing of the ILW	[t]
WM3	Processing of the LLW	[t]
WM4	Processing of the VLLW	[t]
WM5	Processing of the VSLW	[t]
WM6	Processing of the EW	[t]
WM7	Processing of concrete	[t]
WM8	Processing of metals (dominant type) and all types of reusable materials	[t]
WM9	Processing of hazardous materials	[t]
WM10	Processing of conventional non–reusable waste	[t]
WM11	Processing of non-radioactive waste	[t]

TABLE 18. LIST OF LEGACY WASTE MANAGEMENT CATEGORIES

No. of the category	Name of the category	Unit
RLW1	Retrieval of legacy HLW	[t]
RLW2	Retrieval of legacy ILW	[t]
RLW3	Retrieval of legacy LLW	[t]
RLW4	Retrieval of legacy VLLW	[t]
RLW5	Retrieval of legacy EW	[t]

Unit factors for the D&D and waste management categories

The ISDC costing methodology for CERREX-D requires a definition of the next three unit factors for each D&D and waste management categories:

- ***Workforce unit factors*** [Labour.hour/unit] used for calculation of Labour.hours related to individual activities and consequently for calculation of the labour cost;
- ***Investment cost unit factors*** [currency/unit] used for calculation of investment cost for individual activities; unit factors should cover all related investment (capital, equipment and material) costs;
- ***Expenses cost unit factors*** [currency/unit] used for calculation of expenses for individual activities; unit factors should cover all related expenses according to the ISDC definition.

As an initial support to the users of the CERREX-D software, unit factors close to expected realistic values have been supplied (“default” values). It should be noted that these factors have not been taken from one particular origin. The user should review/modify the unit factors to his/her own needs [23].

The analysis of the above-mentioned unit factors for the D&D and waste management categories can be found in the sections I-3 and I-4.

I.1.3. Labour cost unit factors of the Licensee and Contractor

Labour cost unit factors together with the manufactured items are used for the calculation of the labour cost. Labour cost unit factors include payments to personnel involved in ISDC items, payments to funds (social security, insurance, charges, etc.).

The analysis of the labour cost unit factors of the Licensee and Contractor are discussed in Section I-5.

I.2. ANALYSIS METHOD OF THE UNIT FACTORS

Some calculation cases involved in the project did not meet criteria of the analysis, because in these cases only the total decommissioning cost values were available. In this cases the Participants tried to determine unit factors similar to the used CERREX-D unit factors, but in some cases because of the lack of the detailed information and input data the result was questionable.

The data whose values were much higher than the average have been not included. Similarly, the data leading to the misinterpretation of the information were also not included.

In some figures one can see “0” values. The meaning of these values might be different. It is possible that the unit factor is actually equal to “0” or it is possible that it is equal to “0” because the Participant did not use it. (Participant introduced for example new user defined unit factor). The “0” values were not deleted because the “0” value also have information but in the calculation of the average value, only the real non-zero values were taken into account.

In the light of the fact that the CERREX-D software uses 90 different unit factors for the D&D and 48 unit factors for the waste management categories, only few of them are analysed in the following sections.

Possible reasons for their selection for the analysis are the following:

- height differences between the unit factors;
- the unit factors relate to the most expensive items;
- the highest difference between the value of the unit factor and the average value;
- the unit factor relates to the most interesting procedure from technical point of view.

Unit factor values used for the cost calculations by the Participants are marked in figures with a blue circle, and the “default” values with a red square.

I.3. ANALYSIS OF THE UNIT FACTORS FOR D&D CATEGORIES

As mentioned above, the CERREX-D software uses 90 unit factors for the calculation of the decommissioning activities (30 D&D categories x 3 unit factors [workforce unit factor plus investment unit factor plus expenses unit factor]).

I.3.1. Analysis of the workforce unit factors for D&D categories

From the 30 workforce unit factors for D&D categories the most interesting and expensive are the following two items:

- workforce unit factor for dismantling of general equipment (INV6 Dismantling of general equipment) and
- workforce unit factor for demolition of massive reinforced concrete (INV 27 Removal of massive reinforced concrete).

Workforce unit factors for dismantling of general equipment

The general equipment category contains the reactor internals, reactor vessel and other primary loop components [4].

Figure 42 shows applied workforce unit factors for dismantling of the general equipment.

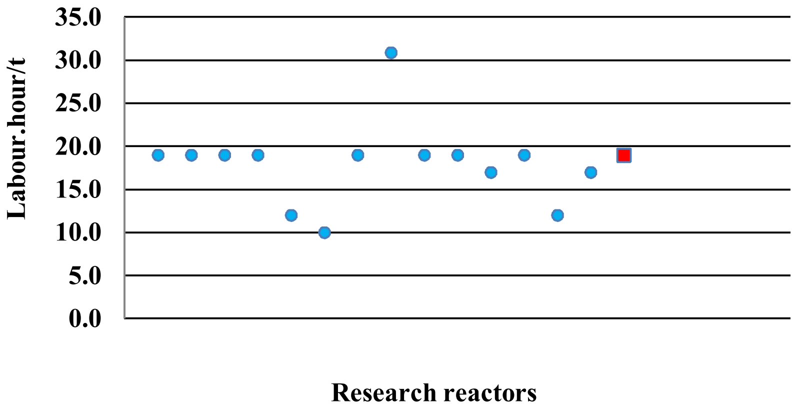


FIG. 42. Workforce unit factor for dismantling of the general equipment.

Figure 42 shows that in case of the workforce unit factors for dismantling of the general equipment, majority of the participants adopted the “default” unit factor value, which is equal to 19 Labour.hour/t. There are six data, which differ from the “default” value, the average of which is 16.4 Labour.hour/t. In this case, the differences between the “default” and used values cannot be considered significant.

Workforce unit factor for demolition of the massive reinforced concrete

Demolition of the massive reinforced concrete is performed after removal of the radioactive contamination from the facility, allowing the use of unit factors typically used in the non-nuclear industry. In all cases, they relate to the concrete crushing method, which is not so expensive but more dusty and noisy. It is evident that, in almost all cases, demolition of the massive reinforced concrete is performed by staff of the Licensee.

Figure 43 shows applied unit factors for demolition of the massive reinforced concrete.

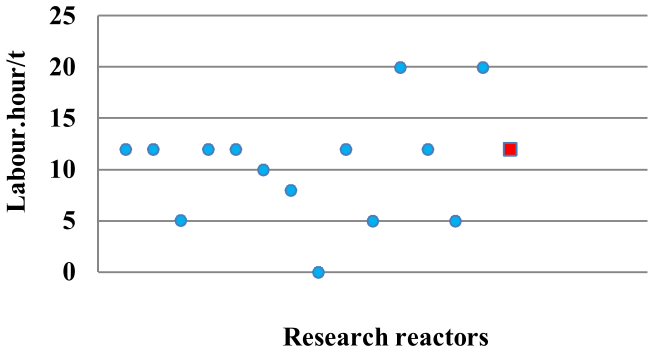


FIG. 43. Workforce unit factor for demolition of the massive reinforced concrete.

Figure 43 shows, that in this case the "default" unit factor value (12 Labour.hour/t) is close to the average of the user-defined factors used in the cases studied, i.e. 10.4 Labour.hour/t.

I.3.2. Analysis of the investment cost unit factors for D&D categories

Investment cost equal to the capital, equipment and material cost for the given D&D categories listed in Table 16. What is included as investment cost is normally defined in the national accounting rules as the limit for procurement of equipment, materials and spare parts.

In this case, it is not possible to make special conclusions from the used investment cost unit factors, because the presence or absence of these equipment and material at the start of the decommissioning is a historical endowment of each facility. Figure 44 shows the investment cost unit factors for dismantling of the cables and cable trays only for information.

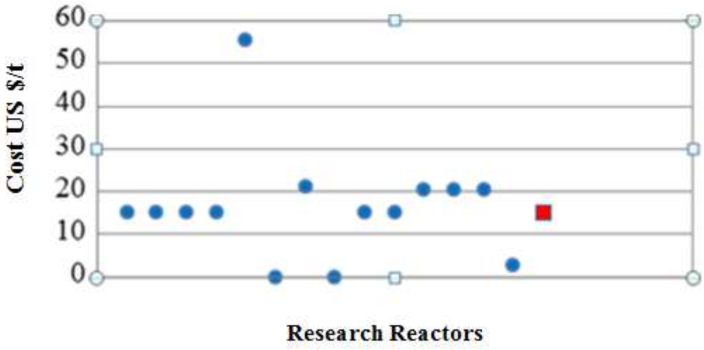


FIG. 44. Investment cost unit factors for dismantling of the cables and cable trays.

One can note that the average of the distinct 6 data points is 23.5 US $/t which is very close to the default (15 US $/t) value.

I.3.3. Analysis of the expenses cost unit factors for D&D categories

Expenses are defined as cost for consumption items, or costs for other expenditures related to the decommissioning cost items where applicable, as for consumables, spare parts, protective clothing, taxes etc.

It is very difficult to create reliable expenses cost unit factors. For the creation of these values it is necessary to make a very detailed analysis of the different D&D technologies. Unfortunately, these factors are not available, and in these cases the default values were generally used. The expenses cost unit factors for dismantling of the pipes and valves mentioned here because these activities are non-negligible part of the decommissioning projects.

Expenses cost unit factors for dismantling of the pipes and valves

Figure 45 shows applied expenses cost unit factors for dismantling of the pipes and valves.

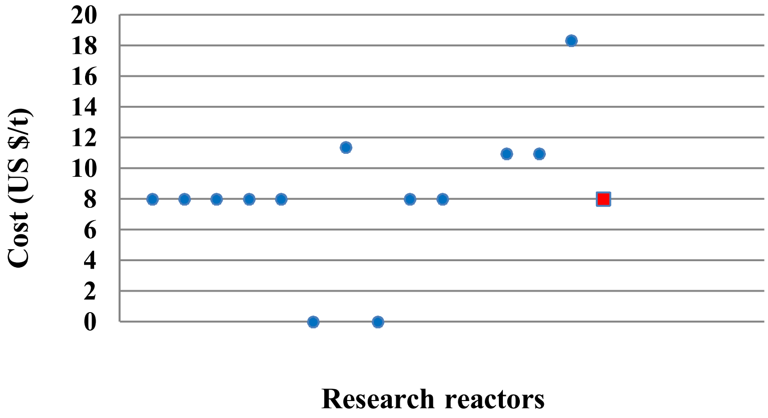


FIG. 45. Expenses cost unit factors for dismantling of the pipes and valves.

The average of the 4 distinct data is 12.9 US $/t, which is slightly higher than the default (8 US $/t) value. Two participants did not use these unit factors.

I.4. ANALYSIS OF THE UNIT FACTORS FOR WASTE MANAGEMENT CATEGORIES

The results of comparison of the waste quantities show that there is only one case when a small quantity of HLW is reported. In most cases, the radioactive waste belongs to the LLW and VLLW categories. For this reason this sub-section deals only with this two types of radioactive waste and as in the case of the decommissioning activities the analysis were performed for the workforce, investment and expenses cost unit factors. It should be noted that VLLW quantities were not provided for some of the analysed cases, because the legislation system of the given country does not use this waste category.

As mentioned above, the CERREX-D software uses 48 unit factors for the calculation of the waste management activities [(11 waste management plus 5 retrieval of legacy waste categories) × 3 unit factors (workforce unit factor plus investment unit factor plus expenses unit factor)].

In summary, no difference was found between the decommissioning and legacy waste management unit factors.

I.4.1. Analysis of the workforce unit factors for the waste management categories

Workforce unit factors for LLW processing

The main steps considered in waste management are treatment (including pre-treatment), conditioning, storing, and disposal of conditioned/packed waste or release/reuse of materials. All types of transport between the main technological procedures in the waste management are considered. Characterization is also included in each relevant step.

Figure 46 shows applied workforce unit factors for the LLW processing.

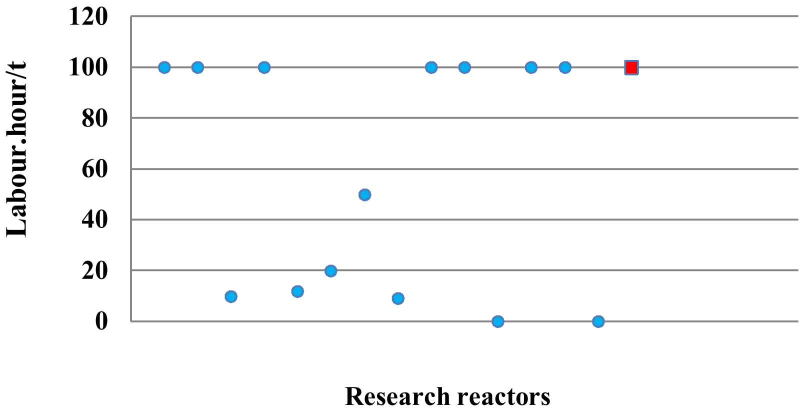


FIG. 46. Workforce unit factors for the LLW processing.

Figure 46 shows that in case of the workforce unit factors for the LLW processing majority of the Participants applied the “default” unit factor value which equals to 100 Labour.hour/t. Only five data differ from the “default” value, and their average value is 20.2 Labour.hour/t. The “default” value seems to be conservative. In this case a lot of participants did not use this unit factor (there are two of “0” values on the figure) the reason that in most cases they introduced new user defined waste management categories.

Workforce unit factors for VLLW processing

Activities are similar to those for the LLW.

Figure 47 shows the applied workforce unit factors for the VLLW processing.

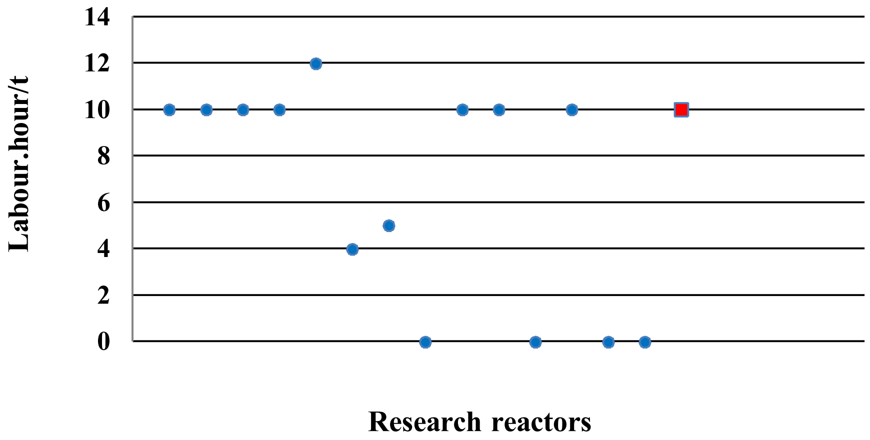


FIG. 47. Workforce unit factors for the VLLW processing.

Figure 47 shows that in case of the workforce unit factors for the VLLW processing majority of the Participants applied the “default” unit factor value which equals to 10 Labour.hour/t. Only three data differ from the “default” value, and their average value is 7 Labour.hour/t. The differences cannot be considered significant. The reason of the lot “0” values are the use of the user defined waste management unit factors.

I.4.2. Analysis of the investment cost unit factors for the waste management categories

In the case of the investment cost unit factors it is very difficult to make analysis because the value of the investment cost unit factors depend largely on the quantity of the existing (purchased earlier) equipment used for the operational waste processing.

For the information, the applied investment unit factors for the LLW and VLLW are shown in Figs. 48 and 49.

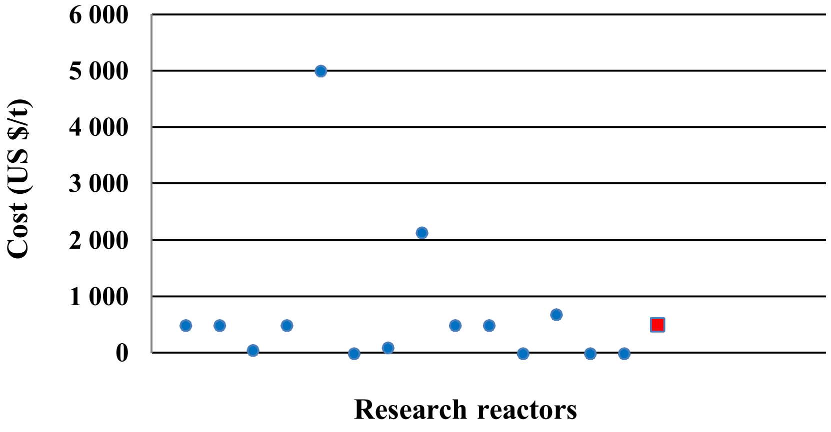


FIG. 48. Investment cost unit factors for the LLW processing.

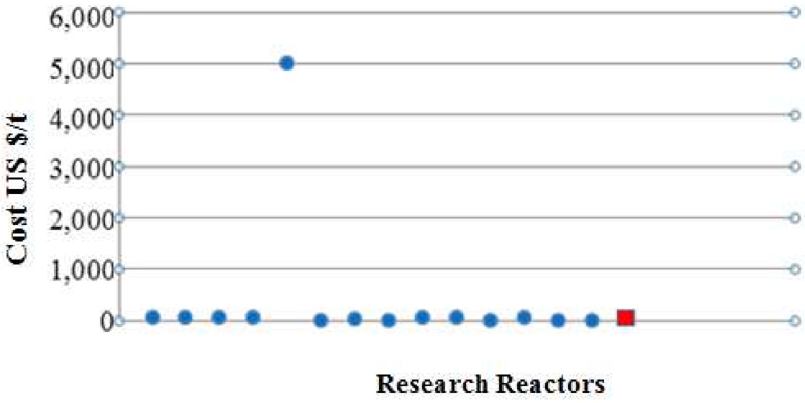


FIG. 49. Investment cost unit factors for the VLLW processing.

The value of 5000 US $/t for investment unit cost factors for LLW and VLLW relates to the site where there have been no previous operational waste management activities. After excluding the values of 5000 US $/t, the average of the remaining data are 397.9 US $/t for the LLW, and 31.7 US $/t for the WLLW.

I.4.3. Analysis of the expenses cost unit factors for the waste management categories

In connection to the analysis of the expenses, the situation for cost unit factors for the waste management categories is little better than for the D&D categories. It could associate with the fact, that the Participants could gain more practice in the waste management during the operational period, than in the dismantling activities during different safety or power increasing activities.

Expenses cost unit factors for the LLW processing

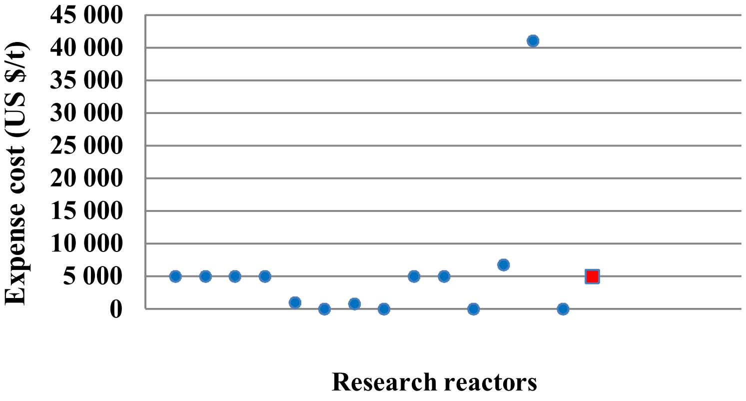


Fig. 50. Expenses cost unit factors for the LLW processing.

Figure 50 shows the applied expenses unit factors for the LLW processing. There is an extremely high value in the Fig. 50. It should be noted that these values (41,082 US $/t) relate to recently successfully performed decommissioning project where the share-out of the total decommissioning cost was performed during the project.

Expenses cost unit factors for the VLLW processing.

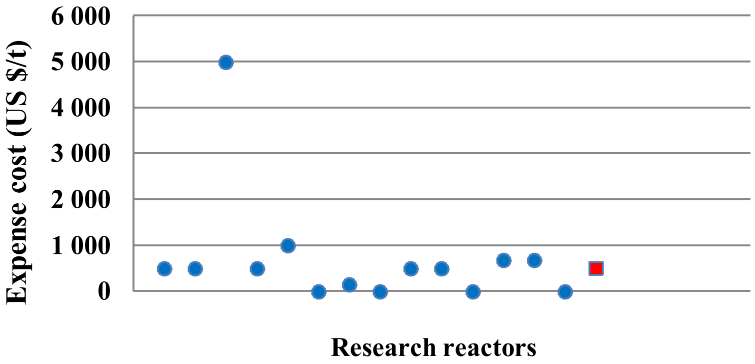


FIG. 51. Expenses cost unit factors for the VLLW processing.

Figure 51 shows the applied expenses unit factors for the VLLW processing. It is seen in the Fig. 51 that except one data the values show good agreement with the “default” (500 US $/t) value. The highest value (5000 US $/t) belongs to the project where the total cost is the highest in the 2000 kW$_{(th)}$ thermal power category.

I.5. LABOUR COST UNIT FACTORS OF LICENSEES AND CONTRACTORS

In the CERREX-D software, the labour cost unit factors mean the hour rates [currency/hour] for the next individual professions [23]:

- auxiliary worker with no specialize training, only general training for works within the controlled area is considered;
- skilled worker with specialized training;
- technician with specialized training;
- technician with specialized training, secondary school education;
- administrative worker skilled for administrative & office work, secondary school education;
- graduated engineer, university level, approx. less than 10 years of experience in the area of subject;
- graduated engineer, university level, approx. 10 years of experience in the area of subject.

In the vast majority of the cases, the labour cost is the most expensive component of the decommissioning cost of the nuclear facilities. The values of the labour cost unit factors widely changing country by country and the analysis of the reason is out of the scope of this project.

Labour rates for contractors are calculated as the percentage to labour hour rates for the licensee. The percentage defined by the user is a special cell of the CERREX-D excel sheet. The percentage ratio of the increase of the labour cost unit factors of the contractors professions to the licensee professions are shown in Fig. 52.

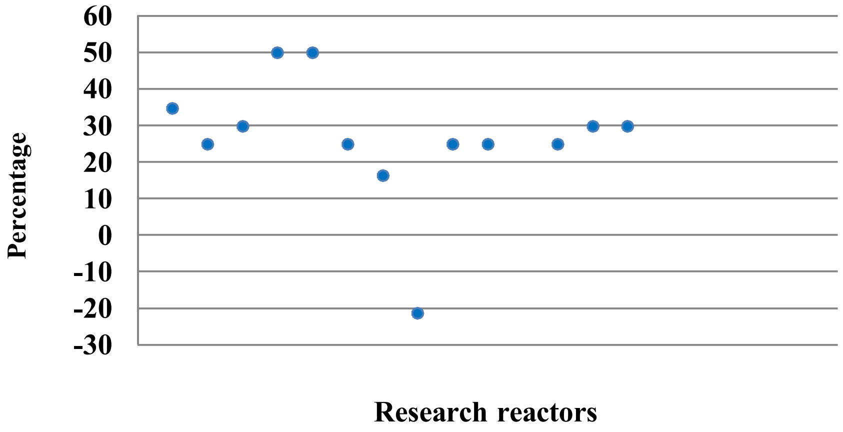


FIG. 52. The percentage ratio of the increase of the labour cost unit factors of the contractors professions to the licensee professions.

It is seen from the Fig. 52 that there are 13 cost calculation derived by the CERREX-D software where the Participants defined the percentage ratio of the increase of the labour cost unit factors of the contractors professions to the licensee professions. After a detailed control of the calculations, realized that only few calculations took advantage of the use of contractors.

The activities where the participants are going involve contractors in the projects are the next:

- final planning of the decommissioning;
- removal of hazardous materials;
- dismantling of the technological systems;
- decontamination of building surfaces;
- waste processing;
- characterization.

I.6. WORK DIFFICULTY FACTORS

I.6.1. Overview of work difficulty factors

There are number of factors that increase the time needed for performing a task under particular conditions. The effects of these factors are taken into consideration by means of WDF, expressed as a percentage of increase of the working time, comparing to an unimpeded working situation.

In the original Guidelines for Cost Estimate [20] the term Work Difficulty Factor (WDF) was named “Adjustment Factors for Work Duration”. The other difference between the literature [20] and the CERREX-D software that in the CERREX-D software there are 2 more factors, the first for the remote operations and the second for the user defined additional works.

The sub sections below, taken mainly from the User’s manual for Costing software CERREX-D for research reactors [23], and they show the WDFs used by CERREX-D software. More than one factor may have to be used in a given case and this feature was used practically by all of the Participants.

I.6.2. Analysis of work difficulty factors

The lists of ISDC calculation items with WDFs for F1 - F7 are shown in the tables IV-1 to IV-7 of the Annex IV. These tables contain information on the calculation levels 2 or 3 depending on the level of the original calculations. If there is only 1 case, then the min., max. and the average values are the same. The Participants used the WDFs not always in the classical sense (not only for the inventory dependent activities).

Respiratory Protection Factor (F1)

The respiratory protection factor is intended to account for the difficulty of a worker performing activities while wearing a full-face respirator, or supplied-air mask. The respirator impedes breathing, obscures vision due to the mask window and fogging, and adds stress from the straps around the head.

The respiratory protection factor may vary from 10% to 50%. Regulatory aspects, e.g. concerning the permissible time for working with respiratory protection, should be taken into consideration if relevant [23].

The list of ISDC calculation items with Respiratory Protection Factors (F1) is shown in Table IV-1 of the Annex IV. The number of the ISDC calculation items to which the participants applied this factor is 38. This factor was applied in particular to ISDC item "04.0501 Dismantling of reactor internals", the maximum value being used (in 5 cases) being 40%, i.e less than the default value of 50% used in the CERREX-D software. The average of the values used for this factor is 23.8%.

ALARA Factor (F2)

The ALARA factor (according to the [20] "Radiation/ALARA") is intended to account for the time spent preparing for an entry into a high radiation or highly contaminated area. This time is used to alert a crew to the potential hazards in the area, the specific activities to be accomplished while in the area, and emergency procedures to be implemented for immediate evacuation. This factor also accounts for the periodic training the crew would receive to maintain their radiation training and certification. The ALARA factor may vary from 10% to 15% [23].

The list of ISDC calculation items with ALARA Factor (F2) is shown in the table IV-2 of the Annex IV. It can be seen from the table that most of the F2 factors relates to the dismantling of reactor internals, reactor vessel and dismantling of other primary loop components. The average of the values for this factor is 13.7%.

Accessibility Factor (F3)

The accessibility factor (according to the [20] "Height") is intended to account for difficulty of working on scaffolding, on ladders, in pipe tunnels, or in other confined spaces. The limited degree of motion possible under these working conditions reduces worker's productivity. The accessibility factor may vary from 10% to 20%. [23]

The list of ISDC calculation items with Accessibility Factor (F3) is shown in the table IV-3 of the Annex IV. According to the table the maximum value does not exceed the above suggested 20%, and the average of the values for this factor is 16.7%.

Protective Clothing Factor (F4)

The protective clothing factor is intended to account for the time a worker needs to put on a protective clothing before each entry to and take off after each exit from a radiation control area. Typically, this represents four changes per day, assuming suiting up in the morning, a morning break, a lunch break, an afternoon break, and end of the shift. The protective clothing factor may vary from 10% to 30% [23].

The list of ISDC calculation items with Protective Clothing Factor (F4) is shown in the table IV-4 of the Annex IV. There are 37 ISCD calculation items in the table, from which 32 belongs to the activities which relates to activities performed in the radiation controlled area. Some Participants extended the use of these factors for activities in the non-controlled area. The average of the values for this factor is 20.4%.

Work Productivity Factor (F5)

The work productivity factor, according to [20] “Work break” is intended to account for site-specific productivity differences of the workforce. These differences may arise through union bargaining agreements, severe weather factors (heat or cold) or other limitations. Experience has shown that worker productivity under stressful conditions improves when workers are allowed a morning and afternoon break; this work break factor may vary from 5% to 10%. The work productivity factor adjustment is at the discretion of the estimator [23].

The list of ISDC calculation items with Work Productivity Factor (F5) is shown in the table IV-5 of the Annex IV. The table contains 32 ISDC calculation items where the Participants used this factor. The average of the values for this factor is 9.8%.

Remote operation factor (F6)

The duration of a given task will become longer if it has to be performed by remote operation instead of hands-on approach. Affected factors are, for instance, the time consumption for maintenance and decontamination of the equipment, the use of direct or indirect vision, waste handling, and force feedback from the tool [23].

The list of ISDC calculation items with the Remote operation factor (F6) is shown in the table IV-6 of the Annex IV. It is well seen from the table that the Participants are going to use remote operation equipment in the case of dismantling of the reactor internals, reactor vessels, primary loop components and external/biological shields. The max. and the average value of this factor does not exceed the 50%. The average value for this factor is 39.2%.

User defined additional work difficulty factor (F7)

There is a seventh WDF introduced in the CERREX-D software, for additional specific working constraints in the actual costing item [23].

The list of ISDC calculation items with User defined additional work difficulty factor (F7) is shown in the table IV-7 of the Annex IV. It can be seen from the table that only a few Participants introduced this WDF and they did it mostly for the dismantling of the reactor internals, reactor vessel and core components, and for removal of other hazardous materials. In these cases, the minimum values are changing between 10-15% and the maximum values are equal to 100%. The average of the values for this factor is 30.6%.

I.7. CONCLUSIONS

The figures in Section 7 show that, in most cases, ‘default’ unit factors were used for the costing cases considered in this project. It is evident that the availability of proven unit factors is a very important input for decommissioning cost calculations.

The original intent of the DACCORD project was to obtain, for each costing case, feedback on unit factors, inventories, applied WDFs and contingencies, calculated cost data and a summary of the applicable decommissioning strategy. It is evident that this exercise needs to be continued on an ongoing basis to enable the development of a significant database of unit factor information.

APPENDIX II. DESCRIPTION OF PARTICIPATING TRIGA REACTORS

II.1. DESCRIPTION OF THE IPR-R1 REACTOR, BRAZIL

The IPR-R1 TRIGA Mark I (Training, Research, Isotopes, General Atomics) is located at the Nuclear Technology Development Centre – CDTN, at the campus of Federal University of Minas Gerais in Belo Horizonte. It was the second Brazilian Research reactor. The IPR-R1 is a pool type nuclear research reactor, with an open water surface and the core has a cylindrical configuration with 91 locations an annular graphite reflector (Fig. 53). The first criticality was achieved on November 1960. At present, the reactor operates at 100 kW(th). The operation regime of the reactor is 12 hours per week, 40 weeks per year. The integrated burn-up of the reactor since its first criticality until present is about 83 $MW_{(th)}$day.

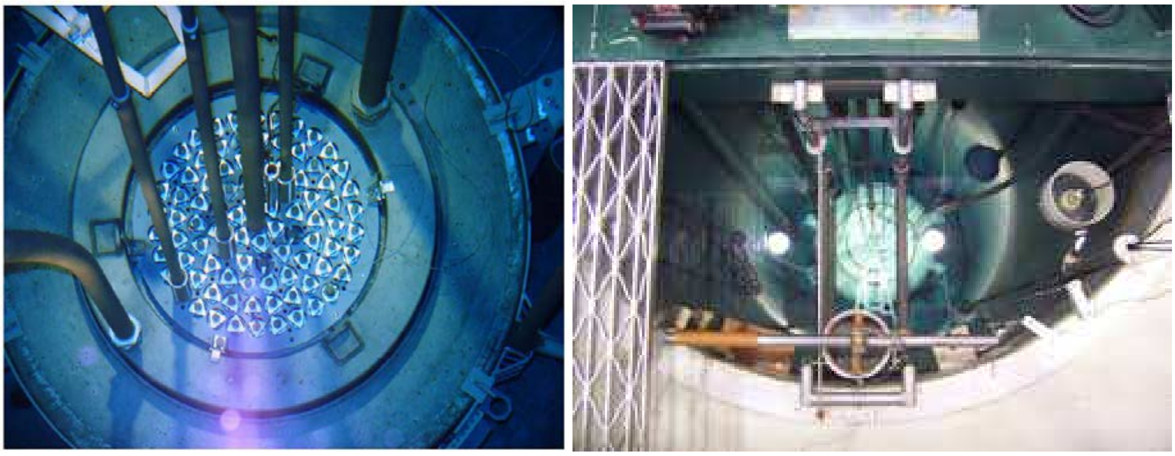


FIG. 53. TRIGA IPR-R1 Reactor Core (photo courtesy CDTN).

Due to the low nominal power, spent fuel is not a problem, except for aging concerns. The fuel is a solid, homogeneous mixture of uranium-zirconium hydride alloy containing about 8.5% and 8% by weight of uranium enriched to 20% in 235U, for stainless steel and aluminium clad elements, respectively. The IPR-R1 is mainly used for thermal hydraulic and neutrons research, neutron activation analysis and applied research, as well as for the production of some radioisotopes, like ^{60}Co that is used in the stainless steel industry, and tracers that are used in environmental research activities. Additionally, it is also employed to train the Brazilian NPP operators.

No incident or accident with radiological consequences occurred during reactor operation [24, 25].

II.2. DESCRIPTION OF THE TRR2000 REACTOR, INDONESIA

The TRR2000 Reactor located in the Bandung Nuclear Area, Center of Applied Nuclear Science and Technology, National Nuclear Energy Agency (NNEA = BATAN) had been operated for 50 years. It was the first nuclear research reactor in Indonesia [26]. Building and structure of the Bandung TRIGA reactor are shown in Figs. 54 and 55 respectively.

Bandung TRIGA Mark II Reactor achieved the first criticality on October 10th 1964 and was operated at a power level of 250 kW(th). The facility had been operated for research, production of radioisotopes and training. Core and core configuration of the Bandung TRIGA reactor are shown in Figs. 56 and 57.

In 1971, the reactor was upgraded from 250 kW(th) to 1000 kW(th). The reactor was operated safely at various level of power until February 1996. Starting from April 1996, the second phase of upgrading activities began.

The objectives of the upgrading:

- Gaining higher thermal neutron flux by increasing power to 2000 kW(th);
- Producing more radioisotopes for backing up the Serpong reactor;
- Higher safety margin: additional control rod, ECCS and better cooling system.

The reactor achieved the first criticality for new power at 2 $MW_{(th)}$ on May 13th 2000, and then name of the reactor is changed call Bandung TRIGA Reactor.

During the second upgrading project, some important components were replaced or modified. The old core with a circular configuration has been modified to a hexagonal one. In addition, a new aluminium tank was placed as a liner inside the old one.

The Bandung TRIGA Reactor is a pool type nuclear research reactor, with an open water surface.

Concrete structured shielding surrounds the reactor and all its facilities.

The TRIGA reactor uses a rod solid fuel element. In this fuel element, ZrH moderator was mixed with the enriched uranium homogeneously.

Total number of fuel elements in the core at 2000 kW(th) power is 107 and three types of fuel elements are used:

- Type-104: 8.5% U = 38 grams U-235 per fuel rod.
- Type-106: 12% U = 55 grams U-235 per fuel rod.
- Type-108: 20% U = 99 grams U-235 per fuel rod.

The types of Instrumented Fuel Element (IFE) are used for measuring the core temperature: type-204, type-206, type-208 and type-306.

Five control rods control the level of reactor power. All rods contain a boron carbide absorbed material (B4C), its bottom part is connected with the rod fuel element. This type of control rod is called the fuel follower control rod/FFCR.

The cycle of reactor operation is 72 hours per week, 24 weeks per year.

Supervision functions, performed by BAPETEN (Nuclear Energy Regulatory Agency of Indonesia) are basically aimed to ensure the safety of workers, communities and the environment.

The inspections, both routine and non-routine are done to assure if a licence that given is used as intended or not. Monitoring system would consist the monitoring of radiation facilities and nuclear installations. The entire system of supervision conducted by BAPETEN always refers to the procedures issued by the IAEA. Therefore, BAPETEN continues coordinating with the police to conduct law enforcement for users who do not follow the rules.

No incident or accident with radiological consequences occurred during reactor operation.

FIG. 54. Building of Bandung TRIGA Reactor (photo courtesy BATAN).

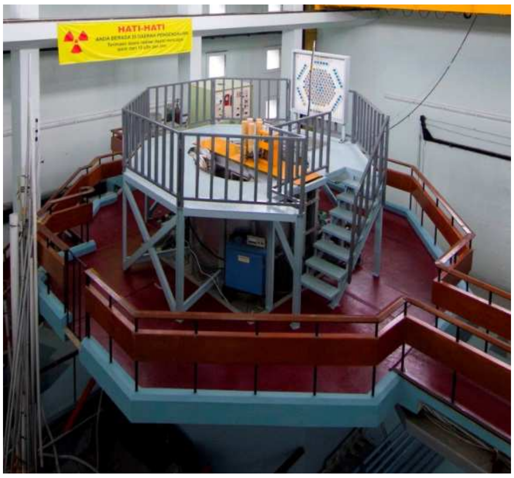


FIG.55. Structure of Bandung TRIGA Reactor (photo courtesy BATAN).

FIG. 56. Core of Bandung TRIGA Reactor (photo courtesy BATAN).

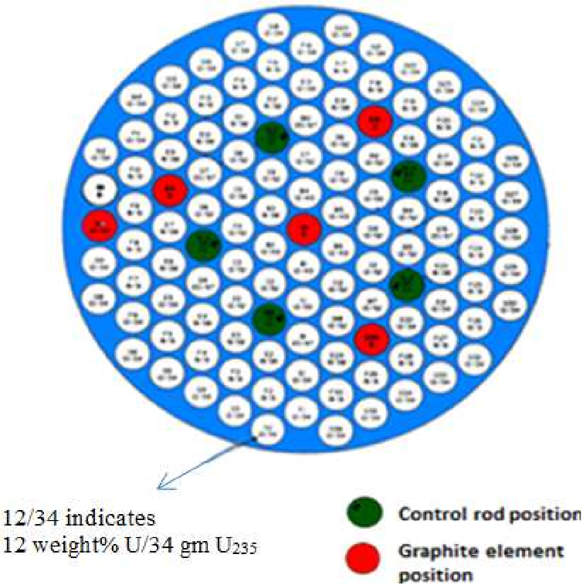


FIG. 57. Core configuration of Bandung TRIGA Reactor (photo courtesy BATAN).

II.3. DESCRIPTION OF KRR -2 REACTOR, REPUBLIC OF KOREA

The Republic of Korea Research reactor KRR-2 (TRIGA Mark-III) has a moveable core TRIGA Mark III, which operated for approximately 23 years up to its shut down in December 1995. The reactor was designed specifically for experimental research and has various experimental facilities such as a rotary specimen rack, an exposure room, radial beam ports, intersecting through ports, thermal columns, a pneumatic transfer system and in-core experimental positions. The KRR-2 maximum operating power was 2 $MW_{(th)}$, the total operating power was 68740 $MW_{(th)}$hr and the peak neutron flux was 7.0×10^{13} n/cm^2/s [27-28].

Reactor hall: The reactor Fig. 58 is located in the reactor hall in the TRIGA III RX Building. Along with the reactor hall, the building also houses several laboratories, storage, equipment and service rooms and hot cells. The reactor hall access is for vehicles and numerous access points for personnel. A crane installed in the reactor hall and be available during decommissioning operations, has a 7.5 ton working load and is pendant operated.

Reactor Shield Structure*:* The steel-reinforced concrete shield structure is shown in Fig. 58 b. The structure is 17.4m long, 9.8m wide and 8.0m in height from the floor of the reactor hall. The structure has approximately 1.5m of concrete below the reactor pool which provides a foundation for the structure and also shielded against soil activation. At the 3.7m level, access in the form of a metal stairway and railings is provided to the reactor water system, the vertical thermal column and the reactor interlock system. A removable checker plate covers the vertical thermal column opening and shield plug.

Reactor Tank*:* The reactor tank is roughly rectangular in shape with dimensions 7.6m long, 3.0m wide and 7.6m deep, one end of the tank is semi-circular in shape with a radius of 1.2m. The tank is constructed from welded aluminium plates which are welded together and embedded in the concrete shield tank structure. The outside surface of the aluminium tank is corrosion protected using an organic material. The reactor core is located near the bottom of the tank which is filled with demineralized water to a depth of approximately 7.3m, providing approximately 6.1m of shielding water above the core.

The beam ports and thermal column are located at the semi-circular end of the tank with the exposure room located at the other end of the tank. A 51mm by 51mm aluminium channel is positioned at the top of the reactor Tank for mounting underwater lights.

Reactor components*:* The reactor core is contained within an aluminium shroud and rigidly suspended from the bridge by two aluminium channels. The reactor core components are contained within the upper and lower grid plates which are constructed from aluminium and are welded to the aluminium shroud. Holes within the upper and lower grid plates position the fuel elements, (now removed), instrumented fuel elements (now removed), control rods (now removed), graphite dummy elements (only four remain in the core), neutron source (now removed), pneumatic system terminus and central thimble. In addition to positioning the components listed above, the lower grid plate, which is 32mm thick, supports the weight of the core.

a) *b)*

FIG. 58. a) KRR-2 Reactor; b) the steel-reinforced concrete shield structure (photo courtesy KAERI).

***Ion chambers**:* Four fission chambers are positioned just above the reactor core area, each chamber is sealed in a cylindrical aluminium container with its lead out wires contained within an aluminium pipe connected to the reactor bridge. Each fission chamber is supported within the aluminium container by an aluminium wire connected to the chamber and clamped to the top of the container.

***Exposure room**:* The exposure room cavity in the concrete shield is approximately 3.05m wide, 3.66m long and 2.74m high. 3.35m of concrete shielding is provided with boron added to the inner 0.30m of the concrete walls, ceiling and floor of the exposure room. The floor of the exposure room is 1.52m thick concrete to protect against soil activation. A motor driven concrete shield door provides access to the exposure room, the door is 3.35m thick with the inner 0.30m containing boron, and the total weight of the door is approximately 50 tonnes.

***Beam tubes**:* Four beam tubes are provided at the thermal column end of the shield structure. These beam ports extend through the reactor structure (the concrete shield) and through the water to the edge of the reactor shroud. The inner sections of the radial beam ports are aluminium, two of which penetrate the horizontal thermal column. The outer sections of the beam ports are constructed from stainless steel. Each beam tube terminates at its outer end with a stainless steel flange. The flange has an aluminium plate with an asbestos gasket bolted over it to seal the tube. Five removable shield plugs are contained within the beam tubes and are constructed from graphite, steel and wood. Two through beam ports are contained within the structure in addition to the radial beam ports. The through beam ports intersect each other in the horizontal thermal column immediately adjacent to the core. They are of a similar construction to the radial beam ports except the diameter of the through beam ports is larger, and the plugs are larger in diameter.

***Horizontal thermal column**:* The horizontal thermal column is contained within the concrete shield structure at the beam port end of the reactor pool, the cavity is lined with welded aluminium, sections of which is lined with 3mm thick boral and 51mm of polyethylene. Blocks of nuclear grade graphite are stacked in the cavity starting from the core end and extending to the location of the reactor pool main well. 0.1m thick shield of lead bricks is stacked next to the graphite. With the exception of an area 0.9m square and 1m long (known as the hohlraum) the rest of the liner is filled with graphite blocks 0.1m by 0.1m in cross section, the longest of which is 1.27m in length. Two horizontal stringers are located near the centre of the column, one above and one below the centreline of the core.

The upper stringer goes all the way from the hohlraum to the inside end of the column while the lower stringer stops at the intersection of the through beam ports. Two 0.15m beam ports extend from the face of the shield and terminate on opposite sides of the thermal column hohlraum. They are made entirely of stainless steel and are welded in a stepped design. To prevent corrosion and concrete intrusion, the outside of the beam ports and reactor liner are covered with an organic material. The outer face of the thermal column is shielded by a motor-driven track mounted stepped door constructed of heavy concrete aggregate of thickness 1.37m.

***Vertical thermal column**:* The vertical thermal column is located in the concrete shield structure directly above the hohlraum, the cavity is lined with aluminium liner which is welded to the horizontal thermal column. The thermal column comprises graphite bars (0.79m long) stacked in a removable basket (0.9m by 0.9m by 0.86m deep) within the column liner. Shield door and shield plugs are located above the column which can be lifted by the building crane.

***Rotary specimen rack**:* The RSR consists of a sealed aluminium carousel located within a well in the reactor core. It was used for the irradiation of samples for the production of radioisotopes. Samples were lowered into the sample receptacle in sample bottles using a sample pick up tool. The carousel could be rotated to any of 41 positions by raising the positioning rod and rotating the drive shaft from the reactor bridge. Following the irradiation period, the samples could then be removed from the carousel through the specimen removal tube. The carousel drive is located on top of the reactor. The RSR has undergone significant activation during its lifetime which is demonstrated in the predicted radiation dose emanating from the stainless steel components of the carousel drive mechanism. The RSR will be monitored following the removal of the fuel rods to ensure that the planned thickness of the shielded container for removing the RSR ILW components is sufficient to reduce dose rates to an acceptable level.

II.4. DESCRIPTION OF THE RTP REACTOR, MALAYSIA

The RTP Reactor also known as PUSPATI TRIGA Mark II 1-$MW_{(th)}$ reactor was designed to effectively implement the various fields of basic nuclear research and education. It incorporates facilities for advanced neutron and gamma radiation studies as well as for isotope production, sample activation, and student training. Reactor is installed entirely above ground.

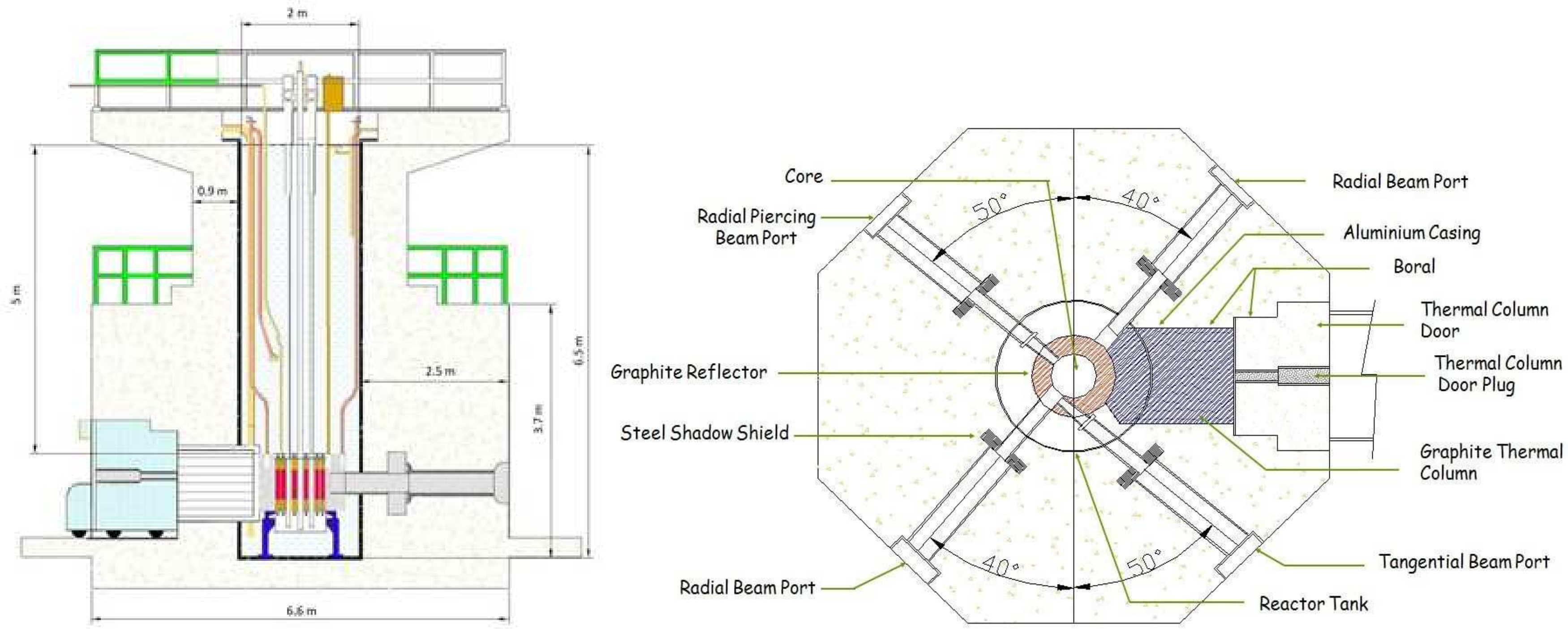
The reactor and experimental facilities are surrounded by a concrete shield structure as shown in Figs. 59 a,b. The reactor core and reflector assembly is located at the bottom of a 6.5ft (1.98m) in diameter by 20.8ft (6.3m) deep aluminium tank. Approximately 17ft (5m) of water above the core provides vertical shielding. The core is shielded radially by a minimum of 7ft. 6in. (2.3m) of high-density concrete, 0.46m of water, and 0.26m of graphite reflector. Summary description of the PUSPATI TRIGA Mark II (RTP) is shown in Table 19.

The PUSPATI TRIGA reactor uses solid fuel elements developed by General Atomics in which the zirconium-hydride moderator is mixed homogeneously with enriched uranium. The unique feature of these fuel-moderator elements is the prompt negative temperature coefficient of reactivity, which gives the TRIGA reactor its built-in safety by automatically limiting the reactor power to a safe level in the event of a power excursion.

The reactor core consists of a circular array of cylindrical fuel moderator elements and graphite (dummy) elements. The fuel elements have 8.9 cm long graphite end sections that form the top and bottom reflectors. About 1/3 of the core volume is occupied by water. A 25.4cm thick graphite radial reflector surrounds the core and the entire assembly is supported on an aluminium framework at the bottom of the tank [29].

TABLE 19. SUMMARY DESCRIPTION OF RTP

Items	Data
Name	Puspati Triga Mark II Reactor (RTP)
Purpose	Research in nuclear physics, radiation chemistry, biology, isotope production, shielding studies and training.
Type	Pool type reactor
First criticality	28 June 1982
Maximum thermal power	1 $MW_{(th)}$ (steady state and Square Wave Modes), 1360 $MW_{(th)}$ (Pulsing mode)
Average power density	22.8 $W \bullet cm^{-3}$
Maximum thermal neutron flux	1×10^{13} $n \bullet cm\text{-}^{2} \bullet s$
Shape and size of reactor core	Cylindrical, 110 cm dia × 89 cm ht.
Coolant	Demineralized Light water
Core cooling	Natural convection
Heat rejection	Two-Loop cooling system
Moderator	Demineralized Light water
Control rod	Boron carbide, B_4C
Reflector	Graphite



a) b)

FIG. 59. a). Schematic Diagram of the PUSPATI TRIGA MARK II Research Reactor; b). Experimental Facility Layout (photo courtesy Ministry of Science, Technology and Innovation, Malaysia © RTP SAR 2014).

II.5. DESCRIPTION OF THE PRR-1 REACTOR PHILIPPINES

Site location and operational history:

The Philippine Research Reactor (PRR-1) is an open-pool-type nuclear research reactor owned and operated by the Philippine Nuclear Research Institute (PNRI), an agency of the Philippine government under its Department of Science and Technology (DOST). The reactor was obtained from the government of the United States of America under the Atoms for Peace programme.

The Philippine Research Reactor (PRR-1) first attained criticality on 26 August 1963 and was first operated at 1 $MW_{(th)}$ on 26 October 1964. The reactor was then operated regularly, usually at 1 $MW_{(th)}$ for a few hours a day until 30 March 1977. Thereby accumulating a total burn-up to 570 $MW_{(th)}d$. Problems with aging instrumentation caused the reactor to be operated at no more than 500 $kW_{(th)}$ from then to 14 July 1980, increasing the total burn-up to 604 $MW_{(th)}d$. The instrumentation was replaced, but problems with the reactor building's ventilation system caused the reactor power to be reduced further to 100 $kW_{(th)}$ until 24 October 1984. The total burn-up had reached only 617 $MW_{(th)}d$ by that date. The reactor was then shut down for conversion to a TRIGA-type reactor.

The Philippine Research Reactor (PRR-1) was converted to a TRIGA-type reactor from 1984 to 1988, when its fuel elements, cooling system and instrumentation system were replaced, raising its rated power to 3 $MW_{(th)}$. The reactor was successfully tested at full rated power, but a leak in the pool liner, problems with other aging reactor components.

The pool liner leak and some of the reactor components were repaired but the PNRI eventually ran out of funding in the late 1990s to finish reactor rehabilitation. All of the reactor's spent fuel elements were shipped back to the USA in 1999. However, some nuclear fuel remains in the facility in the form of 115 slightly-irradiated TRIGA rods, 15 fresh TRIGA rods, and 2 slightly- irradiated plate assemblies. These fuels were removed and placed in a temporary fuel storage tank in 1997 and has been there for almost 18 years. The fuel is much more similar to fresh fuel than spent fuel. The fuel requires only minimal radiation shielding but consequently needs an effective physical security system even more because it is not self-protecting. Like spent fuel, it also needs effective precautions against criticality.

Main Parameters:

The reactor pool is a monolithic free-standing reinforced-concrete structure sitting on the reactor bay floor. The reactor pool was designed to hold about $200m^3$ of water, with the waterline about 8.5m above the floor. The pool water and concrete serve as the reactor’s biological shield.

The reactor pool has three sections: the high-power section, the intermediate section and the low-power section. The intermediate and low-power sections are connected to the high-power section in that sequence going from east to west. The sections are open to each other down to their bottoms.

The high-power section is circular with an internal diameter of 2.6m and a depth of 9.5m, and is concentric with the reactor bay. The intermediate section is rectangular, with internal dimensions of 1.6m by 2.4m, and is 8.7m deep.

The low-power section is almost square, with internal dimensions of 2.6m (8.5ft.) by 2.4m (8.0ft), and is 8.7m (28.4ft) deep.

The reactor core is suspended inside the reactor pool, and can be moved to any of the pool sections. The reactor primary cooling system has 8-inch pipe stubs in the reactor pool that connect when the core is in the high-power section; in that location, the availability of forced cooling allows the reactor to be operated at its maximum power, hence the name of the pool section. There is no provision for forced cooling in any of the other two sections, but the reactor can still be operated up to about 100 kilowatts using natural convection cooling in either section. In practice, the core was operated in the high-power section most of the time, occasionally in the low-power section, and never in the intermediate section. The intermediate section was used for storage of spent fuel.

Radiological Complexity:

There is no known major spill or other major release of radioactivity during the operational life of the reactor. There may have been minor unrecorded spills (e.g., of activated ion-exchange resin or fluids while regenerating the reactor's demineralizer or small mishaps in the laboratories).

In 1988, the pool liner leak released water continuously until the pool was completely dewatered in 1992, but fortunately there had never been a fuel cladding failure in the Philippine Research Reactor (PRR-1) and the water did not carry a significant amount of contamination. However, the water did completely saturate the concrete under the liner, and could have diffused activation products deeper than their places of formation.

Regulation and Clearance:

Dose rate criteria:

The following regulations and safety standards will apply:

- PNRI CPR Part 3, Standards for Protection Against Radiation. 6 September 2004.
- IAEA Safety Series No. 115, International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources. February 1996. STI/PUB/996.

The Philippine Research Reactor (PRR-1) has adopted administrative limits on radiation exposure dose that are generally 1/10 of the regulatory limits specified by the above documents.

The decommissioning of the Philippine Research Reactor (PRR-1) will also have to directly comply with the IAEA safety standards.

Radioactive waste criteria:

The main criteria for solid and site release will be in accordance with the Code of PNRI Regulations (CPR) and IAEA guidance on exemption/clearance principles. This is based on limit of effective dose in the order of 10 μSv/y for any member of the public and either on limit of collective effective dose of no more than 1 Sv/y based on IAEA Safety Series No. 115

International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources

The Philippine Research Reactor (PRR-1) will be guided by IAEA Safety Report Series No. 44 entitled ‘Derivation of Activity Concentration Values for Exclusion, Exemption and Clearance’ on the exemption values of activity concentration for radionuclide of artificial origin in bulk.

APPENDIX III. DESCRIPTION OF PARTICIPATING WWR REACTORS

III.1. DESCRIPTION OF THE WWR-M AND WWR-SM REACTORS

Both the WWR-M and WWR-SM reactors considered in this report are very similar, the basic reactor characteristics relevant to the decommissioning are shown in Table 20.

TABLE 20. BASIC REACTORS CHARACTERISTICS

Details	WWR-M	WWR-SM
Operator	Institute for Nuclear Research of the National Academy of Sciences of Ukraine	Energy Research Centre of the Hungarian Academy of Sciences
Location	Goloseev district (south part of Kiev)	Budapest's western part
Start of operation	1960	1959
Planned final shutdown	2024	2023
Neutron flux	2×10^{14}	2×10^{14}
Major modification	Practically all reactor systems have been replaced except the reactor vessel.	Reactor vessel replacement in 1989.
Accidents/incidents	During more than 50 years of operation there has been no incident exceeding the normal operation limits and no radioactive contamination above the acceptable levels.	
Radiological complexity	The majority of radionuclide contaminants generated by the reactors operation are beta-gamma emitters. These are detected and measured by the beta-gamma counters and gamma-spectrometry. ^{137}Cs is the dominant fission product. ^{60}Co is among the activation products with other radionuclides like ^{90}Sr, ^{125}Sb, ^{144}Ce, ^{152}Eu, ^{65}Zn, ^{154}Eu, and ^{110m}Ag present in small quantities. The ratio of cobalt and caesium activities varies in from 60:40 to 90:10%. The results of low-level alpha- spectrometry of smear samples show that the uranium isotopes contamination is negligible ($\sim10^{-4}$ Bq/cm^2).	
Decommissioning planning	The initial decommissioning programme was approved in 2009; next revision is planned after 2016.	The initial decommissioning plan was prepared in 2005; next revision is planned for 2015.

III.2. DISMANTLING SEQUENCE

III.2.1. General considerations

The goal of the dismantling stage is a segmentation and removal of the reactor systems and components in addition to removal of the radioactive substances outside the reactor. The disassembly of reactor systems, removal of the reactor core and replacement of old equipment is expected to perform using common decommissioning techniques and procedures without further research and development needs.

The dismantling strategy comprises the following approaches:

a) the dismantling is carried out 'from top to bottom' to preserve stability;
b) the dismantling and removal of the separate large components should be performed as whole pieces, where possible, without preceding segmentation;
c) the subsequent segmentation of such components, if necessary.

There are three main principles:

1) the dismantling is carried out ‘room by room’, not ‘system by system’;
2) the dismantling is carried out from the less contaminated to the more contaminated equipment;
3) the minimization of secondary radioactive waste (solid, liquid and aerosols)

The following dismantling sequence may be proposed:

- Vessel removal, including:
    - dismantling of the technological equipment in the reactor upper part and in the reactor hall;
    - dismantling of the thermal column;
    - dismantling of the thermal column’s first disk;
    - dismantling of the Be-reflector;
    - removal of the reactor vessel;
- Dismantling of the primary cooling circuit, including:
- removal of the heat-exchangers;
- dismantling of the primary circuit components;
- dismantling of the ion exchange and electrophoresis filters;
- Dismantling of the spent fuel cooling pool, and;
- Dismantling of the biological concrete shield, including the dismantling of primary circuit embedded units.

III.2.2. Vessel extraction

The reactor vessel extraction is considered challenging due to a high radiation of the vessel and inner parts having been activated during the reactor’s long-term operation. This task requires a detailed planning in order to reduce the dismantling staff’s exposure to be as low as reasonably achievable (ALARA).

Two major optional strategies for the dismantling of the reactor vessel exist: a) vessel segmentation; b) one-piece removal of the whole vessel. The following aspects have been considered for each of the alternatives: safety related risk and impact assessment; technical lifting aspects; necessary building modifications and demolition; radiological impact; cost and time estimations. The removal of the reactor vessel in one piece and consequent cutting into smaller pieces e.g. in the reactor hall, was selected as the preferred option [30]. The advantages are following: known technology; existing ventilation system to be used without modification; the reactor hall overhead crane remains available during the dismantling project; better conditions from radiation protection and safety point of view.

III.2.3. Dismantling of the primary cooling circuit (PCC)

The heat exchangers can also be removed in one piece [31]. This can be carried out by means of the technological hatch between the pump house (in the basement) and the reactor hall. Removal of the covering plates on the hatch will provide an access of sufficient size. The heat exchangers will then be dismantled from their base support to be lifted by a crane. Torch cutting methods (oxy/acetylene) may be used if required. Mechanical saws or hand tools may also be used. All openings will be sealed before removal. The last operation is the lifting of the heat exchangers by the crane to the reactor hall for subsequent preparation for transporting to the disposal site.

The PCC components to be dismantled can be categorized as follows: pipes, piping hangers, valves (check and isolation valves), pumps, supports, instrument gauges, flanges, screws and gaskets. Disassembling the above mentioned equipment will be performed before cutting to reduce the cutting points. The isolation and check valves, the pumps and the supports will be unscrewed and disassembled without cutting. Any liquid or sludge present in the piping should be drained and placed into drums and should be measured to determine the final waste/material disposition. The PCC pipes, after disassembling will be cut into pieces (of about 2-3 m in length) for effective transport, decontamination, characterization and possible clearance. The piping will be cut using circular mechanical saws. Cutting will be performed according to prepared cutting plan.

The water cleaning system components (the ion-exchange filters) connected to the PCC will be cut off and lifted by crane. Torch cutting methods (oxy/acetylene) will be used to disassemble the columns from their support base. Mechanical saws, air powered saws, or hand tools may also be used.

III.2.4. Cooling pond removal

Since the cooling pond is located close to the reactor, its removal will be possible only after reactor decommissioning. The proposed sequence is:

1) removal of the cover metal plate;
2) cutting the connection pipes;
3) extraction of the inner aluminium tank.

Since the external tank is embedded in the concrete of the biological shielding, demolition of the peripheral concrete around the tank will be followed by tank's removal in one piece for subsequent cutting.

III.2.5. Biological shield demolition

The following methods for the demolition of the biological shield should be applied:

- the demolition of concrete using a hydraulic hammer e.g. fitted to a 'Brokk' type remotely controlled demolition robot ; and
- remotely controlled diamond wire-cutting, e.g. for cutting horizontal beam tubes (concrete, steel, aluminium, lead).

The above mentioned solution is acceptable regarding both radiological and economic aspects. The demolition robot, being driven by electricity and remotely operated by one person, can also handle the concrete from the biological shield. It breaks the concrete with a hydraulic percussion hammer and is also equipped with a jet, which can spray water mist over the concrete dust to reduce airborne contamination.

Demolition will start from the inside upper part of the biologic shield downwards so the activated material is removed first. When the concrete demolition reaches the cast-iron rings around the reactor, the rings will be transferred to the dismantling workshop to be cut by e.g. saw. After radiological characterization the material is transported as a waste for cutting and insertion into the storage containers.

APPENDIX IV. REACTOR DESIGN AND LAYOUT, DISMANTLING SEQUENCE AND MANAGEMENT OF MATERIALS FOR PARTICIPATING OPEN POOL REACTORS

IV.1. DESCRIPTION OF THE ASTRA REACTOR, AUSTRIA

The ASTRA Reactor (Fig. 60), a 10 $MW_{(th)}$ multipurpose MTR open pool type research reactor at the Austrian Research Centre Seibersdorf was decommissioned after 39 years of successful operation. The reactor had reached first criticality in September 1960 and was operated at a power level of 100 $kW_{(th)}$ until April 1962. In May 1962 the power level was raised to 1 $MW_{(th)}$ and in August 1962 to 5 $MW_{(th)}$. In 1969 the power level was further increased to 6 $MW_{(th)}$ and three years later to 7 $MW_{(th)}$. Since January 1975 the reactor has been operating on a maximum power level of 8 $MW_{(th)}$ and in the last decade of 9.5 $MW_{(th).}$

The reactor was designed for irradiation of samples from the top through the pool water, by irradiation loops and rabbit systems, by irradiation devices adjacent to the core and by a thermal column and beam tubes. Some of the irradiation facilities and devices were installed at a later phase. This was possible due to the high flexibility of the design of the reactor. These later installed features include a fast neutron irradiation facility for seed irradiation, large volume irradiation chambers and irradiation facilities for NTD-silicon production.

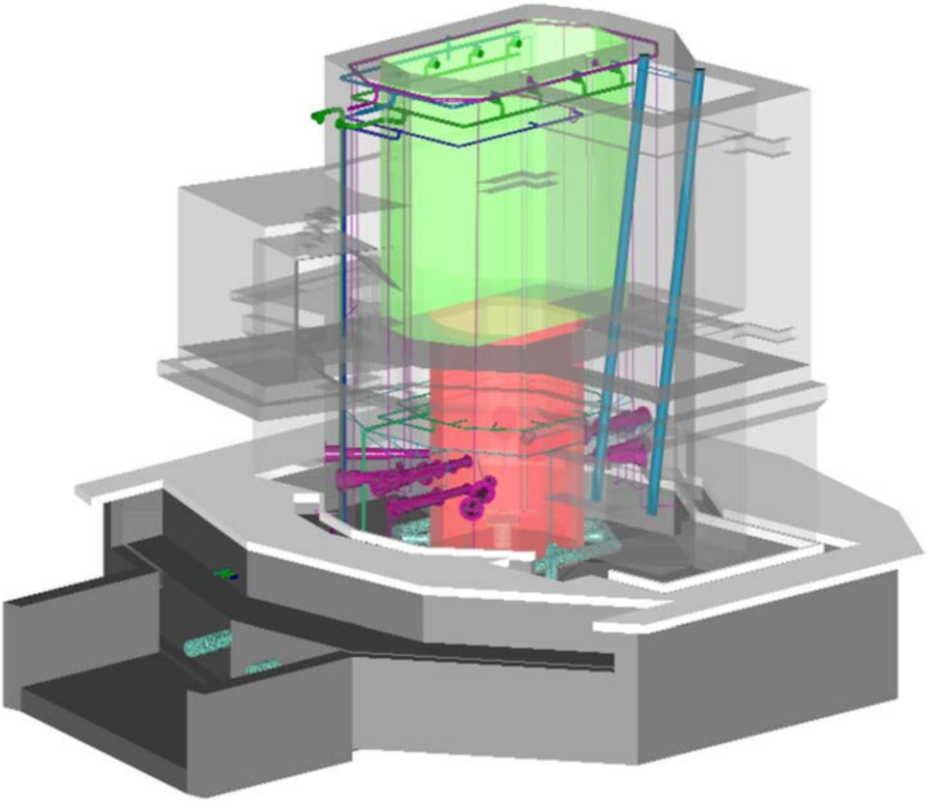


FIG. 60. Astra reactor CAD 3D model (photo courtesy Nuclear Engineering Seibersdorf GmbH).

Decommissioning strategy

The strategy was an immediate dismantling with end-point of unrestricted use. The decommissioning was performed in the following steps:

- removal and final disposition of the fuel elements
- ILW removal (remotely), e.g. reactor components, beryllium reflector elements, reactor and beam tube experimental equipment; dismantling in hot cells; decontamination for release, if applicable.
- LLW removal, e.g. the thermal column and moderator graphite removal, water circuits and auxiliary systems characterization and dismantling, contaminated and activated metals characterization and removal, activated Barite concrete characterization, dismantling the biological shield, radiological clearance of concrete.
- Radiological clearance of the reactor building.
- Full radioactive waste management including treatment and disposal of waste

In October 2006 the reactor building was released from regulatory control [13].

IV.2. DESCRIPTION OF THE DR-2 REACTOR, DENMARK

Description

The Denmark Reactor DR-2 (Fig. 61) was a light water cooled and moderated heterogonous research reactor of the open pool type with a thermal output of 5 $MW_{(th)}$. The reactor was located at the Risø National Laboratory site. Highly enriched uranium was used in the fuel elements. The DR2 first reached criticality in December 1958, and was finally shutdown in 1975. It was used for physics research and production of radioactive isotopes [14].

The DR-2 reactor consisted of the following elements:

- reactor block with a shielded tank, the reactor core, the thermal column and a store called “the igloo” (ground floor);
- primary cooling circuit with a decay tank, heat exchangers, pumps and ion exchanger unit (basement); and
- secondary cooling circuit with a stand-by tank unit (basement and externally to the building).

The open reactor tank was cylindrical, 2 m diameter, 8 m high. The lower part of the aluminum tank was encased by a biological shield in the form of an octagonal baryte concrete, roughly 2 m thick. The reactor core consisted of 36 fuel elements; in certain central elements the fuel plates had been removed and replaced by an aluminum box in which the vertical control rods with neutron-absorbing material were held.

Beryllium elements were located in the outermost position on the reactor core grid plate along three sides, free of the thermal column. No incidents or accidents with radiological consequences occurred during the operation of the reactor.

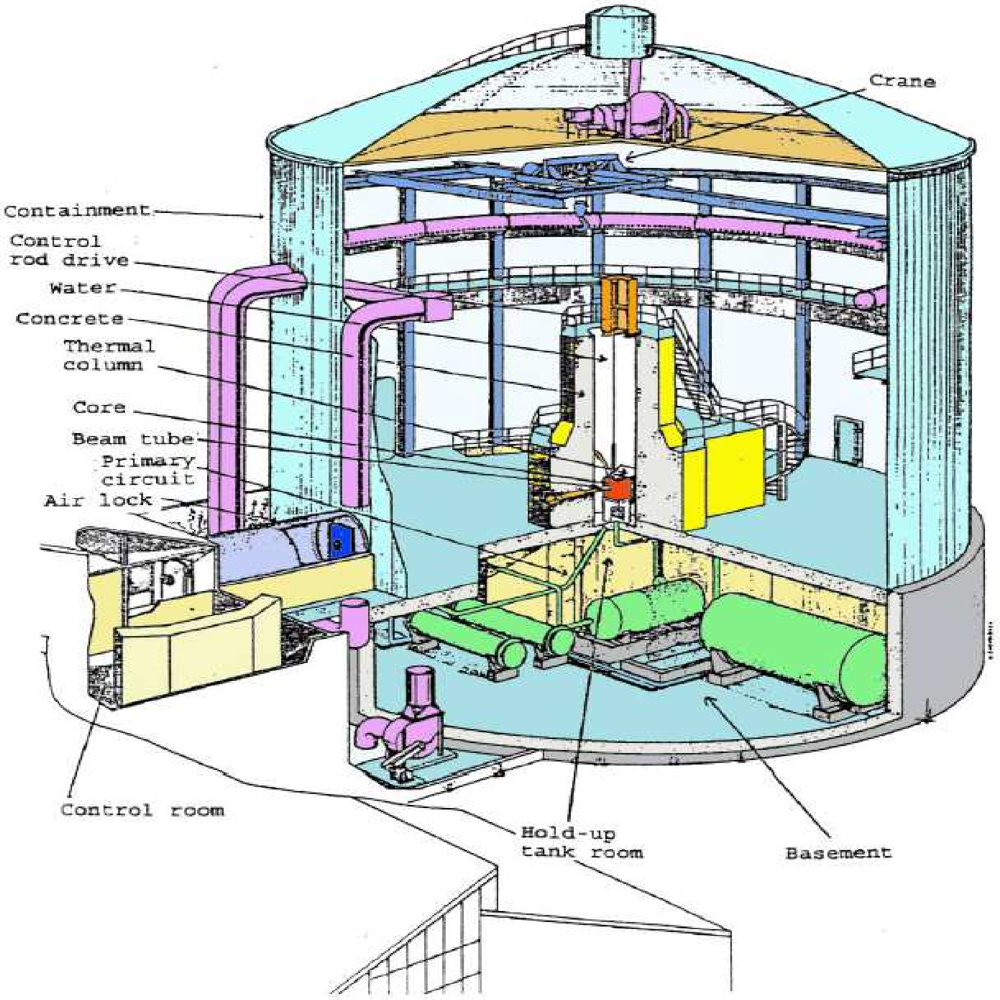


FIG. 61. Perspective of DR-2 reactor (photo courtesy Dansk Dekommissionering).

Decommissioning strategy

The decommissioning steps were following [14]:

- dismantling existing ventilation system in the building,
- removal of items from the store “igloo” (items from operation and post-operation)
- removal of tubes, and instrument thimbles, including shielding plugs
- removal of the thermal column
- removal of the grid plate
- dismantling the cooling circuit and ion exchanger unit (basement);
- demolishing the reactor block and lining tubes (liners); (characterization, demolishing/removal of non-activated and then activated parts)
- removal of stand-by tank unit
- final characterization.

The original end-point was to enable the area and any remaining buildings to be used without any restriction. At the end of the decommissioning project, no attempt was made to clear the building and surrounding area for use without restrictions, since it was decided to continue using the building for work with radioactive materials. However, classification of the site has been lowered [14].

IV.3. DESCRIPTION OF THE GRR-1 REACTOR, GREECE

Description

The GRR-1 (Greek Research Reactor) is a 5 $MW_{(th)}$, open pool type, light water moderated and cooled heterogeneous reactor designed by AMF Atomics. It is located at the Campus of the National Centre for Scientific Research "Demokritos" (NCSR “D”) in Aghia Paraskevi, district of Athens.

The reactor first reached criticality in June 1961. Since April 1964, the reactor operated at the thermal power of 1 $MW_{(th)}$ and in 1971 it was upgraded to 5 $MW_{(th)}$. A further GRR-1 upgrading was performed in 1990 by partial replacement of the water reflector of the reactor core by beryllium. In 2004, it was shut-down and the fuel assemblies were removed to the spent fuel storage pool for safety reasons during the Olympic Games in Athens. In 2007, a decision on refurbishment and modernization of the reactor was taken, mainly concerning a replacement of the primary cooling system. The GRR-1 has been in extended shut down since July 2014. No incident or accident with radiological consequences occurred during the operation period of the reactor.

The reactor pool (Fig. 62) is a concrete structure with stainless steel liner. The reactor core consisted of 34 fuel assemblies supported by an aluminium grid plate accommodating 6X9 core element positions. The reactor control was performed through five control rods composed of Ag-Cd-In alloy. The main experimental facilities of the reactor were six beam tubes for irradiation of samples at the reactor core and the graphite thermal column. The GRR-1 pool cooling system is equipped with three delay tanks, two heat exchangers and three pumps. The secondary cooling system has two cooling towers. The GRR-1 layout and composition as well as the radiological status of the facility is described in reference [17]. Figure 63shows GRR-1 overview.

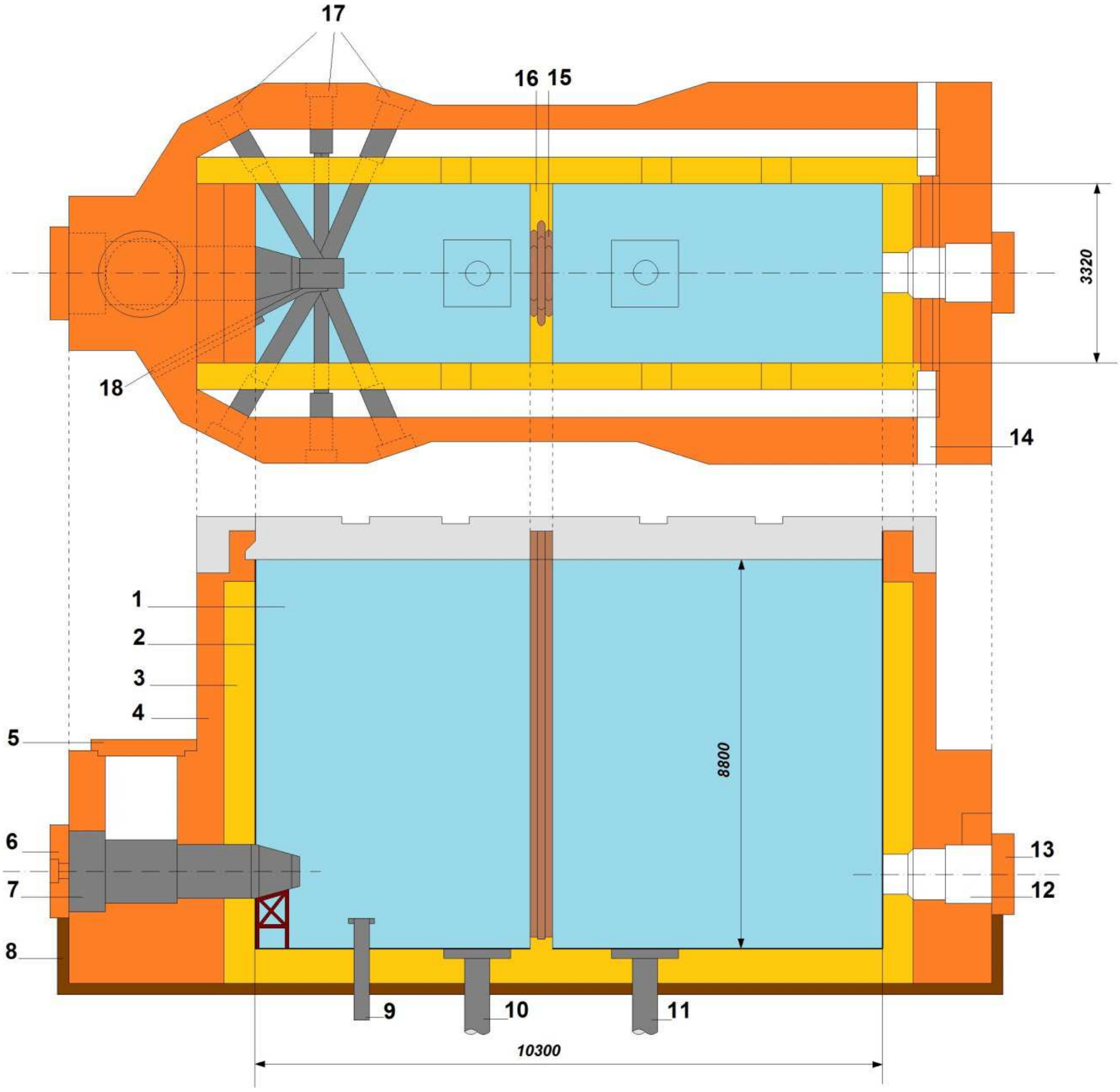


FIG. 62. GRR-1 pool vertical and horizontal sections. 1. Demineralised water; 2. Stainless steel liner; 3. Pre-stressed concrete; 4. Barite concrete; 5. Top cover of the thermal column; 6. Thermal column door; 7. Graphite; 8. Lead Jacket; 9. Cooling water outlet; 10. &11. Cooling water inlet; 12. Dry irradiation chamber; 13. Dry irradiation chamber door; 14. Access part; 15. Aluminium gate; 16. Dividing wall; 17. Beam tubes; 18. Thermal column (Printed with permission from National Centre for Scientific Research "DEMOKRITOS").

Decommissioning Strategy

The strategy is a removal of all activated and contaminated parts without demolition of the biological shielding. The spent fuel will be sent to the USA jurisdiction, according to the agreement with the US Department of Energy for shipment until 2019. The reactor building will be reused in the nuclear sector. Clearance procedures will be followed for release of building structures and materials.

The GRR-1 personnel will carry out all the decommissioning tasks. Pre-dismantling radiological characterization of the primary cooling system by using in-situ gamma spectrometry was carried out as well as neutron calculations for the grid plate, control rods and Beryllium blocks. The partial decommissioning plan for dismantling of the primary cooling system has been drawn up, reviewed and approved. Five out of six beam tubes, the control rods, the beryllium reflector blocks and the active core supporting components (grid plate, plenum etc.) were removed from the reactor pool and transferred to the spent fuel storage pool and other shielded storage structures. Then, the reactor pool as well as the pool cooling system was drained and the radiological characterization of the pool cooling system was accomplished by the collection and analysis of representative samples from the internal surfaces of the systems.

The classification of the waste which will arise from the decommissioning of GRR-1 was based on the considerations of long term safety considering the waste disposal [32].

FIG. 63. GRR-1 overview (Printed with permission from National Centre for Scientific Research "DEMOKRITOS").

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IV.4. DESCRIPTION OF THE JEN-1 REACTOR, SPAIN

Description

The JEN-1 (Fig. 64) was located at the CIEMAT (Centre for Energy-Related, Environmental and Technological Research) site, Madrid, Spain. It was a pool type research reactor, moderated and cooled by a light water, with a thermal power of 3 $MW_{(th)}$. It first reached criticality in 1958. From 1958 till 1984 the reactor was operated almost continuously. The main function was the isotope production. The pool was divided into three areas: (1) the high power zone, a cylindrical well of $60m^3$, where the reactor was located, (2) the low power zone of $228m^3$ of rectangular shape, and (3) the transition area used as an irradiated fuel storage. The drainage system of the reactor had three underground tanks (one of $350m^3$ and two ones of $50m^3$) to collect and control water before discharging.

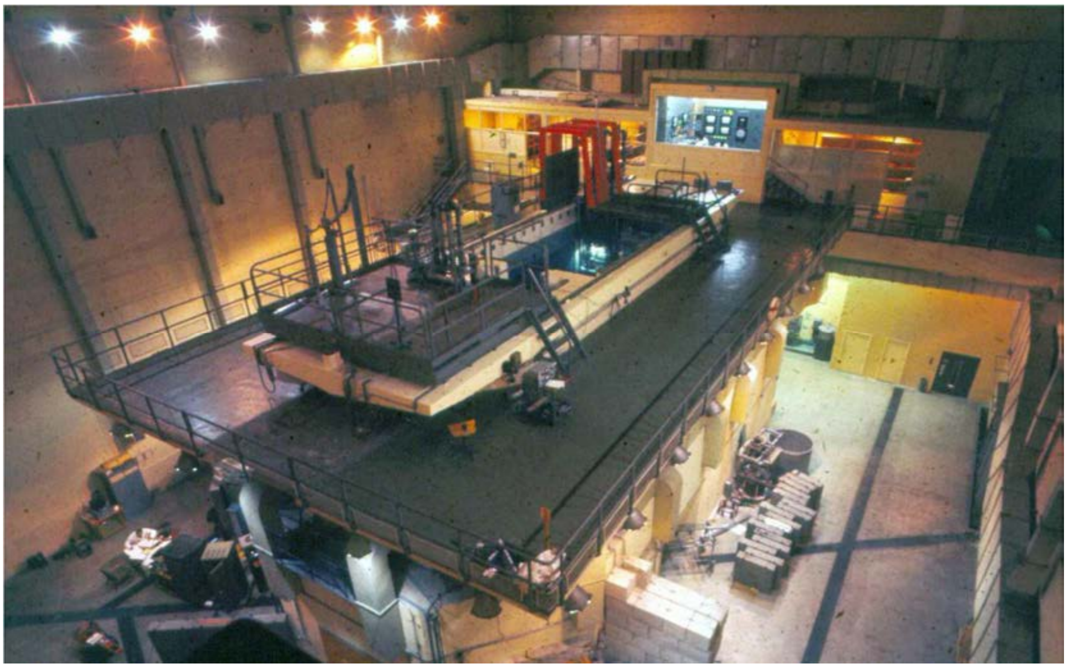

FIG. 64. JEN-1 during operation (photo courtesy CIEMAT).

The reactor was permanently shut down in 1987. In 1992 the irradiated fuel was removed from the site and shipped off to the United Kingdom [16].

Decommissioning strategy

The strategy was an immediate dismantling with an end-point of the reactor building released for unrestricted use. The JEN-1 decommissioning project was authorized in 2005 and the decommissioning of the reactor was completed in 2010. The decommissioning was performed in the following steps:

- preparatory activities (isolating the decommissioning area from the rest of the CIEMAT site, modification of supporting systems as ventilation, fire-fighting, etc.; refurbishment of auxiliary facilities for radioactive waste conditioning and storage);
- dismantling of systems and components in the reactor building;
- decontamination of the reactor building and removal of activated concrete;
- demolition of the pool structure (4 m thick, 10 m height) and the underground tanks;
- buildings restoration and final radiological survey.

This included a waste and material management without prediction for disposal of radioactive waste, project management, and engineering and site support [16].

IV.5. DESCRIPTION OF THE APSARA REACTOR, INDIA

APSARA, India's first research reactor was commissioned in the year 1956 in Bhabha Atomic Research Centre and has been extensively utilized by various users for more than five decades. Figure 65 shows Apsara reactor. The reactor was used for production of radioisotopes, neutron detectors testing, neutron radiography, neutron beam research, neutron activation analysis studies, agriculture and biological studies, shielding experiments, human resource development etc.

FIG. 65. APSARA reactor (photo courtesy BARC).

APSARA is an open pool type reactor loaded with high-enriched uranium fuel. The pool with demineralized water serves as a coolant, moderator, and reflector besides providing shielding. The fuel assemblies and the control elements are supported on a grid plate suspended from the movable trolley. The reactor has a primary and secondary coolant system for the removal of heat from the core and subsequent release to the environment through cooling towers. The vertical layout of the reactor is shown in Figs. 66.

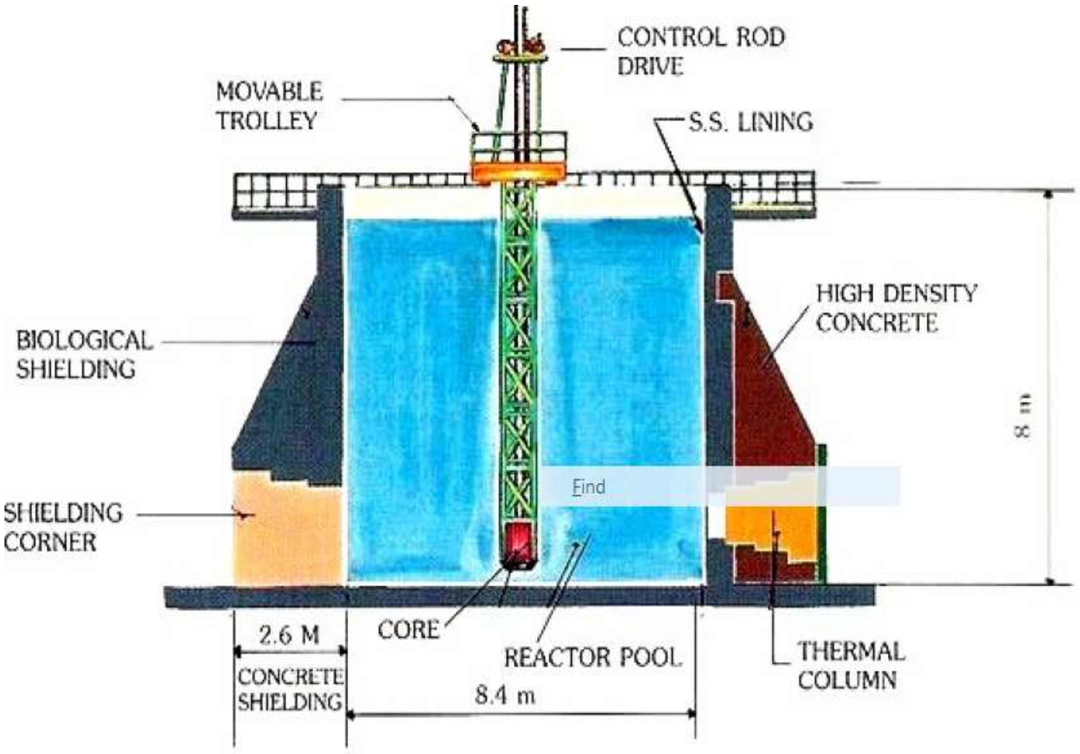

FIG. 66. APSARA reactor vertical section (photo courtesy BARC).

The reactor has been designed for a maximum power of 1 $MW_{(th)}$ operation and is normally operated up to 400 kW(th) since user needs are fulfilled at this power level. After commissioning the reactor and a few years of operation a stainless steel lining of the pool internals was made. During the life span of about 53 years, the reactor has developed a total thermal power of 63 GWh with an average availability factor of 70%.

The reactor was shut down in June 2009 for planned upgrading and refurbishment at the time. The basic features of the reactor are presented in Table 21.

Decommissioning strategy

The partial decommissioning of the reactor started in June 2009 and was completed within a 6 month period. This included removal of fuel and nuclear material, dismantling of core components within the controlled area except the pool concrete structure and the building structure. The fuel was transported in casks and stored in the buffer zone within the Centre.

All the different categories of waste were segregated, packed and transported to the in-house waste processing facility.

The radiological characterization of the reactor pool concrete to classify the future concrete waste was done and completed within 4 month period.

The dismantling of the reactor pool as well as the demolition of the reactor building will be carried out subsequently. There is no known incident during operation of the facility.

TABLE 21. APSARA REACTOR CHARACTERISTICS

Reactor type	Swimming pool
Rated power	1 $MW_{(th)}$
Fuel	High enriched U- Al alloy
Fuel element type	Flat plates
Fuel cladding	Al alloy
Moderator	Light water
Reflector	Graphite, beryllium oxide, light water
Core size	560x560x615 mm
Max neutron flux	10^{12}n/cm^2/sec
Control cum-shutdown	cadmium shut-off rods

Decommissioning strategy

The partial decommissioning of the reactor started in June 2009 and was completed within a 6 month period. This included removal of fuel and nuclear material, dismantling of core components within the controlled area except the pool concrete structure and the building structure. The fuel was transported in casks and stored in the buffer zone within the Centre.

All the different categories of waste were segregated, packed and transported to the in-house waste processing facility.

The radiological characterization of the reactor pool concrete to classify the future concrete waste was done and completed within 4 month period.

The dismantling of the reactor pool as well as the demolition of the reactor building will be carried out subsequently.

There is no known incident during operation of the facility.

IV.6. DESCRIPTION OF THE TAMMUZ-2 REACTOR, IRAQ

Description

The Tammuz-2 reactor (Fig. 67) is located at the Al-Tuwaitha site, one of the most important and oldest nuclear sites in Iraq, about 20 km south of Baghdad. The site consists of a complex of 18 nuclear facilities, having been built-up on the basis of an Iraq-France contract.

The Tammuz-2 reactor was a light water cooled and moderated open pool research reactor, with a maximum thermal power of 500 kW(th), using 93% U-Al sandwich plates for fuel. The main research performed with the reactor involved dry radiography and vertical holes outside reactor core. Tammuz-2 scheme is shown in Fig. 68.

It first reached criticality in 1980, and in 1987 it started operation at its full power. The reactor operated until 1990. In 1991 and during the 2nd Gulf War Tammuz-2 has been bombed and completely destroyed. The total power generated by that time was 2.017 $MW_{(th)}d$.

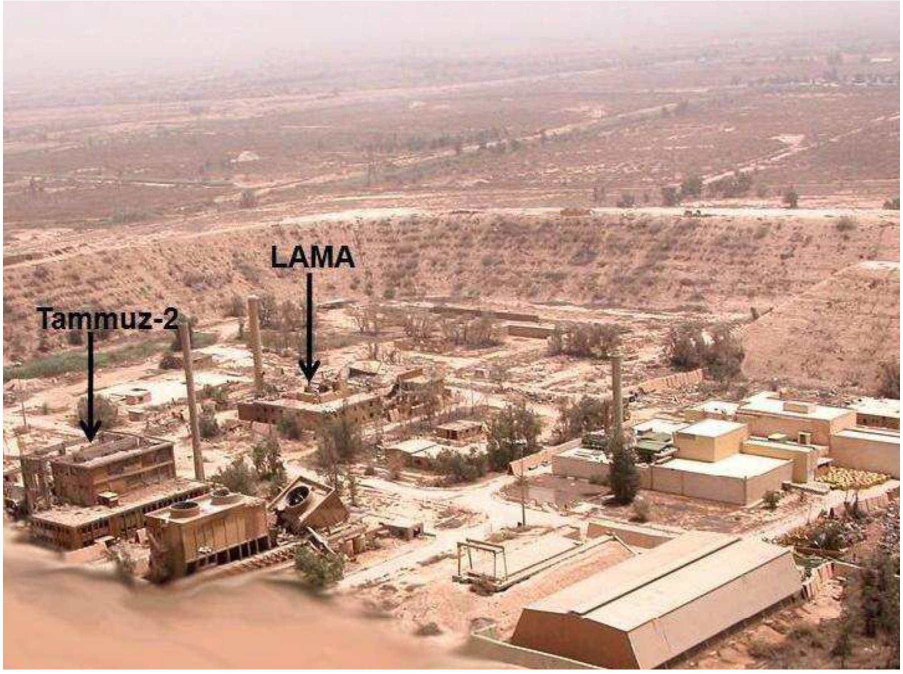

FIG. 67. Tammuz-2 reactor site prior to 1991 (photo courtesy Ministry of Science and Technology, Iraq).

Decommissioning strategy

The Iraqi decommissioning strategy involves at least all those former nuclear sites and facilities that were destroyed during the 2nd Gulf War. The aim is to assure safety and to decrease exposure, in order to protect public and the environment. To achieve this, all radioactive and hazardous material has to be removed. The end-state of decommissioning is to release the site for restricted use. A site remediation is part of the decommissioning.

The material cleared from regulatory control is in accordance with the IAEA standards. However, part of the cleared material is not accepted as conventional waste and is removed as radioactive waste.

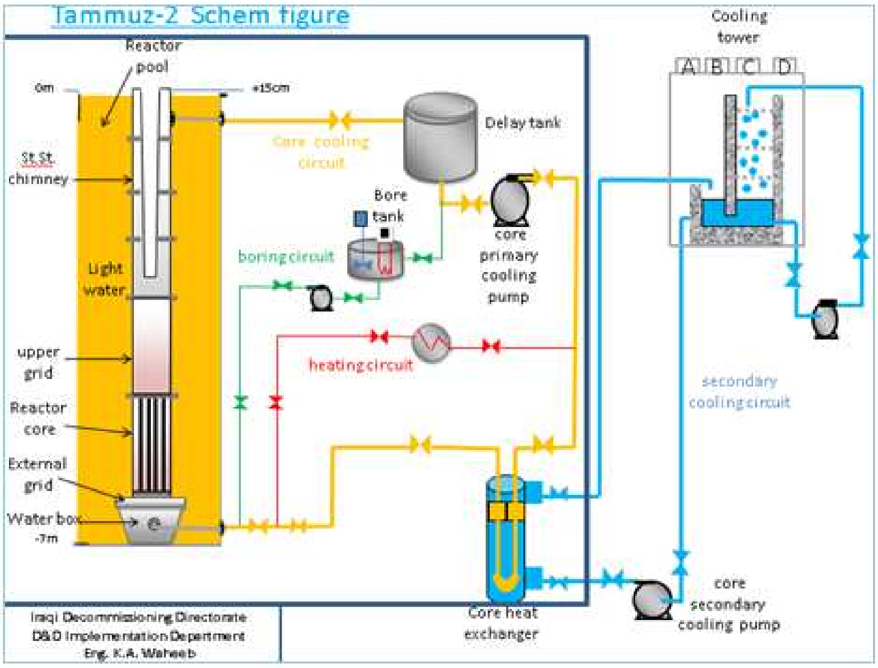

FIG. 68. Tammuz-2 scheme (photo courtesy Ministry of Science and Technology, Iraq).

The radioactive waste was removed from the site to the Radioactive Waste Treatment Station (RWTS) in special drums according to the waste acceptance criteria (WAC), in expectance of installation of the interim storage in the future.

IV.7. DESCRIPTION OF THE SILOËTTE REACTOR, FRANCE

Description

Siloëtte (Fig. 69) was an open pool type reactor, designated as French Basic Nuclear Installation (BNI) No. 21, which began operation in May 1964. The reactor was located on the CEA / Grenoble site, close to the Siloé reactor, and operated by the CEA [16]. Since its commissioning, Siloëtte operated at an average power of less than 1 kW(th) with a maximum power of 100 kW(th).

FIG. 69. Exterior view of Siloëtte (photo courtesy CEA).

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Siloëtte was capable of using cores composed of new or irradiated elements in Siloé. It initially performed a dual role, being first used to conduct studies and reactor physics measurements using:

- The cores of Siloé and Melusine: reactivity measurements, flow, calibration spectra and bars on the core of Siloé and Melusine, and
- Associated irradiation devices: Experimental studies of new related devices, reactivity effects and flow depression.

It was also used as a neutron source for performing various studies and measurements, including:

- Experiments on neutron beams;
- Fast neutron experiments;
- Development of equipment controls and radiation measurements;
- Neutron radiography; and
- Use as a teaching laboratory.

No incident or accident with radiological consequences occurred during operation.

Decommissioning strategy: the main phases of the decommissioning project were:

- 2002: Start of the POCO (Post Operational Clean Out) phase; and
- 26 May 2003: Submission to the dismantling safety documents to the Nuclear Safety Authority.

Completion of POCO

- Dismantling Decree was published in the Official Journal on 2 February 2005.
- May 17, 2005: Internal Safety Commission No. 8 aimed to create two hoppers (openings) on concrete walls at the basin level,
- June 2005: Beginning of the dismantling work,
- September 2006: Completion of final decommissioning operations on achievement of final checks,
- December 20, 2006: CEA request to Nuclear Safety Authority (ASN) for the waste zoning and administrative decommissioning of BNI 21.
- 10 July 2007: Decision No 2007-DC-0063 ASN of 10 July 2007 on the decommissioning of Siloëtte,
- August 1, 2007: Approval of the decommissioning
- 2012: Demolition of the building.

Conclusion

Siloëtte operations resulted in no radiological or chemical pollution of outdoor areas nor of soil under the buildings, avoiding any need for extensive investigations and/or or remediation actions. Furthermore, the achieved end state does not require any ongoing surveillance and the need to retain detailed historical records was minimized.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Bacsko, G.	PURAM, Hungary
Chen, Y.	China Institute of Nuclear Energy, China
Ciocanescu, M.	Institute for Nuclear Research (INR), Romania
Daniska, V.	Decom, Slovakia
Gouhier, E.	Alternative Energies and Atomic Energy Commission, France
Grossi, P.	National Nuclear Energy Commission, Brazil
Gyergyek, A.	Jozef Stefan Institute, Slovenia
Hamayun, N.	Pakistan Institute of Nuclear Science and Technology, Pakistan
Jin, H.G.	Korea Atomic Energy Research Institute, Korea, Republic of
Leibundgut, F.	Paul Scherrer Institute, Switzerland
Ljubenov, V.	International Atomic Energy Agency
Lobach, Y.	Institute for Nuclear Research, Ukraine
Mirvakili, S.	Nuclear Science and Technology Research Institute (NSTRI) Iran, Islamic Republic
Moitrier, C.	Alternative Energies and Atomic Energy Commission, France
Moshonas Cole, K.	Kinectrics, Canada
O’Sullivan, P.J.	International Atomic Energy Agency
Owsianko, I.	National Centre for Nuclear Research, Poland
Park, S. K.	Korean Atomic Energy Research Institute, Republic of Korea
Phetoe, M.	Elias Motsosaledi, South Africa
Poskas, G.	Lithuanian Energy Institute, Lithuania
Ratnawati, N.	Center for Nuclear Material and Radiometry Technology, Indonesia
Rehak, I.	Consultant
Savidou, A.	National Centre for Scientific Research ‘Demokritos’, Greece
Tachibana, M.	Japan Atomic Energy Agency, Japan
Tagliaferri, F.	SOGIN SpA, Italy
Trang, S.	Vietnam Atomic Energy Institute, Viet Nam
Van der Wagt – de Groot, K.	NRG, The Netherlands

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