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COST ASPECTS OF THE RESEARCH REACTOR FUEL CYCLE

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COST ASPECTS OF THE RESEARCH REACTOR FUEL CYCLE

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FOREWORD

Research reactors have made valuable contributions to the development of nuclear power, basic science, materials development, radioisotope production for medicine and industry, and education and training. In doing so, they have provided an invaluable service to humanity. Research reactors are expected to make important contributions in the coming decades to further development of the peaceful uses of nuclear technology, in particular for advanced nuclear fission reactors and fuel cycles, fusion, high energy physics, basic research, materials science, nuclear medicine, and biological sciences.

However, in the context of decreased public sector support, research reactors are increasingly faced with financial constraints. It is therefore of great importance that their operations are based on a sound understanding of the costs of the complete research reactor fuel cycle, and that they are managed according to sound financial and economic principles.

This publication is targeted at individuals and organizations involved with research reactor operations, with the aim of providing both information and an analytical framework for assessing and determining the cost structure of fuel cycle related activities. Efficient management of fuel cycle expenditures is an important component in developing strategies for sustainable future operation of a research reactor.

The elements of the fuel cycle are presented with a description of how they can affect the cost efficient operation of a research reactor. A systematic review of fuel cycle choices is particularly important when a new reactor is being planned or when an existing reactor is facing major changes in its fuel cycle structure, for example because of conversion of the core from high enriched uranium (HEU) to low enriched uranium (LEU) fuel, or the changes in spent fuel management provision. Review and optimization of fuel cycle issues is also recommended for existing research reactors, even in cases where research reactor operators are constrained in their choices relating to the fuel cycle, for example by national policies or the limited availability of technical alternatives. A sound and detailed review of the available fuel cycle related choices and development of a customized economic model for the reactor that can analyse the costs and benefits of the various choices can lead to better decision making and greater sustainability for the research reactor.

This publication provides information on the choices available at each stage in the cycle, together with methodologies for economic analysis of the reactor operations. It includes case studies that show how an economic model can be constructed to support research reactor decision making, and how fuel cycle choices have been addressed during planning for HEU to LEU conversion.

The IAEA wishes to thank all the contributors to this publication. Special thanks are due to K. Alldred who compiled the text. The IAEA officers responsible for this publication were P. Adelfang and I.N. Goldman of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. BACKGROUND

For over 50 years, research reactors have made valuable contributions to the development of nuclear power, basic science, materials development, radioisotope production for medicine and industry, and education and training. In so doing, research reactors provide an invaluable service to humanity.

However, the future of many research reactors is in question due to ever increasing competition for limited government research and development funds, competition in the commercial marketplaces, and the increased emphasis on the safety and security of nuclear facilities. Facilities have to justify their existence and utility to their funding sources, usually Governments, in order to secure continued financial support.

The justification of the utility and continued need for any given research reactor is not purely economic because of the many 'social goods' provided by research reactors. These include the value and societal benefits of the scientific research, training, and other difficult to quantify activities.

However, economic realities are a fact of life. They strongly influence general political opinion and are persuasive (if not deterministic) in many specific decisions. Given that research reactors are now receiving new attention from many perspectives, it is important that cost factors be understood, realistically defensible, and analysed in a manner that reflects modern considerations and techniques. This requires, among other things, that research reactors prepare a strategic plan, and budget and monitor their operations and maintenance costs, including specific fuel cycle expenses (fuel procurement and use and spent fuel management).

Fuel cycle related expenses can be a significant part of the total operating expenses of a research reactor. Thus, cost reductions obtained through the efficient management of the research reactor fuel cycle are an important step toward achieving the sustainability and continued operation of a research reactor. These fuel cycle related expenses include the purchase of fresh fuel, the management of spent fuel, including interim storage and eventual disposition, and the management of the core, which impacts both the need for fresh fuel as well as the amount of spent fuel generated.

In addition, at present there is strong international pressure to convert all research reactors to use low enriched uranium (LEU) fuel. The costs of making this conversion and the implications of the technical choices involved are highly relevant to fuel cycle cost analysis.

Institutions that are contemplating a new research reactor, conversion of a research reactor, or other changes in research reactor fuel related arrangements should assess the cost implications of the available choices, even in cases where fuel cycle and supply choices are limited by political or other considerations.

1.2. OBJECTIVE

The objective of this publication is to provide research reactor operators and associated institutions or organizations with information and an analytical approach for assessing the cost impact of the fuel cycle related activities of their reactors. In doing so, it is hoped that operating organizations can find ways to achieve the most efficient cost structure for their fuel cycle related reactor operations, consistent with the operating needs and utilization requirements of the reactor.

The information presented in the publication may also be used by research reactor operators and licensees to benchmark current operations and then to:

- Develop strategic operational plans and risk assessments;
- Make effective budget forecasts and plans;
- Make beneficial decisions about future cost options and opportunities;
- Evaluate provisions for future liabilities;
- Evaluate consolidations or cooperative programmes.

This publication will be of greater or lesser applicability to reactor operating organizations, depending upon a number of factors. For instance, the information in this publication may assist reactors of higher power and high utilization rates that require regular refuelling to make well informed fresh fuel cycle choices, with improved core management, and reduced spent fuel discharge.

Low power reactors with lifetime cores or requiring very infrequent replacement of fuel assemblies will have less opportunity to optimize their fuel operations, though the spent fuel management choices discussed here are still relevant with important long term economic implications.

1.3. SCOPE

In order to perform a full economic 'analysis' of a research reactor, total operating costs have to be compared to revenues from all sources (public financing, commercial sales, etc.), both for current and planned future operations. Ideally, this analysis starts with a strategic plan stating the intended purpose and uses of the reactor, and defining the reactor capabilities and operating performance necessary for plan implementation. The reactor capability and operating performance specifications provide important criteria for the subsequent fuel cycle and core optimization, as well as a frame of reference for determining which operating costs are acceptable and which are not.

This publication focuses specifically on information and analyses related to the costs of the research reactor fuel cycle, including the procurement and utilization of fresh fuel and the management of spent fuel. It does not examine other cost related aspects of research reactor operation such as labour costs, utilities (electric power and water), consumables, facility and equipment repair, renovation or refurbishment, and safety and security.

The revenue side of the economic equation has been touched upon by prior IAEA publications, and is not covered in detail here other than to note that the strategic plan referenced above should include a plan for maintaining or increasing public funding and/or commercial revenues.

Two very important issues discussed in the publication are HEU to LEU conversion and spent fuel management. The former raises a number of challenges and opportunities requiring a careful re-assessment of all aspects of core and fuel cycle management. The latter is a current and future liability that will require substantial effort and expenditure to resolve. This affects even those research reactor operators that presently have the 'luxury' of being able to return spent research reactor fuel to the USA or the Russian Federation, because these programmes are due to expire within the next few years. All research reactors therefore need to develop plans for long term spent fuel management, as a critical aspect of research reactor fuel cycle economics.

2. THE NUCLEAR FUEL CYCLE

2.1. BACKGROUND

The purpose of this section is to introduce the reader to the main characteristics of each step in the research reactor fuel cycle. The descriptions are not exhaustive but are intended to provide a context for the cost evaluation and a list of references.

2.2. THE NUCLEAR FUEL CYCLE

From the perspective of research reactor cost planning and control, each stage of the nuclear fuel cycle provides an opportunity for cost control, depending upon the research reactor operator's specific circumstances, and includes the following stages, each of which is discussed in the later sections:

- Procurement of enriched uranium in an appropriate form (usually metal chips);

— Fuel fabrication;
— Reactor irradiation;
— Temporary storage of spent fuel;
— Spent fuel reprocessing or disposal;
— Radioactive waste management;
— Transportation of uranium, fresh fuel, spent fuel and radioactive wastes.

The full fuel cycle [1] also includes the steps of uranium mining, conversion and enrichment in addition to the items listed above. However, this is primarily of interest to power reactor operators, who buy sufficient quantities of nuclear fuel to be able to interact with, and optimize, all stages in the cycle.

For simplicity, the fuel cycle has been historically considered to be divided into two basic stages, the front end (from ore to reactor) and the back end (from reactor to geological disposal). Both stages have been widely studied and described, but with a focus on the needs of power reactors. No similar or equivalent work has been done for research reactors for many reasons, including:

(1) Research reactors account for less than 1% of the uranium market. The worldwide nuclear fuel cycle is focused overwhelmingly on the production of <5% enriched uranium oxide for power reactor fuel. The research reactors typically require 20% to 93% enriched metallic uranium to prepare fuel in various chemical forms.
(2) There is little standardization among the research and radioisotope-production reactors; many reactors have unique features.
(3) Traditionally, planning for the design and operation of research reactors did not include fuel cycle logistics or the need to run on an economic basis. As a result, it was not unusual to stockpile sufficient fuel and materials for ten or twenty years' operation, and to simply store the spent fuel indefinitely in water pools.
(4) The volumes of HEU and LEU materials required by research reactors were negligible in comparison with those for the weapons industry. Thus research reactor fuel cycle requirements were relatively easy to satisfy as an adjunct to the weapons programmes.

2.3. IAEA ACTIVITIES RELATED TO THE NUCLEAR FUEL CYCLE

For more than thirty years the IAEA has been involved in supporting activities related to research reactor fuel cycle issues, including core conversion, high density fuel development, fuel storage, and fuel return programmes. Many IAEA Regular Budget and Technical Cooperation activities have supported research reactor conversion and spent fuel return programmes. In particular, after the announcement of the Global Threat Reduction Initiative (GTRI) by United States Secretary of Energy Spencer Abraham on May 2004, and following recommendations of the November 2004 RERTR (Reduced Enrichment for Research and Test Reactors) meeting, the IAEA has strengthened its support to the RERTR programme, to the US Foreign Research Reactor Spent Nuclear Fuel (FRRSNF) acceptance programme, and to the Russian Research Reactor Fuel Return (RRRFR) programme. While RERTR focuses on conversion of research reactors from HEU to LEU, the major goal of FRRSNF and RRRFR is to eliminate inventories of HEU by returning the research reactor nuclear fuel to the country where it was originally enriched. All programmes have been fully supported by the IAEA.

Considering that one of the objectives of the IAEA is to support and improve all aspects of the research reactor nuclear fuel cycle in Member States, during the last years support has also been given to several national and international efforts to develop, qualify, and license LEU fuel for research reactors. These efforts include Russian designed LEU, to allow for the conversion of a significant number of Russian designed research reactors and high density fuel for application in plate type reactors of Western design, tube type reactors of Russian design, and pin type reactors of Canadian design. This development work has been undertaken to provide fuels with the higher densities needed to extend the use of low LEU to those reactors requiring higher densities than currently available in uranium silicide dispersions and to provide a fuel that can be more easily reprocessed than the uranium silicide. The IAEA has also supported Member States that requested assistance to implement national capability to produce nuclear fuel elements for internal consumption.

Finally, the IAEA has also been involved with the issue of research reactor spent nuclear fuel (RRSNF) storage. After discharge from the core, RRSNF is stored pending final treatment and disposal of the fuel or products. Regardless of how long this extended interim storage is drawn out, the resolution of the back end problem will remain, and proliferation, safety, physical security, and fuel integrity concerns will continue and so will continue the commitment of the research reactor operating organization/Member State to ensure safe, secure and reliable management of its own RRSNF. In this regard, the IAEA started a programme to discuss the timeliness, feasibility, scope and other features of a publication intended to make available to the whole research reactor community a consistent set of internationally accepted good practices for storage and management of RRSNF with a focus on long term wet and dry storage technologies and strategies.

3. URANIUM PROCUREMENT AND FUEL FABRICATION

3.1. INTRODUCTION

Presently, there is no new primary production of uranium enriched to 19% ^{235}U or higher, as is required for most research reactor fuels. Such material is sourced from existing governmental stockpiles of enriched uranium, through a small number of vendors and intermediaries.

Uranium for research reactor fuel is normally made available in the form of broken pieces or geometric shapes of uranium metal that can be easily converted to various alloys of uranium and other metals, or to uranium oxide. ASTM International publishes a specification for this material [2]. Uranium for research reactor fuel can be purchased in other chemical forms, for example UF_6, but this is much less common.

The importance of uranium procurement and fuel fabrication in the expense structure of a particular research reactor, and the options for cost management are very much dependent on the reactor’s individual characteristics and constraints. These include:

The type of research reactor and research reactor fuel

For MTR fuels there are a number of competing fabricators that can supply internationally, as well as a number of countries with domestic fuel fabrication. Thus fuel can be purchased through a competitive international tender, either for the purchase of the fuel and uranium together, or to purchase the enriched uranium and fuel fabrication services separately. It should be noted that there are a wide variety of MTR fuel designs, some of which can be provided by a larger number of fabricators than others.

TRIGA reactor operators have limited options for the procurement of fresh fuel, as there is currently only one TRIGA licensed fuel fabricator, the TRIGA International joint venture between CERCA and General Atomics. The only choice the operator has is whether to separately purchase the enriched uranium and provide it to TRIGA International for fabrication of the fuel assemblies, or whether to purchase a fuel/uranium bundle from the manufacturer.

Russian research reactor fuels have historically been supplied only by the Russian fuel manufacturer TVEL Corporation, but there are indications that other suppliers may decide to offer some types of Russian designed fuel assemblies in the future.

The reactor power, flux level and required utilization pattern

Well utilized high flux/high power research reactors have much higher fuel consumption, and therefore both greater costs and potentially greater negotiating leverage than low flux/low power or less well utilized reactors.

Reactor conversion from HEU to LEU fuels

Conversion of the reactor to low enriched fuels is a major change that will impact both the performance and economic aspects of reactor operation. This impact can be positive or negative. The conversion planning should include a strategic review of the current and future uses of the reactor so that the new LEU core can be optimized to the mission of the reactor. The new core size, geometry, fuel density and core layout can be selected to improve reactor utility and economics.

Operators of reactors for which qualified LEU fuels are available, but which have not converted due to the cost of so doing, may seek financial assistance which is available under international programmes such as the Global Threat Reduction Initiative (GTRI).

Provision of commercial services or offering of essential beam line facilities

If a reactor is utilized much for the provision of commercial services, or has commitments to provide access to beam lines, the reliable availability of the reactor and neutron production is essential. Fuel, refuelling choices and optimization of fuel costs are potentially critical in terms of managing revenue producing production schedules.

3.2. URANIUM PROCUREMENT

Several aspects of uranium procurement should be considered:

Separate purchase of uranium, or a fuel and uranium bundle

Some operators may choose to have the enriched uranium procured by the fuel fabricator. In other cases, the operator may procure the enriched uranium themselves and arrange for its shipment to the fuel fabricator. The choice between the two approaches depends upon the market expertise and access of the buyer.

Enrichment level of the uranium

There is an international consensus on the desirability of minimizing, and eventually eliminating, the use of HEU in civil nuclear commerce. The last two decades have been marked by the activity of the RERTR programme to convert research reactors from HEU to LEU fuel, supported by efforts to increase the uranium density of LEU fuel elements so that the reactor performance can be maintained with the change in fuel enrichment.

This trend has gained strength during the last few years, especially because the few countries, all nuclear weapon states (NWS), that are capable of supplying HEU have increasingly limited such sales due to legislative or policy restrictions. For the most part, these few remaining suppliers will not sell HEU to any new customers or facilities, or to existing customers if a licensed LEU fuel design exists, and have instituted restricted or conditional arrangements for supplying HEU to a few existing customers and facilities.

Thus, most research reactors must eventually reduce the enrichment of their core — if they have not already converted — in order to continue operation of the reactor. For this reason, in the long run they should plan to operate their reactors using <20% enriched uranium fuel only.

Sources of low enriched uranium

As noted above, none of the commercial enrichment plants currently produce uranium at the 19.75% enrichment needed for LEU research reactor fuels. The primary supply of 19.75% material is a result of the ‘blend-down’ of excess HEU material, owned in large part by US DOE and ROSATOM. The HEU inventories total several hundred metric tons of HEU. When compared to the worldwide demand for research reactor fuel of 3 metric tons per year it can be seen that these inventories are sufficient to fuel the current fleet of research reactors for the next several decades. Even if the annual consumption of 19.75% enriched fuel increases due to projected core conversions and improvements in reactor utilization factors, the present world stocks will be sufficient to provide a secure supply of uranium fuel for the foreseeable future.

There are three main international suppliers of 19.75% enriched uranium, the USA (Department of Energy (DOE), Russian Federation (ROSATOM) and France (EURODIF). The United Kingdom is a supplier at a smaller scale than the others. For example, in 2008, the US DOE reported that it had set aside about 10 M t U of HEU to be down-blended to LEU at 19.75% enrichment for sale as research reactor fuel to approved customers, of which some 2.2 M t U had been down-blended and delivered as research reactor fuel through mid 2008 [3].

Impact on spent fuel management arrangements

An important factor influencing the selection of uranium supplier is the potential effect on spent fuel management arrangements. If the uranium is supplied by the USA, the resulting irradiated fuel elements are eligible for the US 'take back programme', provided that they are discharged before 12 May 2016. LEU supplied by the Russian Federation qualifies for a parallel Russian return programme. Uranium bought from other countries such as France or the UK does not qualify for either of the spent fuel return programmes and as such must be managed within the domestic back end management programmes. This issue is further discussed in Section 6.1.

Market prices

The price of 19.75% enriched uranium is based on market factors, including the price of natural uranium and separative work units (SWU). These market prices have increased significantly since 2004. As a consequence, in the Spring of 2009 the price for 19.75% enriched metallic uranium ranged between US $11 000 and US $17 000 per kg U, excluding the costs of transport. 19.75% enriched uranium supplied in oxide or hexafluoride form is somewhat more expensive because of the additional processing steps that are required.

Lead times for procurement

The lead times for uranium procurement must also be taken into account, as the time required between the payment and the transfer of the material (due to analysis to be performed and legal arrangements) can be between 3 and 6 months.

Uranium and fuel transport

The transport of uranium and fabricated fuel is of major importance for research reactors because it can be a high proportion of the fuel procurement cost and there can be a substantial lead time that will impact the fuel procurement schedule. This is partly due to safety restrictions applicable to this type of material, the cost of insurance to meet the nuclear liability in the country of origin, and the limited number of available carriers and routes for the transport of nuclear materials. The limited number of uranium suppliers often requires long distance transport of the material to the fuel fabricator.

In many cases, the reactor operator has the responsibility of arranging the uranium transport and will contract with third parties who specialize in such transport. This has two main drawbacks, one being the cost and the other the delays involved. A new hindrance has been added to this situation in the last few years, with the change in the transport regulations and further restrictions on air transport of nuclear material. In addition, there is a growing resistance on the part of air and sea shipping companies to this type of transport, resulting in a need to charter transports for very small quantities of material, further increasing cost and delaying delivery.

As an example, a recent purchase of some 100 kg metallic uranium transported from the USA to Argentina involved a payment of about US $200 000 for transport only. This represented an increase in the uranium cost of about US $2000 per kg U, equivalent to approximately 27% of the cost of the purchased material. There are also other recent examples where the transport cost added 10% to 20% to the cost of the uranium.

The USA to Argentina case cited above also experienced a delay of about 6 months in the time between purchasing the uranium and the arrival in the country due to difficulties in finding a company that would accept the cargo. Such difficulties also apply for the transport of fabricated fuel, where dedicated charter cargo flights or ground transport usually must be arranged.

3.3. FUEL FABRICATION

Research reactor fuel takes forms, with the most common being uranium–aluminium alloys, and uranium oxide or uranium silicide dispersed in an aluminium matrix, as well as the uranium-zirconium hydride fuels used by TRIGA reactors. New fuel technologies are under development to provide a higher uranium density in the fuel meat to enable the LEU conversion of certain high performance research reactors. These high density fuels may also provide an option for reducing fuel cycle costs, even for those reactors that can operate with existing fuel types.

Most research reactor fuels are produced by fuel fabricators and sold to research reactor operators as a complete package that includes both fuel fabrication and the enriched uranium. The price of fuel fabrication is sensitive to the type of research reactor fuel involved and the competitive structure of the fuel market, since some types of research reactor fuels are available from a single supplier, while others can be supplied by a number of competing fabricators.

The price of MTR fuel fabrication can range from US $10 000 to US $30 000 per kg U, excluding the cost of the enriched uranium. The wide range is due to the variety of MTR type fuel designs, as is discussed below. The range of prices for other kinds of fuel elements could be much higher than those related to MTR fuel types due to the complexity and limited opportunities for economies of scale in the production factories.

Lead times between ordering and delivery must also be taken into account when calculating cash flows since they may be anything between 6 months to 1 year. For research reactor operators and managers desiring to make precise plans for reactor refuelling, accurate information should be obtained from the fuel fabricator.

In some cases, research reactor operators or associated national nuclear programmes may decide to fabricate research reactor fuels locally. This decision may be based on a desire to enhance or maintain technical capabilities in the nuclear field. However, if there is high fuel turnover in the reactor and no or limited competition for fuel supply, localized fuel fabrication could be more economic than procurement from an external fabricator. A specific cost analysis needs to be performed to determine if local production is economically advantageous.

The reactor operation cost also has to be minimized and to this end the fuel should have good performance, supporting long fuel cycles and high average fuel burnup at levels required by the reactor core design.

3.3.1. Fuel meat

The first generation of research and test reactors, beginning with the MTR in 1952, was fuelled with U-Al alloy, with high enriched (93%) UAl_3 and UAl_4 particles dispersed in an aluminium matrix, with uranium comprising $18^{w}/_{o}$ of the alloy. These fuels were superseded by U_3O_8_Al and UAl_x-Al dispersion fuels with a higher uranium content of 30–50 $^{w}/_{o}$ by weight [4], which have demonstrated excellent performance.

Starting in 1978 fuels with higher uranium densities were developed under the auspices of the US Reduced Enrichment in Research and Test Reactors (RERTR) programme [5] to support international initiatives to convert reactors from HEU fuel to LEU fuel. By the end of 1987, dispersion fuels of UAl_x, U_3O_8, and U_3Si_2 with low enriched uranium had been qualified up to uranium densities in the fuel meat of 2.3 g U/cc, 3.2 g U/cc and 4.8 g U/cc, respectively. Due to the efforts of the RERTR programme 55 research reactors worldwide have been fully converted to LEU fuels as of 2008, mostly using U_3Si_2Alx dispersion fuel.

However, a number of reactors need even higher density fuels in order to convert to LEU. Consequently an effort to develop U-Mo alloy is in process, with a target minimum uranium density of the fuel meat of 8.0 g U/cc. The irradiation tests for U-Mo dispersion fuels revealed the intrinsic irradiation behaviour of the U-Mo particle to be good and acceptable. However, severe interaction between the U-Mo particles and the aluminium matrix during irradiation caused swelling of the fuel elements. Development work is continuing using various coatings into the aluminium matrix or U-Mo particles are also being investigated [6, 7], and a monolithic U-Mo fuel type is being developed in the USA [8]. The next generation of research reactor fuel will be selected on the basis of the test performance of these fuels.

These high density fuels will make it possible to convert essentially all research reactors to use LEU fuels. However the fuels may also be useful in increasing uranium content in fuel for reactors that have already converted, thus permitting extended fuel residence time and higher neutron fluxes. This offers the prospect of reduced fresh fuel purchases and spent fuel discharges — with a potentially significant reduction in fuel cycle costs even though the higher density fuels are likely to be substantially more expensive than the existing LEU silicide fuels.

For TRIGA reactors, uranium-zirconium-hydride (UZrH) nuclear fuel was developed in the 1950s at General Atomics and its use was extended in the 1980s by developing an LEU UZrH fuel that can be used to convert any existing TRIGA research reactor.

3.3.2. Fuel types

Most research reactor fuels are plate type. A typical plate fuel consists of thin fuel meats of around 0.020 inches (0.51 mm) thickness sandwiched between aluminium cladding plates of 0.015 inch (0.38 mm) thickness. The plates are brazed to a pair of side channels to form fuel elements with water channels between each of the plates of around 0.115 inch (2.92 mm).

However, some research reactors need customized fuels for specific applications. For example, the fuel plates of the high flux isotope reactor (HFIR) are formed as involute curves and assembled in two annular cylinders, with radially graded fuel meat to minimize power peaking, and B4C burnable poison in the inner plates (Figs 1, 2).

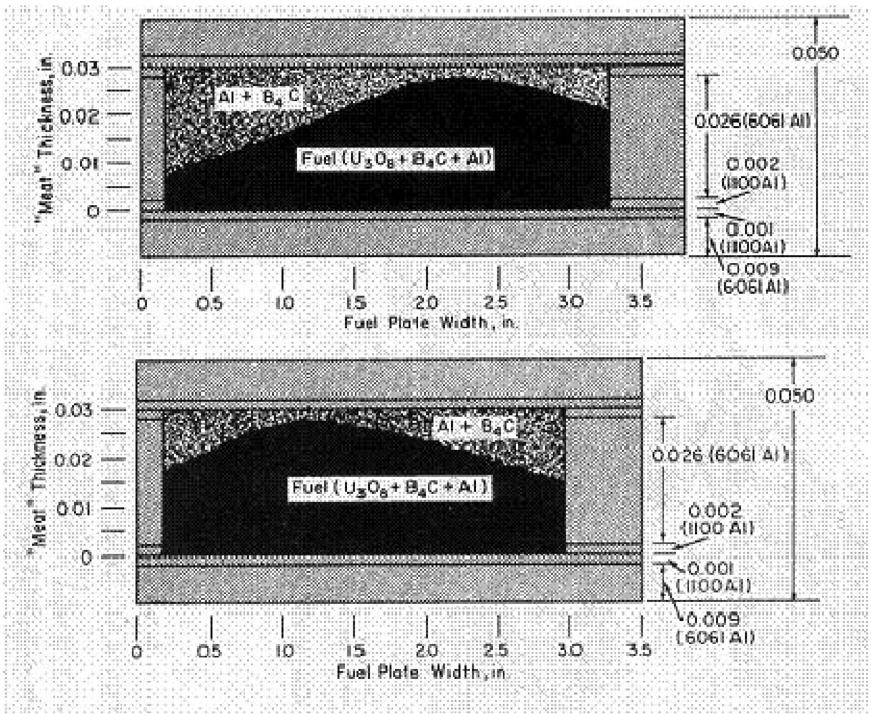
Another example of customized fuel is the tubular type fuel element used in the BR-2 reactor to provide very high neutron flux and thermal power of more than 10^{15} $ncm^{-2}s^{-1}$ and 50 MW respectively (Fig. 3).

During recent years a new U-Al dispersion pin type type fuel has been developed in the Russian Federation (Fig. 4). The design of the fuel element constitutes a pin of square cross-section with spacers at the fins on the corners twisted with a pitch of 320 mm [9].

AECL of CANADA has also developed solid rod type fuels for research reactors. In order to enhance heat removal from the fuel surface the fuel was designed to have 6 longitudinal fins on the cladding (Fig. 5). The HANARO fuel is designed along the lines of the AECL fuels, and is also a rod type.

3.3.3. Fabrication process

In general, fabrication processes of research reactor fuels are different depending on the material and type of fuel meat. In the case of U-Al alloy, a melting and casting process was used. For the dispersion fuels the powder metallurgy process is used. Fuel powder is prepared and then the fuel meat is fabricated by rolling or extruding. Typical flow diagrams of fabrication processes for common research reactor fuels are shown in Fig. 6.



FIGS. 1, 2. HFIR fuel.

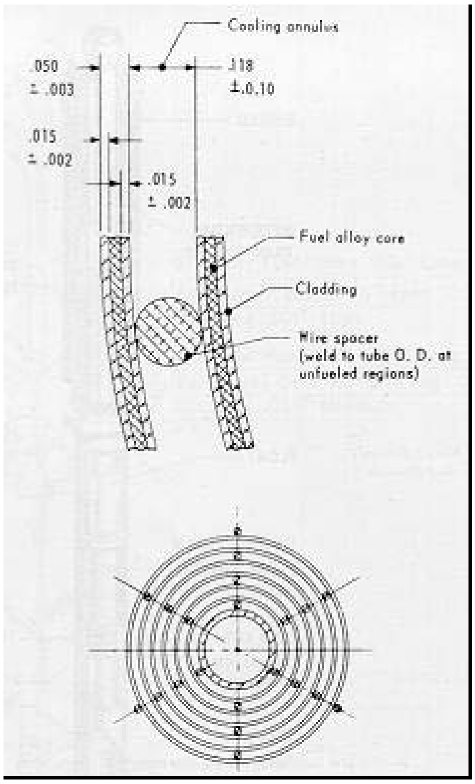


FIG. 3. Annular cylinder type fuel for BR-2.

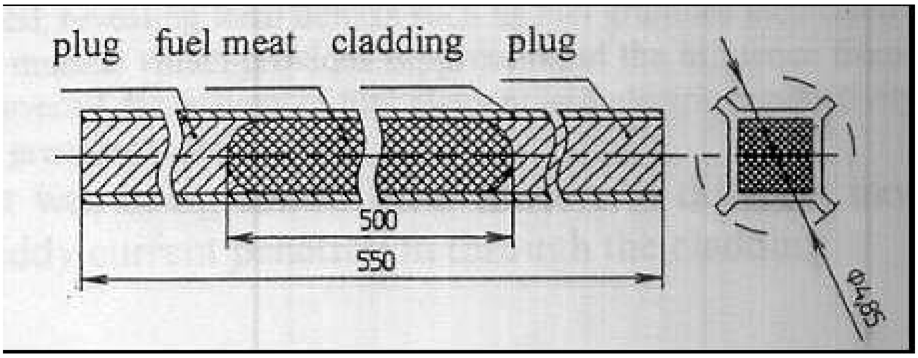


FIG. 4. Pin type fuel.

The following is a breakdown of the various cost categories associated with fabricating research reactor fuel, potentially of interest to those operators or countries that may be considering a domestic fabrication capability. For an operator who is simply procuring fuel elements from an external producer these costs are built into the eventual price charged by the fabricator, and no detailed analysis is needed.

In general, the total cost can be obtained from adding the estimation of capital costs, operating and maintenance costs, and decontamination and decommissioning costs. For the estimate to be meaningful the estimates should be done for a series of fixed time periods and the results adjusted for the time variable value of money. Levelized unit costs are commonly used for economic comparison of different types of projects. See, for example, the OECD publication on cost estimating for GEN-IV nuclear energy systems [10].

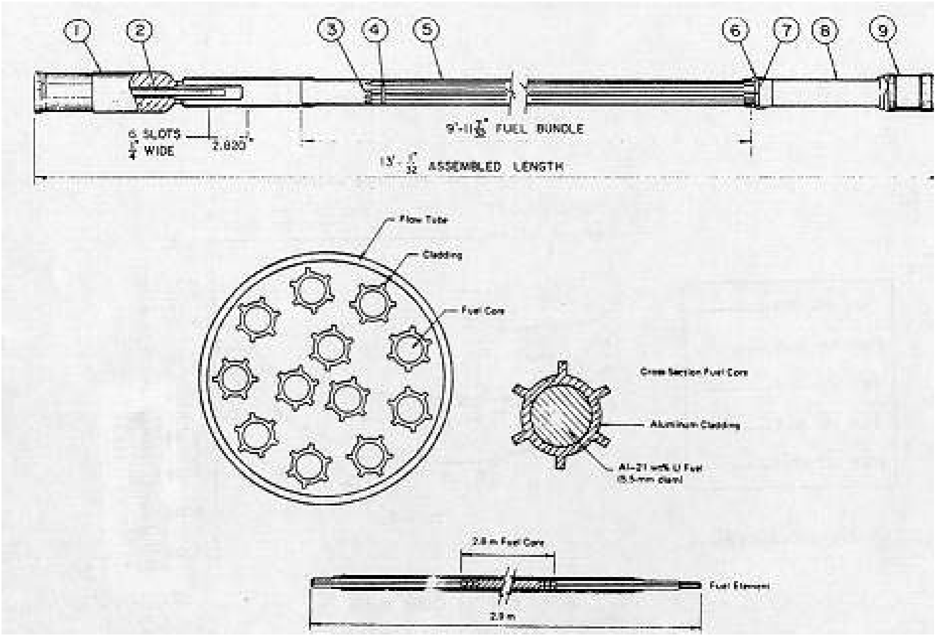


FIG. 5. NRU fuel.

Capital costs

The capital costs consist of direct costs, indirect costs, and contingency. While the construction of a plant is represented by direct costs in investment, the indirect costs consist of associated elements such as design, engineering, licensing, training and so on that are listed in Table 1.

TABLE 1. CAPITAL COST ELEMENTS

Direct costs	Indirect costs
● Site preparation	● Conceptual/final design
● Main process building	● Licences
● Processing equipment, such as:	● Safety analysis report
○ Melting and casting furnace,	● Environmental permits
○ Rolling machine,	● Building permits
○ Atomizer,	● Taxes and insurance
○ Extruder,	● General and administrative costs
○ Heat treatment furnace,	● Engineering and construction management
○ Cutting machine, lathe, and so on.	● Start-up and testing
● Q/C equipment, such as:	● Initial training
○ Eddy current tester,	● Contingency factor
○ Real time X ray radiography machine,	
○ Blister tester,	
○ Material testing machine,	
○ Gamma scanner, etc.	
● Administration facility	
● Fire protection	
● Off-site facilities	

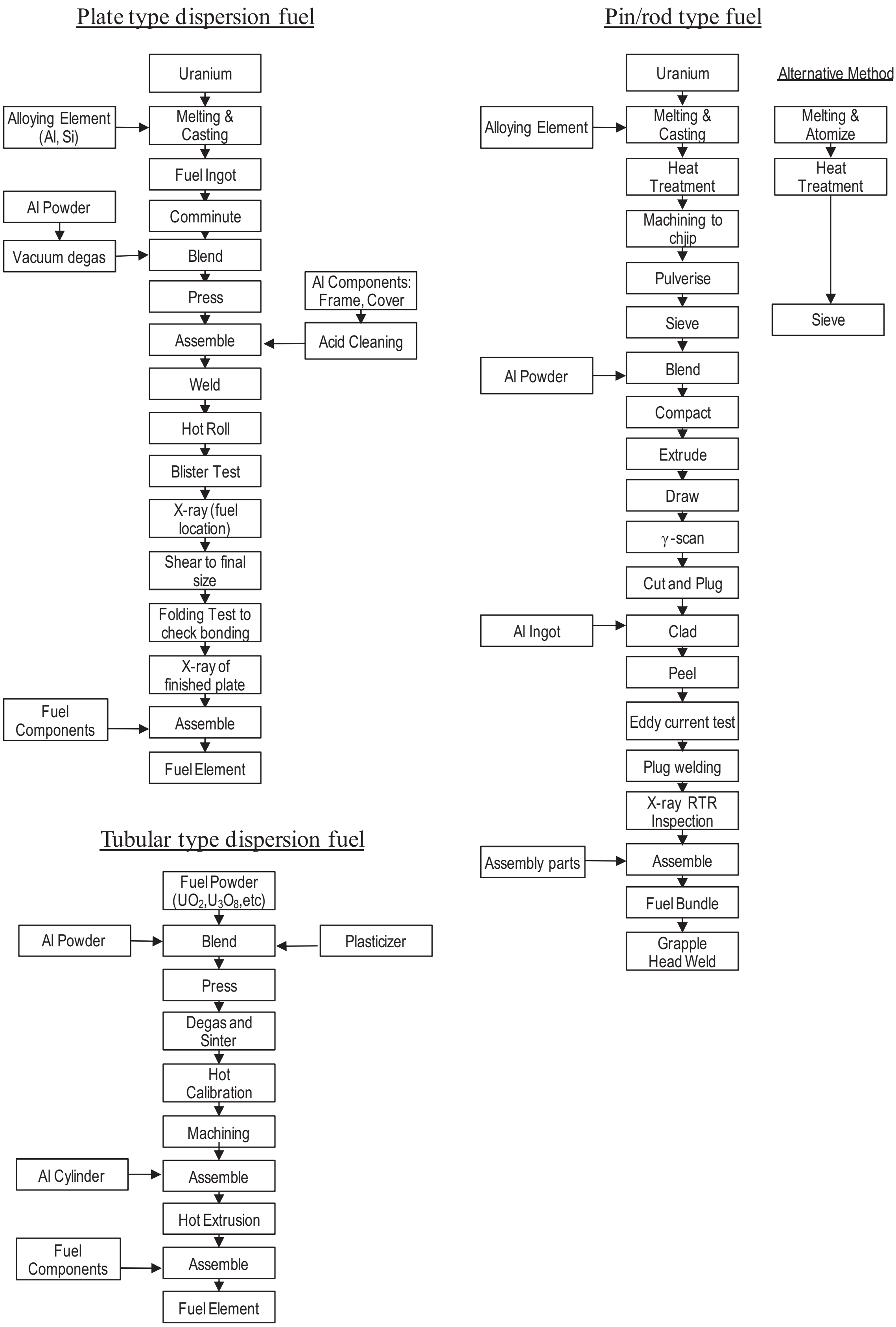


FIG. 6. Typical fabrication processes for research reactor fuel.

Each of these costs should be calculated using the most reliable data available. It is often difficult to arrive at a precise value since there are many technical and monetary uncertainties associated with the items to be estimated. To take account of such uncertainties a contingency factor, or some other method of including uncertainty, is usually applied to the capital costs. The contingency factor is dependent on the uncertainties involved in the estimation and the completeness of the plans or designs for the facility construction, but it is generally taken as a value in the range of 10% to 40% for the sensitivity analysis.

Operating & maintenance (O&M) costs

O&M costs include all costs that arise from plant operation and maintenance during plant lifetime. The costs included in this category are labor, materials, utilities, equipment replacement, waste disposal, etc. Items comprising labour, materials and utility costs are shown in Table 2.

Decontamination and decommissioning of the fuel fabrication facility

Decontamination and decommissioning costs must be taken into account from the very beginning of operation of any nuclear facility. The cost of decommissioning depends on the type of facility involved and the standards operating in the relevant country, particularly the radiological standards applicable at each stage and the level of decontamination that is required to be reached at each step of the decommissioning process. These costs are likely to vary from country to country. However, a typical decommissioning provision for a uranium processing facility such as a research reactor fuel facility would be around 10% of the capital costs. This would then be divided into annual charge or a charge per fuel assembly produced in order to build up the decommissioning fund during the operating lifetime of the facility.

The main factors affecting this range of values are the quantity of fuel elements to be fabricated, the fuel factory design, the fuel type to be produced, etc.

3.3.4. Transport of fuel elements

Given the fact that there are very few fuel factories in the world, it is the usual practice for the supplier companies to assume responsibility for delivery of the fuel elements to the reactor site. Typically the costs of transporting fuel include the cost of the container, the transportat itself and insurance to deal with any potential nuclear liabilities.

Costs can be minimized by using the full capacity of the container and reducing the number of shipments where possible. The transport of fuel elements is often as, or even more, expensive than for metallic uranium due the more fragile configuration of the assemblies and the higher volume of the fuel elements.

TABLE 2. ELEMENTS OF OPERATIONS AND MAINTENANCE COST CATEGORIES

Labour costs	Material cost	Utility costs
● Sum of:	● Uranium metal ingot	● Electricity
○ Wages	● Alloying elements	● Fuel oil
○ Taxes	● Aluminium powder	● Water
○ Benefits	● Fuel assembly components	● Transportation
● For personnel in:	● Process additives	● Spare parts
○ Plant operation	● Process gases	● Chemicals
○ Maintenance	● Analytical and inspection supplies	● Miscellaneous
○ Plant management	● Waste containers,	● Janitorial supplies
○ Administrative	● Inert gases	● Office supplies
○ Safety & security	● Filters	
○ Environment	● Health physics supplies	
● QA, compliance & standards	● Personal protection devices	

4. CORE MANAGEMENT ISSUES

4.1. REACTOR CORE AND FUEL DESIGN

Irradiation of the fuel in the reactor presents a number of potential options to optimize the use of the fuel, including fuel shuffling to obtain the greatest utility from each fuel assembly. In addition, reconfiguration of the core during LEU conversion may provide opportunities to reduce overall fuel cycle costs or to improve the reactor performance in selected areas.

Core management activities are generally the responsibility of the research reactor operator or licensee. The need for active core management depends to a large degree on the purposes and utilization of the reactor and whether a degradation of performance (for example, due to burnup of the fuel or conversion to LEU) has a measured economic impact on the reactor operation. For some reactors, reduced core performance may have little or no economic impact. Examples of this are reactors dedicated to training or activation analysis.

For other reactors, a carefully selected core management plan can create fuel cost efficiencies, by integrating economic analysis with the technical design requirements. This analysis includes evaluation and assessment of reactivity and control requirements, fuel assembly loading sequence, power distribution and core capability.

To improve fuel utilization a number of strategies can be adopted. Some common strategies are:

To increase the fuel burnup prior to discharge, thus reducing the quantity of fuel to be purchased as well as the quantity of spent fuel that must ultimately be disposed. New, high density uranium fuels may help in this regard, and this is a consideration when planning the conversion of a reactor to LEU fuels. If necessary, additional burnup can be achieved by qualifying the fuel elements for a higher burnup limit than warranted by the fabricator. To do this the operator would need to demonstrate the safe performance of the fuel and the reactor at the higher burnup. However, it must be understood that extending the burnup of the fuel also incurs some additional costs that need to be considered.

While most research reactor fuel is usually guaranteed by the fabricator for 40–50% burnup, experience has shown that careful core management and fuel monitoring can extend burnups by as much as 5%. In a 10 MW reactor dedicated to the production of radioisotopes this could reduce reactor fuel consumption by one fuel element per year, equivalent to a cost saving in the order of US $100 000 per year of operation.

Fuel shuffling: The core power (or heat flux) distribution must be controlled to satisfy thermal limits and the established safety parameters for the reactor. Conditions are closest to thermal limits in core locations where heat flux is highest, i.e. where neutron flux is highest and accumulated irradiation is lowest. In general, fuel with high irradiation (burnup) has lower reactivity and, thus, by shuffling fuel elements or assemblies during refuelling, it is possible to improve thermal margins.

Depending upon design, it may be beneficial to relocate irradiated fuel to different locations in the core during refuelling periods. This strategy of shuffling can achieve higher burnup while increasing margins during operation. To the extent that fuel movement does not delay the refuelling period significantly, shuffling is often beneficial.

Adoption of a programme cycle to avoid premature fuel discharge: Irradiated fuel that is expected to exceed burnup limits before the next refuelling period must be discharged. However, the programme cycle (average power level and cycle duration) can be selected to minimize the discharge of fuel that has not reached the desired burnup.

Operating schedule: Many research reactors are engaged in activities that require very flexible operating schedules. For example, training reactors may be shut down on weekends, and some research facilities remain dormant during holiday periods. Reactors engaged in irradiation services may be able to schedule production so that a period of full power is followed by an extended shutdown. In any case, efficient planning and core management scheduling can promote the efficient use of nuclear fuel.

Core monitoring programme: An important part of a core management programme is the monitoring of selected core parameters to identify early needs. This is not only essential for reactor operating safety, but is also important for reducing fuel cycle costs. For example, early identification of small fuel defects, as indicated by the release of radioactivity, would allow action to be taken to avoid further damage to the fuel and the consequent increase in the cost of the fuel cycle.

Revised core management strategies can be put in place both for reactors that are undergoing conversion from HEU to LEU fuels (including by partial or whole core replacement), and for reactors with equilibrium cores that want to extend the time between fuel element replacement while maintaining the neutronic profile of the reactor. Fuel shuffling and periodic single fuel element replacement can be used to maintain required core performance while minimizing loading of fresh fuel. The conversion of a reactor from HEU to LEU fuels provides the operator with a unique opportunity to re-assess the core management strategy for both the conversion period itself and for the subsequent operations.

In terms of optimizing the transition from HEU to LEU, there are two possible routes. The first is to replace only a limited number of the HEU elements with LEU, with the objective of achieving optimal burnup of the HEU elements in the core. This could have two benefits. The first is that the costs of refuelling will be spread over a longer time period with a number of distinct planned phases. The second benefit is that the whole process occurs under the control of management at a time of their choosing, rather than being driven by the need to refuel at the end of the take back period (if available) by an inflexible date. Partial refuelling may have disadvantages in that smaller quantities of fuel will be ordered and transported, which could result in higher costs.

The second approach is to remove all the old fuel and introduce a limited number of new fuel elements and, if necessary, utilize burnable poisons or special elements with lower densities of uranium than those used in the equilibrium core. There are cases where partial cores have been loaded and achieved a very similar performance to those utilizing a full core at equilibrium state.

For an existing research reactor with an approved fuel type, there are typically just a few specific operating requirements relating to core management. These include operating cycle length, fuel burnup at discharge, and design margins. In general, the cycle length and fuel burnup should be selected to minimize costs within certain constraints. The selection of design margin often involves engineering judgement; the smaller the design margin, the greater the risk of a fuel failure during future operations. Operating with larger design margins, on the other hand, implies higher fuel costs.

Research reactor fuel technology continues to evolve, driven in part by the international efforts to develop high density fuels to enable the conversion of more reactors from HEU to LEU fuels. These high density fuels may offer economic benefits for other reactors, despite being more expensive initially, because they offer the prospect of higher per-assembly burnup, thus reducing the number of assemblies that must be procured, and more flexibility in spent fuel management compared to the currently qualified and commercially available LEU silicide fuels. These high density fuels are still under development and are expected to be commercially available some time after 2010.

Increasing the uranium loading (fuel density) generally results in the ability of the fuel to be resident in the reactor for a longer period of time while maintaining performance. However, there are certain limits to the benefits that can be achieved, as higher density requires the use of burnable poisons (e.g. cadmium wires in the reactor, or boron mixed in the fuel meat matrix, which in turn can lead to increased uranium consumption.

The use of increased density fuel also has some potential problems, particularly the limitations of being able to remove the extra heat from the core and the capacity of the control rods to achieve sub-criticality or indeed control the reactor. If these limits are reached with the higher density fuel available there are ways to deal with this problem. One example is the introduction of burnable poisons, but this has limitations since the fuel element costs will rise due to the increase in materials needed and also the reduced burnup due to the presence of the burnable poison at the end of the fuel's lifetime.

Another option is to introduce special fuel elements with lower densities and have a fine-tuned shuffling scheme, in order to manage the different types of fuel. This strategy also has limits, because the number of fuel elements in the core of this type of reactor is relatively small, which means that there are few options where these elements can be introduced.

Further options for increasing the fuel density in a given reactor are related to changing the control rods or the water velocity in the core. However, these approaches would require significant re-engineering and therefore cost outweighing the expected saving in the fuel cycle. In these cases a detailed analysis of the costs would be required to ensure that the benefits outweigh the costs.

Thus, utilizing different core management strategies can have important benefits for improving fuel efficiency and have the potential for lowering costs for the reactor operator.

5. SPENT FUEL MANAGEMENT

5.1. SPENT FUEL STORAGE

Spent fuel must be stored upon discharge from the research reactor or critical facility. After discharge from the core, research reactor spent fuel is stored under water, usually in 'at reactor' (AR) facilities, until the short lived fission products and alpha emitters have decayed. The water provides both radiation shielding and thermal cooling. The decay heat from the short lived radioisotopes could melt the fuel cladding unless the fuel assemblies are adequately cooled. This wet storage can be extended either in AR facilities or away-from-reactor (AFR) facilities, in some cases for long periods of around 50 years. There are opportunities for management of storage pool water chemistry to help reduce the costs of long term wet storage. Alternatively, the spent fuel can be transferred to dry stores (AR or AFR) and stored dry for even longer periods. Neither of these strategies can be regarded as the end point of the research reactor fuel cycle. The ultimate treatment and/or disposal of the spent fuel will eventually require a permanent repository.

A large variety of fuel types and fuel assembly geometries are in use in research and test reactors. Consequently, special storage conditions are often necessary, as well as different types of transport casks and different techniques for dealing with failed fuel. A range of different methods for the interim storage of irradiated fuel elements, such as water pools, dry canisters, dry silos and concrete vaults have been developed in the last 20 years. In addition, transport casks are also being used as a dry storage method in some instances. All of the methods listed are used both at research reactor sites and at specially constructed AFR facilities.

5.1.1. Interim storage

'Interim storage' means the secure storage of spent fuel for a period of perhaps 50–100 years pending the availability of repository facilities for final disposal of the fuel facilities. In many cases these facilities will not be available until after the end of the research reactor's operations.

Countries with large commercial nuclear programmes may already have infrastructure for long term spent fuel management that is able to accommodate the interim storage of research reactor spent fuel. However, this compatibility between the power reactor and research reactor requirements is not automatic and appropriate planning activities should be taken well in advance of facility construction or the need for AR storage of research reactor spent fuels. Research reactor fuel is very diverse in shape and form, has more corrosion prone materials and higher uranium enrichments relative to LWR fuel. These physical differences introduce technical and regulatory challenges for research reactor spent fuel projects.

At the moment, none of the planned commercial spent fuel management facilities include specific provisions for research reactor fuel (or residual waste from research reactor fuel reprocessing). At a minimum, research reactor owners, even in countries with large commercial nuclear installations, will have to develop packages that meet all regulatory requirements of these facilities.

Countries without commercial nuclear power programmes will face an even more daunting task. They must either develop local sites and facilities to manage spent fuel (or the high active waste returned from reprocessing), or negotiate access to facilities in other countries. The latter route would require modification to the foreign nuclear waste exclusion laws that all countries with commercial nuclear power programmes have. There has been discussion of a multinational facility for research reactor waste [11], though no such facility is planned or under construction at the time of writing of this report.

Interim storage of spent fuel may involve either an engineered above ground facility or an engineered repository. Constructing such a facility is a difficult and expensive task even for countries with large nuclear programmes. Consideration of research reactor spent fuel in isolation will exaggerate the cost impact because of the relatively small quantities of fuel involved. In addition, international concerns for the possible loss of social stability and control of these materials in some countries or regions could complicate or delay the construction of required facilities.

Because of the adverse economics of this situation it may be desirable to work towards international agreements for regional or multinational storage arrangements and facilities. Such solutions would enable larger facilities and spread the fixed costs over a larger number of users.

In any case, continued research reactor operations require at least an interim option for active above ground management of spent fuel or reprocessing waste for a long period of time. The implications are not trivial.

5.1.2. Wet storage

There is substantial experience with short term storage (up to 30 years) of research reactor spent fuel management in the existing wet pools associated with operating research reactors. Water quality must be carefully controlled to avoid spent fuel corrosion during storage and a concern about the potential leakage of radioactive fission products into the environment. The capital costs for these pools are 'sunk' and the operating costs are relatively low and included as part of the average facility's operating budget. It is likely that research reactor spent fuel can be successfully maintained in such pools as long as the pool does not become full or until operations cease. We refer to these situations as 'terminal' conditions.

When either of these 'terminal' conditions is realized a new solution will be needed. Continuing to store the fuel in the existing research reactor wet pools after reactor operations cease is not recommended because this would require high, ongoing costs for monitoring, water quality control and security. The possibility of an independent, modern wet storage facility is discussed below for the sake of completeness. But for reasons discussed below, long term interim storage of research reactor spent fuel (or reprocessing waste), most likely will involve dry storage technologies.

To date there is much less experience with long term research reactor spent fuel in dry facilities. The discussion below therefore considers the schemes that are under development or investigation as well as those in actual use.

5.1.3. Independent dry storage vaults

To date, the only independent facilities devoted to the interim storage of research reactor spent fuel and reprocessing wastes are dry storage vaults. Generally, a dry storage vault includes storage tubes that provide the containment for each fuel assembly while the vault design provides shielding as well as cooling by natural convection.

The HABOG facility in the Netherlands is a multi-function dry storage vault that stores spent MTR fuel from the research reactors at Petten and Delft, as well as high active waste from reprocessing of spent fuel from the commercial power plant operations at Borssele and Dodewaard. The facility is a reinforced aircraft crash and flood resistant structure that has been designed for fifteen years of active use and 85 years of passive operation (Fig. 7).

The HABOG is a vault type facility with two separate compartments: one for storage of non-heat generating high level waste from the reprocessing of spent power reactor fuel, such as fuel element cladding, hulls and ends; the other for storage of the heat generating, vitrified HLW from reprocessing of spent fuel from the NPPs, and of unreprocessed spent fuel from the research reactors. The canisters of heat generating waste are stacked in vertical, air cooled storage wells, which are filled with argon to prevent corrosion of the canisters and are equipped with a double jacket to enable air cooling through natural convection while avoiding direct contact of the cooling air with spent fuel or vitrified HLW canisters. Upon receipt at HABOG the research reactor spent fuel is repacked in steel canisters, which are then filled with helium to prevent chemical deterioration of the spent fuel during long term storage.

The HABOG project was initiated in 1994 and commissioned at the end of 2003 at an estimated cost of US $100 million after several delays. This total includes ~US $75 million for design, licensing, site development and construction of the major receiving facilities and the hot cell and US $5 million each for the five associated storage areas.

In South Africa, spent fuel from the SAFARI-1 research reactor is stored in the Thabana Pipestore dry storage facility after an initial cooling period of at least two years in the reactor pool. The Pipestore comprises subsurface sealed stainless steel storage pipes positioned in boreholes that are lined with normal borehole lining and cement pipe for possible acid neutralization. The pipe openings are sealed with lead plugs and an airtight flange, and filled

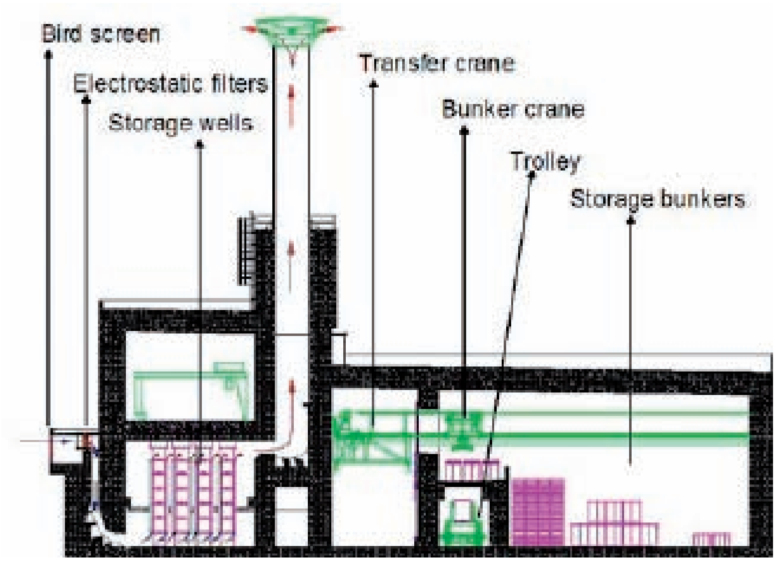


FIG. 7. Cross-section of the HABOG facility in the Netherlands [12].

with an inert gas. The subsurface pipestore/borehole design was selected to provide both radiation shielding and heat transfer.

Another major storage facility for research reactor fuel, the Idaho Spent Fuel Project (ISF), is under development at Idaho Falls in the USA. This is planned to hold the spent fuel accepted under the FRR SNF programme, spent TRIGA fuel, and spent fuel from the Shippingport and Peach Bottom power reactors. The facility has been designed for 50 years of operation and is based on the Alstec modular vault dry storage (MVDS) technology. Additional storage modules can be added as needed in 60–100 MTHM increments.

The interior of the ISF is shown in Fig. 8. The facility consists of three main functional areas, the cask receipt area, the transfer area and the fuel storage area. Fuel is accepted into the cask receipt area, then repackaged into canisters in the transfer area, and then placed into storage in the storage area.

The ISF facility uses the DOE standardized spent fuel storage canisters that are intended to be compatible with a future high level waste repository The ISF is designed to easily retrieve the canisters from storage for shipment to the geological repository when this becomes available.

The initially quoted cost of this storage facility was US $137 million according to a competitively bid contract awarded to Foster Wheeler Environmental Corporation (FWEC). By comparison, the total investment for a ten module (~650 MTHM) dry storage vault constructed at a reactor site is estimated at around US $58 million, because advantage can be taken of shared infrastructure.

The cost of loading an MVDS is approximately two times that of a dry storage cask loading since, in this case, casks are used to transfer the fuel from the reactor pools to the facility. The factor of two results from the fact that the cask must be loaded at the reactor and unloaded again at the ‘vault’ to complete the transfer.

The cost of *unloading* an MVDS when it is time to remove the fuel to a final repository is ~20% less than a wet pool if the fuel must be transferred to alternative containers for final disposal, because no fuel drying operation is required.

Operating cost information for an MVDS is scant. The best current estimate requires a permanent staff of ten professionals to manage and maintain the facility, with several of them involved only part time, during loading activities. Thus the facility O&M cost can be estimated at ~1 million Euros/year for a facility in Western countries.

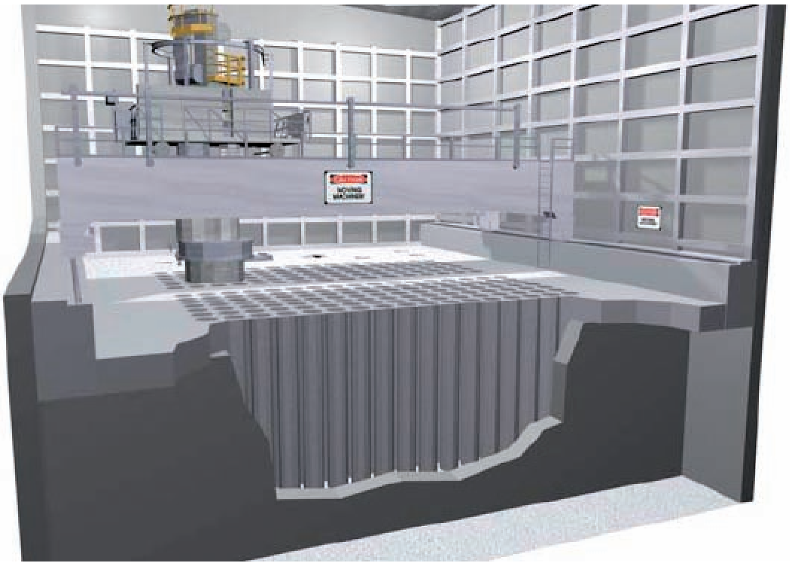


FIG. 8. The proposed Idaho spent fuel project storage vault [13].

TABLE 3. POTENTIAL ADVANTAGES AND DISADVANTAGES OF DRY VAULT STORAGE

Dry vault storage	
Potential advantages	Potential disadvantages
● Regulatory ease under most circumstances ● More adaptable to different fuel types than cask systems ● More adaptable for spent fuel cooled less than five years ● Easy to extend with addition of new modules if needed	● High up front costs ● Less modularity ● Reduced flexibility after construction ● High operating cost ● Higher decommissioning costs

5.1.4. Independent wet storage pools

Wet pool storage of spent fuel is a normal procedure at all operating research and power reactors. As a result, there is a large amount of experience and regulatory comfort with this mode of spent fuel management. In principle, an independent wet pool for the long term storage of spent fuel could be used for research reactor fuel storage, though the higher reactivity of the research reactor fuel has resulted in dry storage systems being developed for use when the spent fuel must be removed from pools at the reactor sites.

Typically, an independent wet storage facility consists of a bunkered, reinforced concrete building that is qualified to resist an aircraft crash, and which contains an access hall with a large capacity crane, a cask receipt and conditioning area, a fuel transfer machine, a cask unloading pool, a fuel storage pool with modular storage racks to store the spent fuel, and an additional pool designed for storage of tools and fuel inspection equipment.

For long term storage of research reactor fuel in wet storage pools, a corrosion monitoring programme (CMP) is recommended to track any water quality related effects on the corrosion of spent fuel cladding and/or of other structural materials. Such a CMP usually involves the exposure of test coupons to the basin water for a pre-determined period followed by corrosion evaluation of the coupons and the determination of water parameters at periodic intervals.

It is noteworthy that all of the large wet pool storage facilities, other than those in Sweden, are co-located at the sites of operating reactors or a reprocessing facility. Wet pools require active safety and security systems that are costly and difficult to justify in isolation, thus the investment and operating cost for this long term solution normally is affordable only within the context of the other site functional infrastructure, and as part of a larger nuclear power programme.

TABLE 4. POTENTIAL ADVANTAGES AND DISADVANTAGES OF WET POOL STORAGE

Wet pool storage	
Potential advantages	Potential disadvantages
● Regulatory ease under most circumstances ● More adaptable for use with high burnup fuel ● More adaptable for spent fuel cooled less than five years ● Relatively low unit costs if there is a large facility is constructed for the storage of LWR fuel	● High up front costs ● Less modularity ● Reduced flexibility after construction ● Higher operating cost (especially at closed reactor or independent sites) ● Higher decommissioning costs

The cost of loading an independent wet pool is approximately two times that of a dry storage cask since casks are used to transfer the fuel from the reactor pools to the facility. The factor of two results from the fact that the cask must be loaded in the reactor and unloaded again at the ‘pool’ to complete the transfer. The cost of unloading a wet pool ‘store’ when it is time to ship to a repository is the same as that of a dry storage cask loading at a reactor pool.

5.1.5. Dry cask storage

With the few exceptions noted above, cask systems (either metal or concrete) have been chosen for all commercial storage facilities for nuclear power reactor fuel worldwide for the past 20 years, and similar multi-purpose canister (MPC) systems have been developed for use with research reactor fuels. Such casks should be considered as a possible option for future dry storage of spent research reactor fuel.

Generally, the multi-purpose canister (MPC) system is characterized by the use of a (relatively) thin walled MPC, and many fuel assemblies. Once loaded the MPC becomes the ‘package’ for all future spent fuel management steps, and ‘bare’ spent fuel assemblies need not be handled separately.

An example of an MPC cask system for spent research reactor fuel is the CASTOR-MTR 2 cask from GNB in Germany [14] (see Figs 9, 10), which has been developed to accept spent fuel from the German research reactors. The cask is designed for both transport and up to 40 years of interim storage of the fuel. The cask body is made of ductile cast iron and weighs about 18 metric tons. The CASTOR MTR 2 has both primary and secondary lids with the interstitial space filled with helium. The helium gas pressure is continuously monitored during storage to confirm the leak-tightness of the cask. The cask can accept several different types of inner basket, depending on the type of fuel to be stored. A detailed description of the loading and use of these casks was presented at the RRFM meeting in 2003 [15]. Another MPC cask system for the South American countries is being developed under the IAEA regional cooperation project RLA/3/008.

Loading and unloading costs

It takes three or four professionals about 20–25 hours to prepare and load fuel into one MPC container. Allowing for supervisory and health physics personnel effort, MPC based systems are estimated to require about 100 person-hours to load and store one MPC container. Using a nominal labour rate of US $100 per person-hour, this amounts to US $10 000/container.

For eventual off-site transfer (to a repository for example), an MPC must be removed from the storage overpack and transferred to the transport overpack. This action is the reverse of the canister loading (excluding operations for individual fuel assembling handling and weld closure). There is no practical experience with this aspect of the system since such fuel transfer is pending the availability of a final repository. However, we estimate that this transfer can occur in one day with a staff of 3–4 people (~30 person-hours). Again, using a nominal labour rate of US $100 per person-hour, this amounts to US $3000/cask or approximately US $0.30/kg.

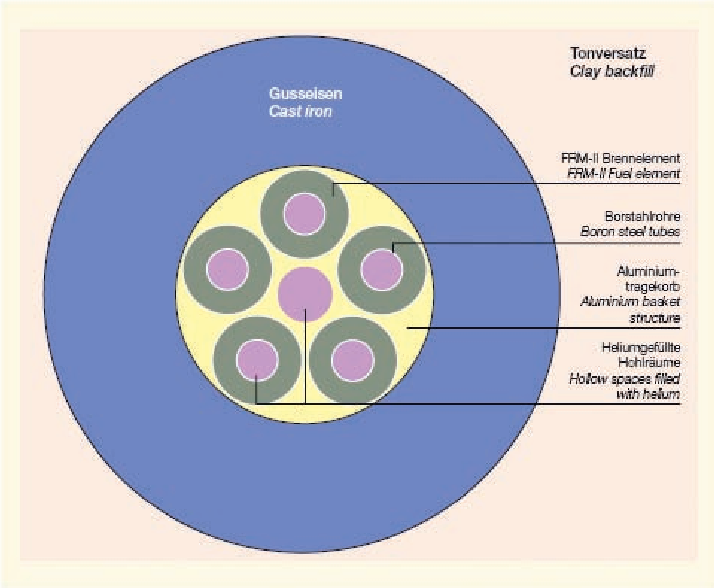


FIG. 9. Schematic model of a CASTOR MTR2 cask with 5 FRM-II spent fuel elements courtesy GRS Jahresbericht 2004/2005.

FIG. 10. The CASTOR MTR2 cask courtesy VKTA, RRFM 2003.

Annual operating and maintenance costs

Costs of cask based storage facilities relate mostly to security surveillance, annual maintenance, and routine health physics and safeguards checks. Experienced cask operators storing power reactor fuel estimate the operating costs of an AR cask storage facility at US $650 000 to US $1 million per year, depending upon labour rates and access to shared resources.

Transport costs

Eventually, fuel in a long term dry storage facility will need to be transported to a final repository and there will be additional costs associated with this activity. The costs will be dependent upon the destination and the length and complexity of the route. The present value costs of this transport are likely to be small if the operation is performed many years in the future. The costs of transport from a spent fuel storage facility to a final repository are common to all technology options, and so are not a distinguishing factor when selecting a spent fuel management approach.

5.1.6. Storage facility decommissioning cost provisions

Most national regulatory bodies require a fund to be established for facility decommissioning, which is related to the facility initial investment. The size of that fund is determined by many important factors that vary from site to site, including those shown in Table 5.

However, typical decommissioning funds range from about 2 to 10 per cent of the overnight capital cost of the facility, depending upon the scale and complexity of the facility and the types of nuclear material that the facility is designed to process. For example, there are inherent differences between storage systems. For example, failed fuel in a wet storage pool (and to a lesser extent a dry storage vault) may spread radioactive contamination to a greater percentage of the facility than in a facility with individual, sealed dry storage casks. This, in turn, would lead to a higher expected decontamination cost.

Likewise, after reactor closure and de-fuelling, dry storage casks can be re-utilized or moved to some central location, presumably a disposal facility where cask decommissioning can be accomplished in a more cost effective manner. The wet storage pool and the dry storage vault will have to be decommissioned in situ, which is likely to be more costly.

In any case, since decommissioning costs occur well into the future, they have low present value. And, while they are important from the point of view of adequacy of the ‘decommissioning fund’, they generally are not an important factor in determining the choice of a storage system or supplier.

5.1.7. Facility construction lead times and payment schedules

The design and regulatory review phase of an interim long term spent fuel storage facility typically represents about 10% of the overnight capital cost of the facility and usually begins around 4 years before the planned start of operations. The first 2 years cover regulatory approvals, basic site development and long lead procurement items, and account for around 25% of the overnight capital cost. A further 60% is likely to be incurred during the construction of facilities and storage modules in the 2 year period immediately prior to operation. A typical capital cost expenditure curve for the initial facility (and first modules) is shown in Fig. 11.

TABLE 5. SITE SPECIFIC FACTORS IN DECOMMISSIONING COSTS

● Institutional framework	● Scope
● Nuclear energy policy and legislation	● Facility characteristics
● Regulatory framework (exemption levels; criteria for radioactive waste disposal; occupational dose limits)	● Type ● Design and vintage
● Financial responsibility	● Size
● Infrastructure development	● Plant location
● Technology	● Operational history
● Availability of disposal facilities	● Technical approach
● Human resources	● Economic factors
● Decommissioning plans	● Labour costs
● Status	● Materials and equipment
● Strategy	● Costs of waste management and disposal
	● Contingencies

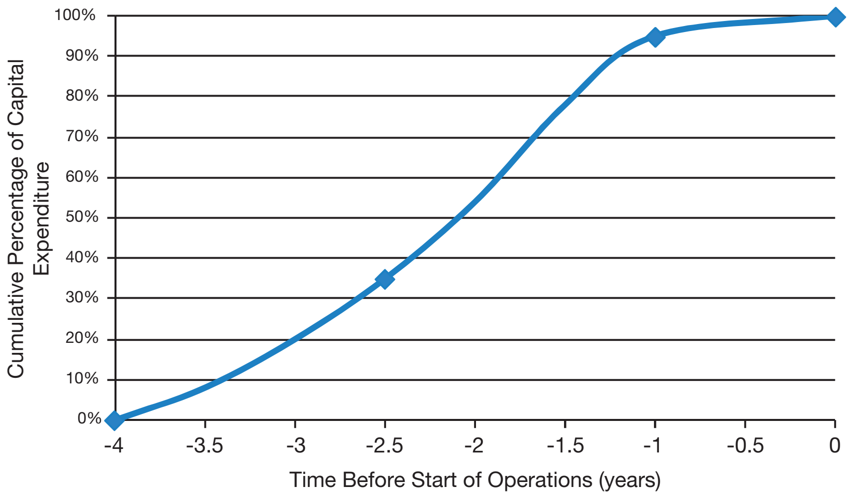


FIG. 11. Sample capital expenditure curve.

Subsequent module additions can be delivered with lead times of 15–18 months. (Note: In this context module means either one additional MVDS storage module, 3–6 dry storage casks or one comparable set of wet storage racks).

Based on all commercial evidence to date, there does not appear to be any significant difference in the lead times between the various technologies, and these payment schedules can be applied to each type of storage system.

5.1.8. Interim storage summary

There are several technologies with reasonable availability for dealing with the problem of long term storage of research reactor spent fuel. However, taking all relevant factors into account, it is likely that an independent facility for this purpose would require an initial investment in the order of US $100 million and as much as US $1 million/year to operate and keep secure. For a small national programme, this cost is likely to be prohibitive. Regional facilities would have the advantage of sharing or distributing the cost but introduce new cost and political issues.

In any case, as noted above, the regulatory, infrastructure and fixed construction costs are the major expenses, which are quite independent of the nature or the amount of material being managed. A mechanism for research reactor owners to finance and amortize the cost of these management facilities should be identified early and appropriate economic provisions made.

Normally, such facility costs are paid (directly or indirectly) by the users or beneficiaries of the reactor output or product in the price for services rendered, that is, through income collected during the operation of the reactor. An appropriate fund or reserve is established to pay for the eventual facility construction and operation. To the extent that this recovery mechanism is not available the cost will probably revert to the State.

It should be noted that even if reprocessing is selected as the preferred route for spent fuel management, provision for long term storage or vitrified HLW is likely to be required, pending final geological disposal.

In all cases, a thorough understanding of the total research reactor spent fuel management cost is needed, and a specific plan for funding those costs should be established at the earliest possible time. This plan should be periodically reviewed and updated as necessary to ensure that the research reactor is not faced with a very large and unanticipated financial liability at the end of reactor operations. Some options and tools for performing such evaluations are presented in Section 6.

5.2. SPENT FUEL TREATMENT

Proper nuclear waste management is a key issue for the nuclear industry, including research reactors. The citizens of most countries regard it as one of the major concerns relating to the nuclear industry.

An important aspect of nuclear waste is that it has the potential to impact the environment for tens of thousands of years. It is clear then that the choices made today cannot be based solely on short term economic and technical information. A research reactor operator has the same responsibility to define a spent nuclear fuel management plan that satisfies safety and public acceptance requirements as an electrical utility that operates nuclear power generating stations. However, due to the small quantities of fuel used in research reactors, the economic aspects related to nuclear fuel waste management are generally very unfavourable. The economics can be improved significantly if the research reactor operators can make use of an existing spent fuel and radioactive waste management programme, for example, as part of a national policy.

Research reactor fuels have important differences from power reactor fuels. The dimensions, uranium enrichment levels and corrosion resistance of the cladding and fuel material are quite different. The higher residual enrichment and the more corrosion prone aluminium cladding have to be specifically addressed when considering either long term storage or repository disposal. This includes the options for mechanical and chemical treatment of the fuel, and/or encapsulation of the fuel to better adapt it to disposal in geological repositories.

For spent fuel treatment, two main approaches can be considered, reprocessing and conditioning for disposal. Both processes produce long lived radioactive wastes that eventually need to be disposed of in geological repositories, though the type and the final volume of waste for disposal differs between the two approaches.

Spent fuel reprocessing includes the recovery of usable fissile material from irradiated fuel assemblies, in addition to separation and treatment of the fission product and actinide wastes. For a detailed review of fuel reprocessing, its techniques and applications to different types of fuels, see IAEA-TECDOC-1467 [16].

All of the operating commercial reprocessing plants around the world are based on the plutonium and uranium recovery by extraction method (PUREX) solvent extraction process. This process is capable of recovering more than 99.7% of the uranium and plutonium and of processing high burnup spent fuel. However, the different research reactor fuel types have differing degrees of acceptability to the commercial reprocessing facilities. For example, the widely adopted uranium silicide fuels are more difficult, and therefore potentially more costly, to reprocess than other common fuel compositions.

Other spent fuel reprocessing technologies are under development, but not yet in commercial operation.

Reprocessing of research reactor fuel results in the separation of the non-volatile radionuclides as high level liquid wastes, high level solid wastes (HLW) which are normally returned to the country from which the spent fuel originated, and low level solid and liquid wastes which may be retained by the reprocessor in exchange for a small additional amount of HLW supplied to the owner of the fuel. Section 5.2.2 provides more information on spent fuel reprocessing.

Spent fuel conditioning refers to the treatment of the fuel to achieve physical and chemical characteristics that match the requirements of a repository, and to reduce the fissile content of the uranium as appropriate to satisfy non-proliferation requirements. Several conditioning technologies are under development. Some involve mechanical compaction or comminution of the fuel, followed by mixing with depleted uranium or a neutron poison; others include encapsulation of the fuel in vitrified HLW; or dissolution without reprocessing, followed by dilution with depleted uranium and vitrification. The primary waste stream from conditioning is LILW, rather than the HLW that results from reprocessing, because the thermal output of the conditioned spent fuel is below 2 kW/m^3.

5.2.1. Consideration of the national nuclear policy

Any national nuclear policy is likely to play a key role in the decision making process undertaken by a research reactor operator. Obviously, the influence of the national nuclear policy will have a large effect on the technical choices and the economics of spent fuel and radioactive waste management.

If there are other national nuclear facilities (e.g. other research reactors, commercial power generators, etc.) then there is scope for co-operation between the different entities which should result in a reduction in the cost to any one of the parties. For example, the cost of constructing a dedicated AFR interim storage facility would be prohibitive for a single research reactor but justifiable if it is used by a number of different operators.

5.2.2. Reprocessing of spent fuel

The existing research reactor spent fuel reprocessing options use the PUREX process in which the spent fuel elements are dissolved in nitric acid and the uranium and plutonium they contain are separated and stored as oxides, and the HLW comprising the fission products and remaining actinides are immobilized in a glass matrix. The process also creates LILW waste streams from process materials, reagents and equipment which can be encapsulated in cement or bitumen and disposed of with other LILW wastes.

The major steps in the PUREX process are:

(a) Head end process — the fuel is dissolved in boiling nitric acid. In some reprocessing schemes, the nitric acid is made more aggressive by addition of hydrofluoric acid, mercury or silver in order to more rapidly dissolve the fuel. Any undissolved residues (including pieces of fuel cladding and fines) are monitored for residual fissile material content and treated as solid waste.
(b) Solvent extraction — uranium and plutonium are separated from the fission products and other actinides using aqueous and organic solvents. The aqueous solvent is nitric acid and the organic phase is tributyl phosphate (TBP) in an organic carrier such as kerosene.
(c) Separation and purification of U and Pu using a second solvent extraction step.
(d) Conversion of uranium and plutonium to oxide forms for storage or re-use.
(e) Concentration and packaging of the liquid and solid high level waste radioactive wastes, high level waste (HLW) and low and intermediate level wastes (LILW) from the initial separation and subsequent processing.

To reduce the ^{235}U enrichment of less than 2%, the research reactor fuel is reprocessed together with spent fuel from power reactors. The resulting 'reprocessed uranium' can then be used in the production of new fuel if appropriate measures are taken to manage the minor uranium isotope content in the reprocessed uranium. The uranium contains the isotopes ^{236}U, which acts as a thermal neutron absorber, as well as ^{232}U and elevated levels of ^{234}U, which present gamma and alpha radiation challenges for the fuel fabrication facilities respectively.

The plutonium can be recycled into fresh mixed oxide (MOX) fuel or can be stored pending a repackaging for final disposal. In this latter case, the small amount of separated plutonium is incorporated within containers of vitrified high level waste.

If reprocessing is selected as the spent fuel management option, the future use of the reprocessed uranium and plutonium has to be defined. The research reactor operator could transfer the ownership title of the uranium and plutonium to a third party for recycling. For example, in a country with a nuclear power programme, the research reactor operator could have an agreement with an electricity utility to transfer the title of the recovered fissile material and agree to a common management of the reprocessing wastes. The financial terms for so doing would depend on national policy, as well as the prevailing price levels within the nuclear fuel markets. At the time of writing this report, the nuclear fuel markets would view the reprocessed uranium as an asset, and the plutonium as a liability.

The advantages of reprocessing spent research reactor fuels include:

(1) A significant reduction in HLW volume of between 30 and 50 times when compared with the option of direct disposal of the research reactor spent nuclear fuels [17], with a potential for reduced costs for eventual repository disposal;
(2) Reduction of the long term radiotoxicity by a factor of 10 compared to direct disposal of spent fuel;
(3) Packaging of the primary waste stream, containing 99% of the radioactivity into a durable form suitable for repository disposal;
(4) Reduction in non-proliferation concerns because of the decreased uranium enrichment;
(5) Reprocessing and conditioning can provide an extended period (~15 years) for the development of other solutions for waste storage;
(6) It is possible to have an agreement with the reprocessing company that includes all phases of the delivery of the reprocessing wastes to the country of origin and management of the recovered fissile material.

Authorization and any necessary licences must be obtained from the relevant authorities in both the research reactor country and the reprocessor country. These include the authorization for cask reception at the reprocessing site, spent fuel unloading and storage, reprocessing of the spent fuel, and the administrative authorizations for the subsequent nuclear material and radioactive waste transfer.

At present, only U-Al and uranium oxide fuel types are accepted for reprocessing. Silicide fuels can also be reprocessed but require greater levels of dilution than U-Al fuels. Consequently, the acceptance conditions are determined in accordance with the reprocessor's general schedule, and the cost of silicide fuel reprocessing can be prohibitive because of these technical constraints. However, it is possible that reprocessing methods for silicide fuels will be developed with costs comparable to that of U-Al fuels if these fuels remain in general use.

The cost of reprocessing of research reactor fuel is typically in the range of US $10 000/kg to US $15 000/kg of spent research reactor fuels, excluding transport costs.

A number of operators in high income countries with US origin fuel have chosen not to participate in the US take-back programme or for direct disposal, and instead have opted for spent fuel reprocessing.

5.2.3. Conditioning of spent fuel

Several different spent fuel conditioning technologies are in different stages of development [18, 19], which can be divided into two primary categories:

(1) Those which result in a metallic final product:
- **Press and dilute or poison**. The spent fuel is mechanically compressed and mixed with either depleted uranium or a neutron poison;
- **Chop and dilute or poison.** The spent fuel is chopped into small pieces and mixed with depleted uranium or a neutron poison;
- **Melt and dilute.** The spent fuel is melted, diluted with depleted uranium and then further alloyed with aluminium to form a eutectic (Fig. 12). This process has been developed at the Savannah River Technology Center (SRTC) in the USA.

(2) Those which result in a glass or glass ceramic matrix final product:
- **Can-in-canister**. A critically safe quantity of non-processed spent fuel is placed in a can which is back-filled with HLW glass to form a solid disposal unit with a radiation barrier to deter unauthorized interference;
- **Plasma arc treatment.** The spent fuel is co-melted with depleted uranium and neutron absorbers in a plasma centrifugal furnace, and then converted into an HLW glass waste form;
- **Glass material oxidation and dissolution system.** The spent fuel is placed in a glass melt furnace where it is oxidized by lead dioxide and then converted into a LILW glass waste form;
- **Dissolve and vitrify.** The spent fuel is dissolved and mixed with depleted uranium to reduce the enrichment, and the mixture is then vitrified as a LILW glass waste form.

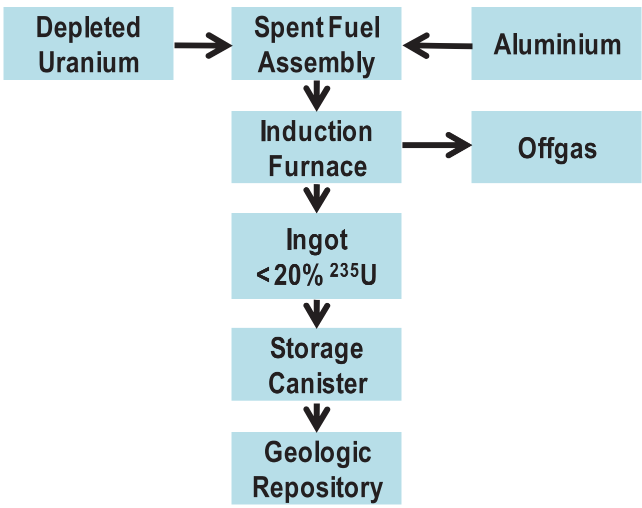


FIG. 12. Process schematic of the melt-dilute process [19].

The advantages of spent fuel conditioning include:

(a) Packaging of the spent fuel into a durable form suitable for repository disposal;
(b) Reduction in non-proliferation concerns because of the decreased uranium enrichment;
(c) Plutonium is not separated from the spent fuel, and therefore presents a lower non-proliferation risk and financial liability.

5.3. RADIOACTIVE WASTE MANAGEMENT

The radioactive wastes related to fission and activation products which are produced during the operation of the reactor must be appropriately processed, packaged, and disposed of. The choices of processing route and facilities are likely to impact the reactor operating costs, and therefore potentially important for cost minimization. Radioactive wastes are normally immobilized using super-compaction, cementation, encapsulation in bitumen, or vitrified and then stored pending a final disposal in a geological repository. The HLW wastes from reprocessing are usually vitrified and then stored pending final disposal in a geological repository.

5.4. DISPOSAL

Ultimately, the spent research reactor fuel or the reprocessing waste from that fuel must be disposed of in a geological repository.

A geological repository is an underground installation for the disposal of nuclear material. Most proposed repositories will be located several hundred metres below ground level in a stable geological formation. At present there is no international market for spent fuel disposal services, except for the take back programmes of the USA and Russian Federation, although several parties have advocated regional repository concepts.

Geological disposal has been the subject of intensive R&D studies and remains a controversial issue in public opinion. Due to the significant cost involved in establishing a repository, most of the countries with small quantities of spent fuel or radioactive waste will not be in a position to implement self-sufficient national repository programmes and instead will seek to benefit from multinational cooperation for the implementation of a nuclear repository.

5.5. INTERNATIONAL SPENT FUEL TAKE-BACK PROGRAMMES: USA AND RUSSIAN FEDERATION

As previously mentioned, spent fuel management is a critical aspect of research reactor fuel cycle economics. At present, two programmes exist to ‘take-back’ fresh and irradiated research reactor fuels that were exported or provided to reactor operators. These programmes represent an important opportunity for research reactors using fuel with uranium originally enriched in the USA and the Russian Federation to manage their spent fuel with minimal complications.

According to these programmes, certain countries have a limited opportunity (2010 for Russian spent HEU fuel now in cooling ponds, later for material still in reactor cores); and 2016 for US origin spent HEU and LEU fuel to take advantage of offers to ship back spent research reactor fuel to the country of origin. While the primary purpose of these programmes is to enhance international nuclear non-proliferation efforts, they also serve as an important function in terms of addressing countries’ needs for a short term solution to research reactor spent fuel management.

Further, many of the countries eligible to participate in these programmes can do so at little or no cost, thus offering a highly attractive means to manage their spent fuel. However, the programmes address spent fuels that are in use or storage at the current time. No Russian LEU fuel (which will be provided to a number of countries over the next several years) will be covered, and US origin LEU fuels that may be exported prior to 2016 are eligible to be returned to the USA, but must be removed from the reactor by May 2016 and shipped to the USA by May 12, 2019.

In any event, planning for alternative spent fuel management — and/or reactor closures — will become a necessity as the 2016 deadline approaches.

5.5.1. US foreign research reactor spent fuel acceptance programme

The USA established a programme in 1996 (replacing the ‘off-site fuels programme’ that had expired earlier) to take back both *specified* HEU and LEU research reactor fuel of US origin, for research reactor operators in 41 countries that have either converted to LEU or are committed to doing so. The site http://www.rertr.anl.gov/FRESEARCH REACTORSNF/EISREACT.html gives more detailed information.

The return of spent HEU fuel is the first priority under this programme, but certain LEU fuels (primarily uranium silicide) consisting of US origin enriched uranium exported to foreign research reactors that have converted to LEU (or started up with LEU fuel) are also eligible. This programme is part of nuclear non-proliferation efforts to convince research reactor operators to convert from using HEU fuel to LEU fuel in order to strengthen global security by minimizing and eventually eliminating the civil use of HEU.

As of April 2009, 46 shipments of spent fuel from 27 countries had been received by the USA under this programme, totalling 8587 fuel assemblies.

The programme had been scheduled to terminate in May 2006, but the USA announced in November 2004 that the programme had been extended for a ten-year period. Consequently, eligible operators may continue to irradiate eligible fuel until May 12, 2016, and the fuel must be returned to the USA by May 12, 2019. In other words, research reactor operators on the list of eligible facilities may make use of this offer to return the spent research reactor fuel to the USA

Furthermore, research reactors from countries defined as ‘other than high income countries’ eligible for this programme do not have to pay any of the costs of returning the spent fuel to the USA. Operators from high income countries are responsible for paying the cost of the transport of the fuel to the USA, and also for paying the US Department of Energy a fee for spent fuel storage services.

For the high income countries with eligible US origin fuel, the costs of participating in the take-back programme are known and can be well characterized and compared to other options, such as spent fuel storage or reprocessing. For high income countries, the fee is limited to US $4500 per kilogram of total mass for aluminium based spent fuel containing highly enriched uranium (HEU), and for TRIGA spent fuel US $3750 per kilogram of total mass for aluminium based spent fuel containing low enriched uranium (LEU).

The cost of shipping the spent fuel to the USA from high income countries is not included in this fee, and is borne by the reactor operators. Preparation, packaging, and transport costs depend upon the number of spent fuel assemblies and their geographic location. Substantial experience has already been accumulated in this activity, and facilities which have shipped fuel can be consulted to determine approximate costs.

Some eligible operators in high income countries have decided to either manage the spent fuel themselves, or have arranged for the fuel to be reprocessed. These decisions, primarily from European countries, were based on comparative cost factors as well as programme conditions (such as conversion to LEU), and schedule/shipping constraints and deadlines.

Some other than high income countries have not participated in the programme either because they did not convert reactors from HEU to LEU (due to either cost or technical reasons) or because they did not want to shut down operation of their reactors by the former programme deadline of May 2006.

Source documents related to this programme, including the specific countries and types of fuel that are eligible to be returned to the USA, are available on the internet at: http://www.rertr.anl.gov/FRRSNF.html.

5.5.2. Russian research reactor fuel return programme

A programme to repatriate both fresh and spent HEU for research reactor fuels enriched in the Russian Federation (and the former Soviet Union) and used in Russian/Soviet designed research reactors was initiated several years ago in cooperation with the USA, the Russian Federation and the IAEA. The programme identified thirteen countries that have such material and are thus eligible to participate in the programme.

The Russian return programme focuses on HEU (>20% enriched) fuel originally exported from the Soviet Union/Russian Federation to Soviet/Russian designed research reactors and which is now in spent fuel storage pools or in the core of those reactors. The US Department of Energy (or other potential donors) provides funding for the return of such HEU fuel. LEU fuels that were exported in the past are also eligible to be returned under this programme, but the Department of Energy does not provide financial assistance for the return of these fuels, the costs for which must be borne by the individual countries or by other donors.

New LEU fuels currently being exported from the Russian Federation to reactors being converted as part of LEU conversion and HEU return projects under the global threat reduction initiative (GTRI) are not eligible for return.

The programme to return the existing spent HEU fuels in storage ponds at reactor sites is scheduled to be completed by the end of 2010, but current HEU cores that are discharged may be returned after 2010 with DOE financial assistance.

Significant preparatory work and studies have been carried out by the USA, the Russian Federation and the IAEA in the development of this programme, including the conduct of joint site visits and the preparation of reports on necessary infrastructure at the research reactor sites, cask options, and transport and logistical variants.

As of October 2008 there had been eighteen shipments returning Russian origin HEU fuel, thirteen of un-irradiated (fresh) fuel, and five of irradiated (spent) fuel. All such shipments, with the exception of one shipment of fresh HEU from the Vinca Institute near Belgrade in 2002, have been carried out by the IAEA with US extra-budgetary funding.

The first shipment of spent Russian HEU research reactor fuel (from Uzbekistan) took place during the period from January through April 2006. It was followed by shipments from the Czech Republic in 2007, and from Latvia, Bulgaria and Hungary in 2008. The shipment from Hungary was the largest shipment (about 154.5 kilograms) of Russian origin HEU spent fuel. Shipments from other eligible sites are now in various stages of planning; efforts are being made to streamline the technical and administrative preparations, and the IAEA has and continues to assist Member States to prepare for shipments by holding workshops, preparing guideline documents, and addressing issues such as transit arrangements.

6. FINANCIAL RISK MANAGEMENT AND MODELLING

6.1. ECONOMIC ASSESSMENT

Research reactor managers face the problem of having to decide on a strategy for the future operation of their reactor, which will include refuelling or conversion to LEU fuel. These decisions will be based on a number of factors including safety, performance and costs. Whilst the first is of the greatest importance, the cost component is becoming increasingly important. In order for research reactor managers to make informed decisions relating to the fuel cycle, they need to understand the economic consequences (costs and revenues) of each potential course of action.

The case for refuelling may arise for a number of reasons. For example, the fuel currently in the reactor has reached the end of its life and must be replaced for safety reasons, or the performance of the reactor has deteriorated as the reactivity of the fuel has declined. There may also be a need to change from HEU to LEU fuel. For example, the problem of a decline in core performance may be addressed either by full or partial refuelling, or in some cases by shuffling the fuel to obtain maximum performance from the existing fuel. For this decision to be made the costs and benefits of shuffling versus refuelling need to be assessed.

In order to minimize the cost of the fuel cycle the operator needs to consider a range of information, the exact nature of which will vary with the operator’s particular circumstances.

Reactors that qualify under the US or Russian spent fuel take-back programmes have limited liability for the costs of spent fuel management and any associated radioactive wastes, and thereby can avoid the cost of both interim storage and final disposal. The cost of replacing the fuel can be compared to the benefits of continuing to provide reactor services. However, even reactors that qualify under the take-back schemes may find that local circumstances make other spent fuel management options economically viable if, for example, spent fuel transport costs exceed the costs of local waste storage solution.

Those reactors that do not qualify for the take-back programmes have no option but to include the costs of spent fuel storage and disposal in their economic analysis.

6.2. ECONOMIC MODELLING AND DECISION SUPPORT TOOLS

An economic model that can be used to evaluate options for a research reactor fuel cycle is an important tool for research reactor operators. This model should evaluate the direct financial costs, opportunity costs and benefits of the different options for the research reactor fuel cycle. Some analysts also recommend that a dollar value be estimated for intangible items, such as stakeholder satisfaction, user satisfaction or public acceptance.

The basic tool to help understand the impact of changes to the reactor configuration or the reactor fuel cycle, or to help compare different options, is a cost–benefit analysis. This is an evaluation and comparison of all of the potential costs and benefits that may be generated if the project is completed. The outcome of the analyses will show whether a project is financially feasible, and will show which of several options is the most favourable.

To conduct a cost–benefit analysis, the benefits of a given change or investments are summed and then the costs required to make the change or investment are subtracted. The benefits may include additional revenues, if a commercial service is provided, and/or savings, in terms of reduced operating or spent fuel management costs, for example. In addition, the benefits may include intangible items such as improved stakeholder or user satisfaction if a financial value can be associated with them.

The cost assessment must include the investment monies spent on new equipment, facility upgrades, staff training, core analysis, and so on. It also includes any increases in operating and maintenance costs that may result from the project.

In order to compare costs and benefits that occur at different times, for example when there are investment costs in year 1 with savings or additional revenues in each of the subsequent years, the net present value (NPV) analysis method (see Appendix 1) is required to take proper account of the reduced value of future costs and revenues. The NPV is a direct measure of the potential return on an investment, and the typical figure of merit for determining the economic viability of a project.

When alternatives are to be compared, the NPV analysis should be performed for each option to determine the best alternative from an economic perspective. This technique is amenable to relatively easy spreadsheet analysis for simple ‘one-off’ projects; all of the popular computer spreadsheet programmes provide built in NPV functions.

The analysis can become more complex because of the unpredictable cost and timing of many items, and because of the need to project circumstances, cost and revenues 10 or 20 years into the future. This can be addressed by modelling several different options or several cost–benefit streams with flexibility to alter assumptions and input variables to adjust for changing political/economic conditions over the long term. This is referred to as ‘sensitivity’ analysis in the case of multiple ‘deterministic’ calculations using variable assumptions; or, ‘risk’ analysis in the case of stochastic, (probability weighted) calculations.

Risk analysis introduces some analytical complexities and requires some additional understanding of the probabilities of variation in major assumptions or (possible) future events. But it has the advantage of more rigorously quantifying how future uncertainties can affect the decision at hand. Some risk assessment concepts are discussed below.

Figure 13 shows some items (costs and revenues) that might be included in a typical deterministic economic model for a research reactor’s overall operations.

The ‘comparable project’ technique is often used at an early stage of a project for screening purposes among various options. Here, the probable range of costs for each option can be estimated by comparison or extrapolation of historical data of similar projects. Once the functional requirements for a facility are defined, a preliminary order-of-magnitude figure can be drawn up regarding the broad investment for the project options.

If the conditions surrounding the project are similar to other facilities for which costs are available, then the project costs can be deduced with reasonable overall accuracy, perhaps including some appropriate adjustments from these reference cases for non-applicable conditions. Adjustments may involve simple linear or ‘scaling’ relationships with respect to some project parameters such as size, power, etc. Such determinations can be made in-house or by consultants with special knowledge of the commercial businesses of interest.

Using the ‘comparable project’ technique, an initial screening analysis can be undertaken without great expense to select the most favourable options. After that, a detailed cost–benefit analysis usually would be required for high accuracy budgeting and financing purposes for the short listed options.

It should be noted that, if a specific project or group of projects is to be evaluated, it is the incremental costs and benefits that should be considered in the analysis. That is, only the changes in costs and benefits that are directly attributable to the option(s) or project(s) under consideration should be used in the analysis. Preparing this

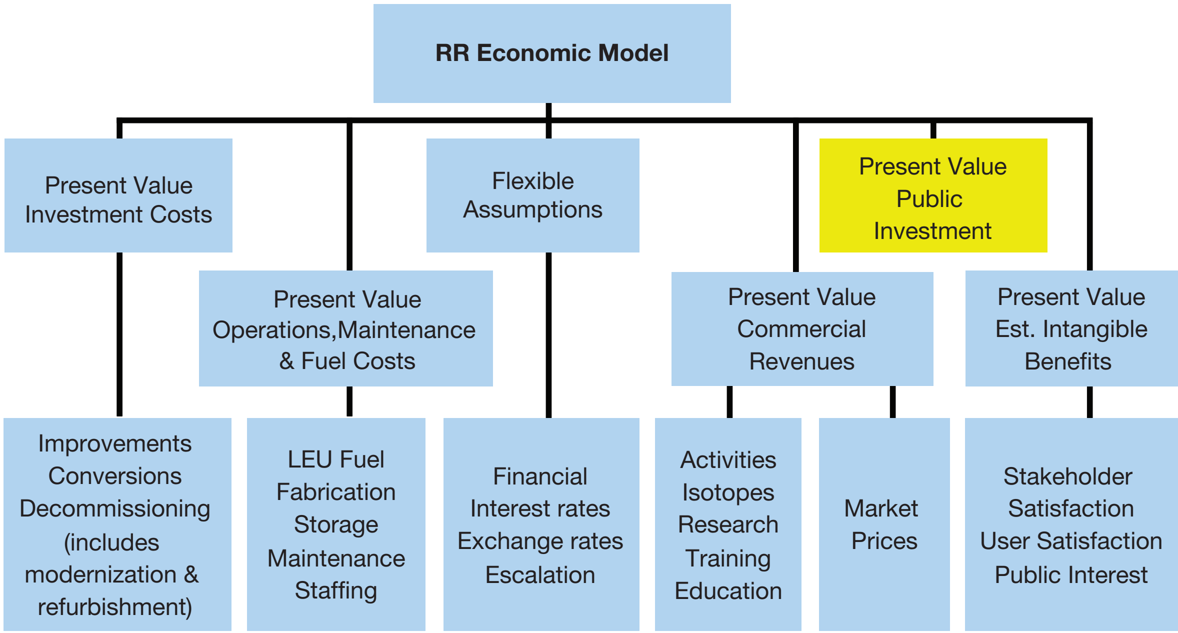


FIG. 13. Typical factors to be considered within a research reactor economic model.

incremental analysis will be much easier and quicker than attempting to build a comprehensive model of the reactor's operations.

Using these evaluation tools, the research reactor owner can:

- Establish an economic 'base line' for specific local conditions;
- Prepare budgets and plans;
- Price services and products;
- Evaluate the impact of changes/options;
- Perform viability assessments;
- Evaluate new projects and commercial opportunities;
- Test the analysis sensitivity to changes in the assumptions;
- Analyse joint or regional projects.

6.3. RISK AND LIABILITY MANAGEMENT

The economics of the fuel cycle of any research reactor will be subject to inherent risks and uncertainties, irrespective of the stage of the cycle being considered. These risks can and will impact the achieved costs and benefits if they are not fully considered and understood, with a potential to impact the economic management and planning of the whole research reactor in some cases.

Research reactor stakeholders can reasonably expect a high level of risk management awareness from any research reactor facility site licensee, and an attitude to risk assessment and goal setting that seeks to eliminate or minimize adverse financial impacts. Research reactor stakeholders include senior management, government departments responsible for funding and investment, clients for the research reactor services, regulators, employees and persons living near the facility.

Issues such as technical failure, instrumentation problems, contractor delays in new fuel production or delivery, new regulatory or legal requirements, serious accident, sudden loss of client business or external funding, are examples of damaging risk issues which could have significant financial consequences, and therefore contribute to the financial risk. The question arises as to how research reactor operators can prevent, mitigate and manage these risks to avoid potential for future financial losses.

6.4. MANAGING FINANCIAL RISK AND LIABILITY

It is important for research reactor operators to recognize that risk management requires a total commitment and 'buy in' of senior managers, staff and external stakeholders, especially the site licensee and its management board. This is crucial if effective management is to be achieved.

A good starting position is to increase risk awareness and understanding throughout the research reactor management team. The team should develop a comprehensive risk register that addresses in detail risk issues to the overall business plan that considers the strategic planning options embracing the nuclear fuel cycle; the risk categories should include technical, performance and commercial risk. Such a risk register will address income, revenues, costs and liability issues related to some expected events considered important, in the context of this publication, such as refuelling options and fuel reprocessing, but other significant operations and events should also be considered such as future decommissioning and cleanup liability, future investment and external funding expectations, the veracity of the revenue business plan, etc. Only by inclusion of all factors that can affect the successful and safe running of the reactor can a reliable and useful business model be built.

The risk register enables simple and comprehensive modelling that defines and simulates the research reactor processes and performance. It is a dynamic document to be updated and reviewed at frequent intervals. It forms the core of strategic planning and underpins future success in research reactor operations, budget definition and many other issues such as transfer of risk by insurance, setting of realistic financial provisions for any future liabilities to meet accounting standards and future expenditure commitments, as well as overall liability management. A senior member of research reactor staff should be appointed to manage the risk register and its financial implications.

The key here is to engage and encourage the entire research reactor staff in continuously defining risk and assessing financial consequences.

7. CASE STUDIES

7.1. CASE STUDY OF A FINANCIAL RISK ASSESSMENT FOR A RESEARCH REACTOR

The following is an account of the procedures and activities associated with producing a total financial model for a research reactor that incorporates the effects of various internal and external events. The case study covers the examination of the business case and the associated financial risks for the continued operation of a research reactor. Whilst the scope of this case study is much wider than a specific analysis of fuel cycle costs, it provides an analytical approach and framework that is equally applicable to the evaluation of fuel cycle economic issues and could be used for fuel cycle cost optimization.

7.1.1. Objective

The objective was to help optimize the business strategy for a research reactor, including refuelling and decommissioning risks. In addressing this objective, it was anticipated that several commercial and financial options for future operations would emerge. One of these options was selected for the business strategy, so forming a defensible, transparent and rigorous business case to meet the needs of the reactor stakeholders.

The key stakeholders are the owners of the reactor, the regulatory bodies, other Government agencies, internal and external customers, employees, local authorities and, possibly, environmental pressure groups.

7.1.2. Background

The reactor was built to serve essentially as a research tool. It now has an important commercial role providing neutron services to a wide scientific and engineering market in such areas as isotope production, fission chamber power measurement calibration, and medical analysis. The reactor also has a training role for nuclear engineering, power and propulsion, nuclear regulators, nuclear industry personnel, etc.

In order to continue operating in the longer term, the reactor required life extension measures such as core refuelling and improved core cooling. There was also a need to maintain and update a detailed regulatory approved plan for complete reactor decommissioning and waste disposal. A key condition of the nuclear site licence is for the licensee to make adequate financial provisions for decommissioning and to periodically respond to the Government requirement to draw up and obtain approval for decommissioning strategies. Such strategies include justification for timetables and adequacy of the financial provisions.

The reactor staff estimated that it would not be cost effective to operate the reactor after 2017 without either refuelling or other significant technical improvements to the reactor. A full refuelling would have allowed the reactor to operate until 2028, and a partial refuelling would have allowed it to operate for about a decade. A full decommissioning programme approved by the regulator would also be required.

The costs of decommissioning had been estimated based upon recent experience of decommissioning other research reactors in the country. These estimates have been internally and externally reviewed and have an uncertainty of €1.5 million. A five year defuelling and decommissioning period was taken as a baseline.

7.1.3. Scope of work

To achieve the objective of this study, the following scope of work was undertaken:

(a) Review documents and data available which were pertinent to the work. These include existing documentation on the reactor strategic plan and business objectives, and decommissioning cost information.
(b) Assess the current business and financial strategy usng the documentation and comments provided. Suggest revisions on the strategy to include critical elements for the development of a defensible business case.
(c) Review and develop further the reactor risk register using current methods of risk and liability management.
(d) Develop a dynamic, computer based financial model which reflects the options for financing business operation, refuelling and decommissioning. The model took into account:
    - technical risk;
    - performance risk;
    - commercial risk.
(e) Use the financial model to quantify the financial impacts of expected activities and options in terms of cash flow, and net present value (NPV) up to the period covering the end of decommissioning, full site clearance and termination of the licence

The model addressed a range of uncertainty issues and introduced the element of risk to financial impacts by assessing probabilities of occurrence of various scenarios and their financial outcomes. In addition, the model allowed the risk assumptions to be changed, allowing profitability and/or cost consequences to be assessed as a function of input variability. Legal, regulatory, health and safety risks were considered as appropriate for input to the model. Their cost implications were included in the business case model based on available data.

The model showed the cumulative probabilities of various cost outcomes to allow management decisions to be made on the basis of most acceptable, most advantageous cost decisions.

Key business solutions included reactor refuelling strategies or other life extending options, and optimum funding and timing options for decommissioning. Provisioning approaches, finite risk and insurance programmes, financial drawdown details and insurance remedies were to be considered, if appropriate. Because research reactors vary both in their design and their mission it is necessary to develop a customized financial model for each case.

7.1.4. Methodology and analysis

The analysis began with a review of documentation and the current business strategy, including the preliminary definition of options and scenarios for the future of the reactor. The steps required to determine decommissioning costs and appropriate financial provisioning included:

— The preparation of a detailed risk register;
— The identification of strategic options;

— The development and interpretation of computer based financial models to compare NPVs for each identified option.

Data gaps in four categories were then identified and resolved:

Refuelling — Questions relating to decay of fuel flux, fuel rod contract conditions, disposal of spent fuel and lack of domestic nuclear fuel sources. After review, it was decided that these issues were sufficiently well known that they could be defined in the risk register with adequate allowances for probability of occurrence and impact.

Technical faults — Questions relating to timing, costs and technical issues for upgrading the reactor crane for possible fuel rod removal, and changes and upgrades to the ventilation system. Start dates and likely range of costs were supplied for inclusion in the risk register.

Operations costs and questions — Questions related to the true costs of operations, and if the evaluation of how much saleable time is available. It became clear that reactor unavailability was dominated by reactor down time in summer due to higher ambient temperatures. The possibility was raised of cooling the building to improve availability.

Business questions — Questions related to how income projections could be developed. A revised marketing plan was made available as a basis for future income projections.

Key strategic options were identified based on the assessment of current business strategy and discussions with reactor staff. These options formed the basis of the probabilistic financial models. The options were consistent with the operating strategy at the time, but were widened to include extended reactor usage in summer made possible by building cooling. The options were:

— Full refuelling with decommissioning at some future date, no later than 2028;
— Partial refuelling with decommissioning;
— Partial refuelling with improved building cooling with decommissioning;
— No refuelling with decommissioning (described as NONE);
— No refuelling with improved building cooling with decommissioning (NONE with cooling).

A risk register was prepared to catalogue and quantify significant risks that were relevant to the strategic options. The function of the risk register was to facilitate the quantification of risk for the probabilistic models, to identify the risks associated with different parts of the business model, and to determine the possible impact of these risks on future outcomes. These risks were identified and then assessed by their impact and likelihood of occurrence using a risk assessment workshop in collaboration with reactor and other relevant staff.

Risks were assessed for the following key components of the business model:

— Income;
— Operating costs;
— Refuelling costs;
— Cooling costs;
— Decommissioning costs.

The resultant risk register catalogued 70 risks with probability distributions and financial impacts. Subsequently, a further 60 risks were derived from the business plan to give a total catalogue of 130 risks. All risks were peer reviewed by an independent nuclear expert. Examples of elements of the risk register structure and content are shown in Table 6. The majority of the risks (seventy) were associated with operational risk, e.g. income, operating costs, refuelling risks and decommissioning. The remaining sixty risks were associated with the future business plan.

Four critical risks were identified and assessed that had the particular significance that they could impose unplanned early decommissioning and so adversely impact the operator’s liability funding strategies, and insurance. These risks were loss of license to operate and significant accident in the income group, and obsolescence and adverse green pressure in the safety case group.

TABLE 6. SELECTED EXAMPLES FROM THE RISK REGISTER FOR RESEARCH REACTOR

№.	Title	Description	Distribution/magnitude	Comments
Income				
I1	Alternative technology	ICPMS is major competitor but the market now stable. Advanced MS is new threat with €30k–€40k income already lost	Discrete 90%: no expenditure 10%: €15K (10% probability of an additional €15K spend)	This risk only relevant in the first two years — after that it has either happened or is not going to happen
I2	Reliability of reactor	Reactor does not function all the time. This figure categorizes reactor downtime in terms of the resulting loss of income.	Discrete 75% — fully operational 20% — 10% loss of income 4%–25% loss of income 1%–100% loss of income	Figures represent the loss of annual operating time — applies to every year whilst operating
I3	Loss of staff	Reactor cannot function because of lack of staff required by safety license	Discrete 75% — fully operational 20% — 10% loss of income 4% — 25% loss of income 1% — 100% loss of income	Figures represent the loss of annual operating time — applies to every year whilst operating
I4	Catastrophic failure	Reactor cannot function because of failure of part of system	Discrete 99% — everything OK 1% — 6 month shutdown with loss of income	Annual risk Income loss considered during the shutdown period
Operational expenditure				
OE1	Plant investment	Investment required to maintain operation of reactor	85% — no impact 15% — €100K	One off risk
OE2	Legacy issues	Removal of asbestos or similar	90% — no expenditure 5% — €100K 5% — €400K	One off risk
OE3	Accident elsewhere	Accident affects procedures and incurs costs	95% — no expenditure 15% — €75K	Annual risk
Refuelling				
R1	Manufacturing costs	Variance in cost of new rods	Triangular. €200k, — 50%,+100% (Apex at €200k, lower bound at €100k, upper at €400k)	Total refuel costed at €200K (all 24 rods)
R2	Safety case — removal and refit	Cost of safety case required by regulator in order to refuel	Triangular €75k, €60k, €130K	One off certainty
R3	Transport issues	Cost of transporting rods to and from reprocessing plant	Modified triangular 95% — €170k +/– 25% 5% — impossible	One off risk
Decommissioning				
D1	Discharge authorization	Need for authorization for discharges during decommissioning	80% — no expenditure 20% — €100k	
D2	Difficulty in removing fuel	Current crane set up possibly inadequate for task.	65% — no expenditure 35% — €200k	
D3	Route to reactor inadequate	Preliminary survey will remove this risk	99% — no expenditure 1% — €20k	
D4	Changes in site require municipal approval	NNC Liaise with local authority	99.9% — no expenditure 0.1% — €5k	

All unspecified costs were assumed to have a triangular uncertainty distribution of 100%, –50%, +200%.

7.1.5. Financial model development

The core of the analyses involved the creation of a customized financial spreadsheet model of the reactor operations and issues. The financial model structure is a flexible and dynamic spreadsheet. It embodies a quantitative description of the discrete costs and returns of the current and projected activities of the reactor. It uses both deterministic and stochastic techniques to evaluate the NPV of the various strategic options.

The deterministic model

The deterministic model was used to explore the five key strategic options and 208 permutations of refuelling dates, decommissioning dates and levels of business performance within these options. This model used single point values for the different costs and revenues likely to occur during the course of the period to be considered (i.e. it did not use any probabilistic risk assessment). The NPVs of the various options and permutations were calculated using the operator accepted discount rate of 3%, which was appropriate for these particular circumstances. Higher rates may be more suited to other locations and operations. The deterministic model expressed NPV as a single value for each of the permutations within the options considered.

The deterministic model was built in the form of a multi-sheet computer spreadsheet in MS-EXCEL© and formed the central engine upon which a probabilistic analysis could later be added. The first step was to separate the reactor's financial processes into four principal types: income; operational costs; refuelling costs; and decommissioning costs. The data were organized so that the magnitude and timing of the cost or revenue were inserted into the spreadsheet at the relevant position, ensuring that the income or cost occurred at the correct point in the life cycle of the reactor.

The 'decommissioning costs' page was more complicated because it contained the explicit estimated decommissioning costs of the previous report to the operator and also the Gantt chart of activities that was used to distribute these costs temporally so that the decommissioning costs for each year of decommissioning could be calculated. The decommissioning page was designed to be highly flexible so the user could make changes to the decommissioning plan and see the effect of these changes immediately. The decommissioning period was defined as the five year span from the point of cooling down being initiated (duration: 2 years) to full decommissioning and site remediation being completed (duration: 3 years).

The sensitivity of the operator's business performance programme was tested. Income projections from the business plan were not available at the time in which the deterministic model was constructed. In order to provide some rationale for input, a 0% to 150% range for revenue improvement above the present level was factored into the programme.

The five key options were modelled deterministically. The income, operating costs and refuelling cost spreadsheet pages in the deterministic model were kept simple in structure by requiring that costs or incomes were stopped or started at a time appropriate to the modelled option, i.e. relevant to the date and type, and decommissioning dates selected by the user from the drop down menus on the 'User Interface' page. The 'Income' page also required the user to vary business income and the period over which this increase was to be phased.

Based on the initial deterministic model assessment, the strategic option 'no refuelling with cooling decommission in 2028', emerged as the leader over other competing strategies (Option 4 in Fig. 14). Thus NPV values from various permutations of this option were an early pointer to the operator cash flow requirements (Fig. 15).

Stochastic (probabilistic) model

A stochastic model was developed by incorporating the operational and business risks, as defined in the risk register, into the deterministic model. This enabled the probabilities of the predicted outcomes to be calculated and allowed events that could not be predicted with certainty to be included in the analysis. The stochastic model used a Monte Carlo approach to predict NPVs from a range of input scenarios and probabilities. Thus the NPV for each permutation of each option from the stochastic model was presented as a frequency distribution of outcomes.

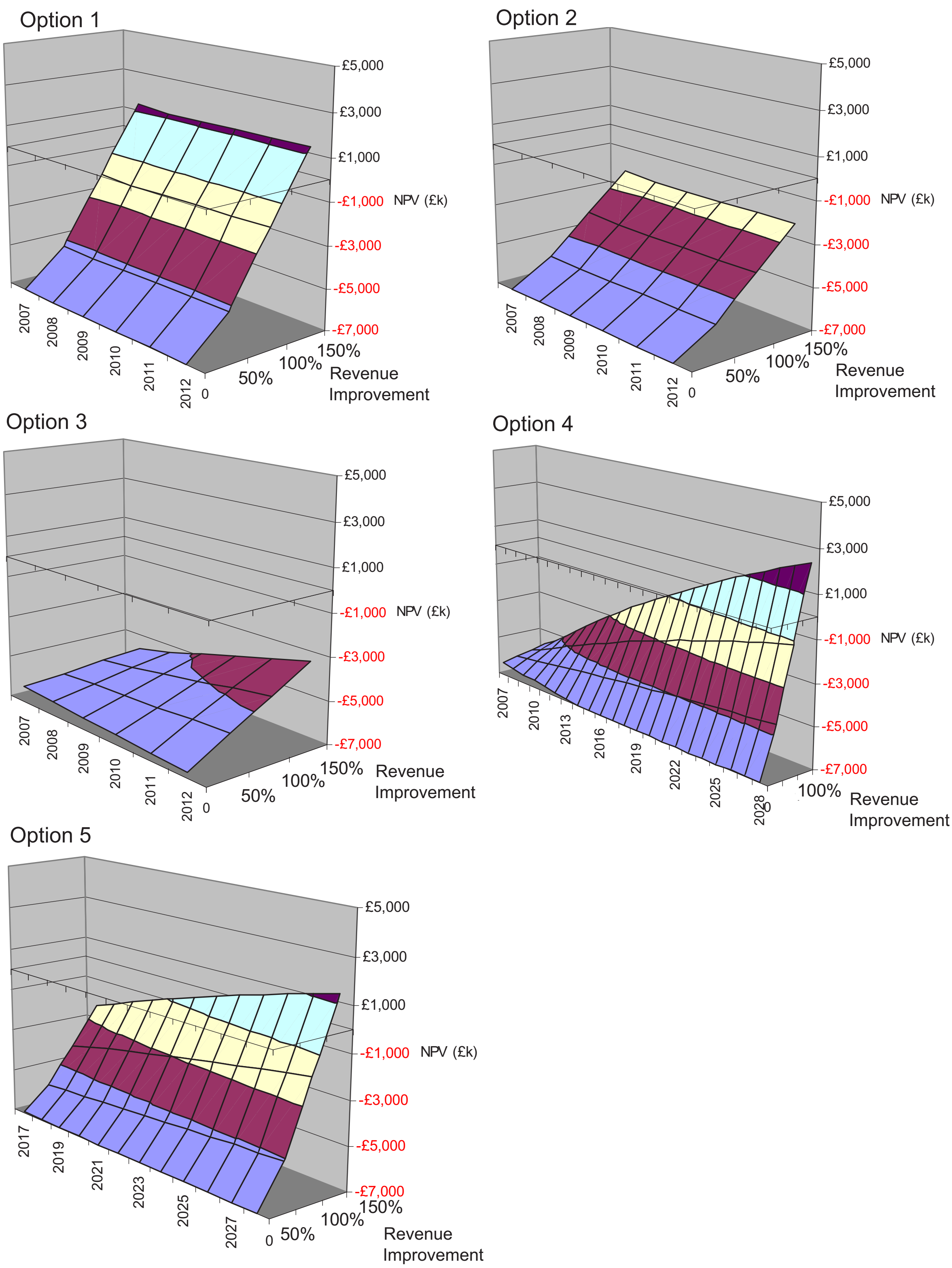


FIG. 14. Outputs from the deterministic model showing the most favoured option (highest NPV).

The construction of the basic deterministic model had allowed the project team to visualize how to schedule income, running costs, and decommissioning costs for each strategic option, and it provided a useful check that the deterministic model was correctly structured. At this point the probability based input variables were added to the model. As discussed above, the risk register and the business plan defined these risks.

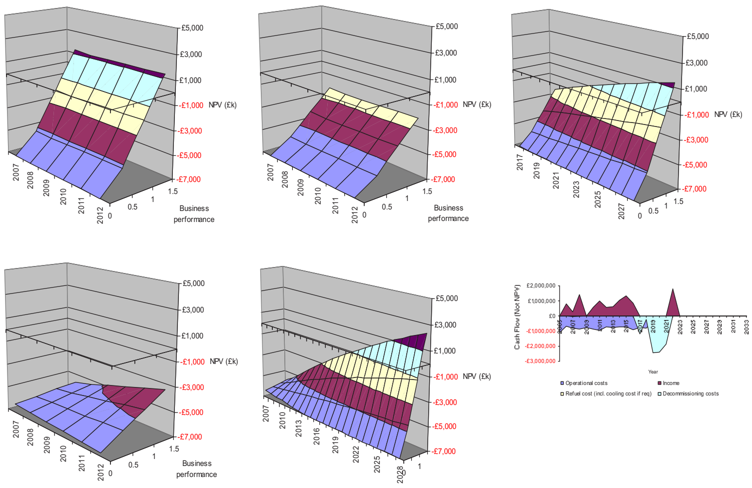


FIG. 15. Operator cash flow requirements for the most favoured option (highest NPV).

The existing single point values were replaced with the appropriate probability distribution associated with the particular value. For example, the deterministic model used a value of €71 000 for the cost of insufficient transport flasks being available, whereas the probabilistic model used a triangular distribution ranging from €36 000 to €143 000 with a most likely value of €71 000, as specified by the risk register workshop. Thus when the model was run 100 000 times using Monte Carlo sampling, the value of this item could range anywhere between the two extreme values but with a greater probability of coming from the central portion as defined by the distribution.

Stochastic variables were linked within the model as they would be in reality. For example, a delay in refuelling through extended delivery of fuel or the regulator not issuing a license would have an impact on the 'Income' page and stop all income for three and nine months respectively or, in the unlikely event of both occurring, a full year.

Five options and 624 permutations were evaluated in the stochastic model. Curves of cumulative probability for NPV for each of five initially defined strategic options were produced with decommissioning start dates of 2007, 2012, 2017, and 2028. In each case the model considered scenarios in which a government funding option was either included or totally excluded. Evaluation of the cumulative probability curves indicated that refuelling options (full or partial) represented greater risk of incurring higher costs compared with other options. A typical example of graphically presented output is shown in Fig. 16, which shows a typical output of the model based on a hypothetical research reactor using realistic but non-specific data.

Figure 16 shows which source the costs and returns are coming from. Operating costs (blue) are fairly constant but income (purple) is much more variable, e.g. 2010 income is very low while in some years, e.g. 2009, income exceeds costs. The large peak at the end, following decommissioning, shows income generated by the sale of the reactor plot. Decommissioning costs are not visible, indicating that the provisioning was adequate in this instance. A small white negative peak in 2007 is seen indicating where the cost of cooling is introduced.

Results of the analysis

Review of the output from the stochastic modelling showed that three of the strategic options appeared to be less viable. The reasons for this were mainly the added cost and risk associated with refuelling, for example the uncertainty surrounding fuel recycling and disposal of intermediate level waste. Consequently, in consultation with senior reactor staff, it was proposed to exclude refuelling options from further consideration.

A second phase of stochastic modelling was undertaken on the following four options:

— No refuelling, decommissioning to start 2007- end 2011;
— No refuelling, cooling, decommissioning 2012–2016;

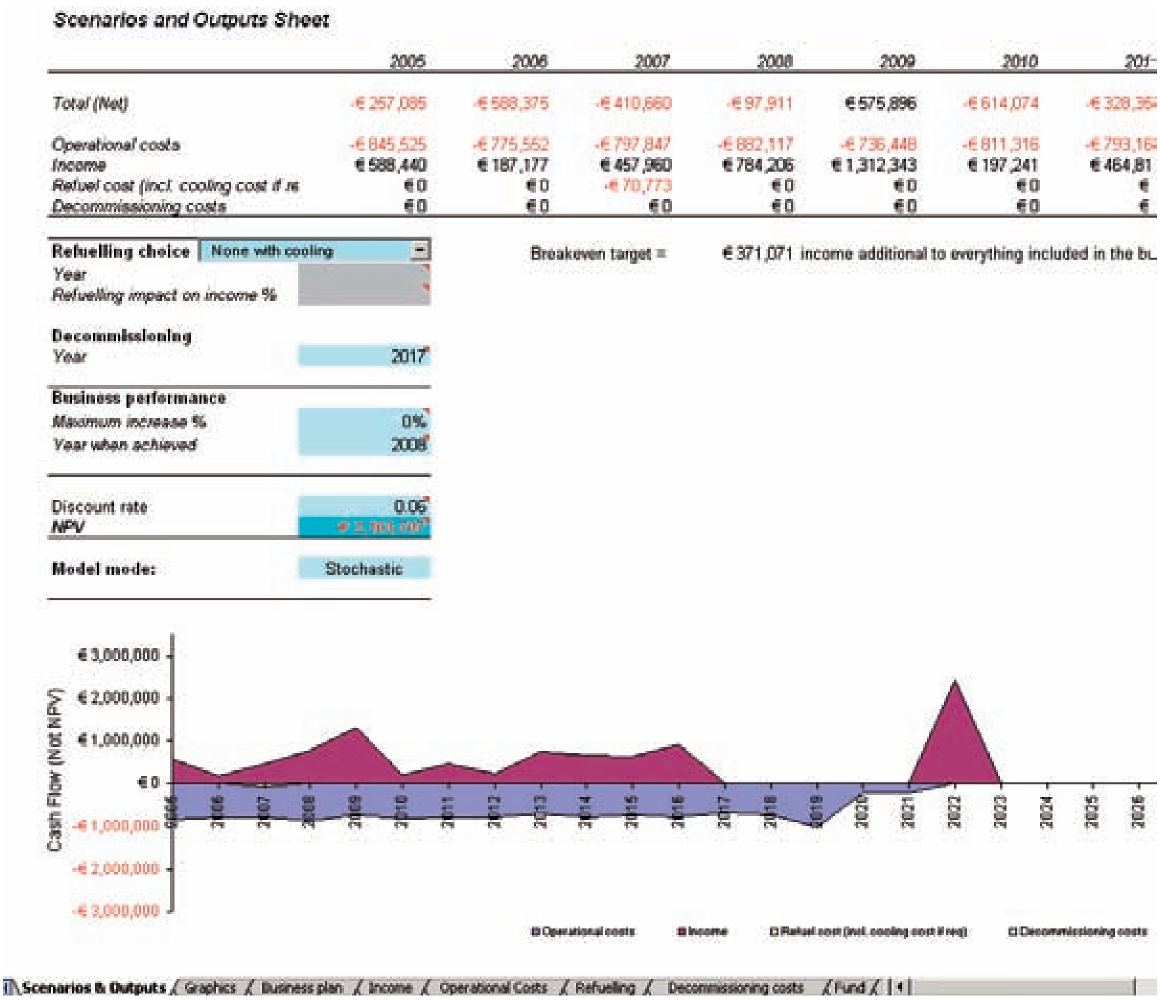


FIG. 16. Output from the stochastic model.

— No refuelling, cooling, decommissioning 2017–2021;
— No refuelling, cooling, decommissioning 2028–2032.

The primary aim of this second stage of the work was to provide the operator with estimates of decommissioning costs in order to support decisions on provisioning for the future liabilities. The outputs from this work were cumulative probability curves showing NPVs for decommissioning costs only, either inclusive or exclusive of a contribution from the government. This was achieved by developing a unique decommissioning module.

Sensitivity analysis that was performed as an integral part of the modelling exercise highlighted the activities that had the largest influence on NPV. These were found to be the business performance (the improvement in revenues), and external funding through the government bodies.

The analysis of decommissioning costs showed that variability in decommissioning costs was mainly a result of the unique estimates of individual tasks. Early closure would not in itself affect the costs of decommissioning (at least in constant price calculations), but would have a major impact on the financial shortfall provisioned by the operator to cover the costs of decommissioning.

The analysis also identified certain critical risks of unplanned decommissioning or ‘showstopper events’:

— Loss of licence: nuclear regulatory action in the event of a breach of licence conditions;
— Significant accident;
— Safety case obsolescence: if the reactor cannot be safely re-commissioned after refuelling;
— Political pressures forcing a security review.

Actual occurrence of any of these events could provoke early reactor shutdown and commencement of the decommissioning phase before the date specified by an option's expected decommissioning year. Some of these showstopper events are associated with specific activities and it is not difficult to anticipate that an activity such as full refuelling would entail more risks (environmental, logistical, political and, thus, financial) than the 'no refuelling' option. Similarly a 'no refuelling' option would not suffer the same probability of an adverse political pressure objection as the refuelling strategies. Thus some options had lower occurrences of showstopper events than others and the simulated effect of these risks are represented in the model and appear in the outputs.

The question of provisioning for decommissioning was also addressed in the model, and the outputs are shown in Fig. 17 and Table 7. These show the cumulative distribution of decommissioning costs based on the range of outcomes from 10 000 simulation runs. The range from 20–50% of cumulative costs is highlighted (costs are expressed as negative values, thus the lower end of the cumulative curve represents the highest costs). This is the range of normal provisioning within the nuclear industry, setting aside funds or otherwise accounting for this level of expected future cost in the accounts.

Table 7 shows the range of percentile values for total decommissioning provisions required for the period from 2005 to 2021, by which time the final costs will have been incurred in a planned operating life to 2017. The table shows that the decommissioning will cost at least €3.26 million, and that there is a 50% probability that it will cost as much as €4.3 million. The fields in the table shown in bold show the decommissioning costs that have a 20 to 50% probability of occurring. This represents the range of values that might normally be considered for provisioning; it is normal to provision at the 50% level, since this covers the midpoint of the expected range. The worst case estimated with planned operations and closure would require an additional €4.6 million to cover all costs by 2021. In practice, it would be unlikely that this would be required within one year, because the decommissioning programme is spread over a five year period and the higher costs could be spread across several years during the programme as they are identified.

A more significant concern would come from early unplanned closure, before sufficient provision had been accumulated. Some protection can be gained from insurance against mechanical causes of closure, but other risks (political, for example) cannot be covered. Risk of early closure as a result of unexpected regulatory requirements should be mitigated by a close cooperative approach with the relevant government authorities.

The information from this analysis can be used for financial planning and financial risk management considerations, and for provisioning purposes. It can also be used to satisfy regulators, such as on health and safety issues or providing defensible decommissioning planning and adequate provisioning statements. Figures can also be produced to meet financial accounting standards.

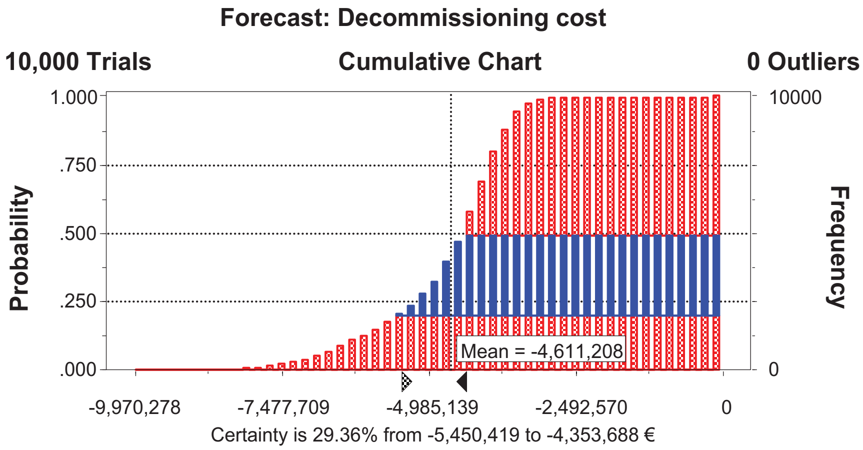


FIG. 17. Cumulative distribution of decommissioning costs.

TABLE 7. FORECAST DECOMMISSIONING COSTS

Forecast: Decommissioning cost	
Percentile	€
0%	9 970 278
10%	6 258 057
20%	5 435 152
30%	4 896 078
40%	4 574 634
50%	4 336 985
60%	4 150 754
70%	3 973 948
80%	3 784 143
90%	3 542 923
100%	3 262 475

7.2. ARGENTINA — RA-3 REACTOR CASE STUDY

7.2.1. Introduction

The RA-3 is a pool type reactor located at Ezeiza Atomic Center, 30 km from Buenos Aires. The reactor reached criticality in 1967.

It was originally designed with a nominal power of 3 MW and is now operating at 10 MW, with 120 hours of full power per week. This operation scheme allows the generation of all Molybdenum (Mo^{99}) requirements in Argentina for medical purposes.

The core was designed with MTR fuel type with curved plates and HEU, dispersed in aluminium. The HEU used in the reactor was provided by the USA and was used over a period of 20 years. After this period of time, the international Reduced Enrichment for Research and Test Reactors (RERTR) initiative led to ever increasing limitations on the ability to procure HEU and demonstrated the ability to convert the reactor to LEU.

7.2.2. Reasons for the core conversion

At the end of the 1970s Argentina became an active member of the RERTR project, and had the opportunity to irradiate mini plates of dispersion fuel of high density and silicide mini-plates at the Oak Ridge test reactor. This irradiation, and the good results achieved, allowed Argentina to develop the process in order to manufacture dispersion fuels of LEU, with densities greater than 2.3 g U/cm^3 needed to maintain the performance of the reactor sufficient to continue the production of radioisotopes.

The main reasons for taking the decision to make the change were:

— Difficulties in purchasing HEU;
— The need to increase the spent fuel capacity;
— The availability of more than one uranium supplier;
— Local capability to supply enriched uranium.

7.2.3. Results achieved

To perform the core replacement, two suppliers were contacted, and both had the capability to fulfill the specification for the LEU fuel. The quoted prices differed by 3%, and the differential, along with the chemical composition was used to decide the preferred supplier. This allowed the least cost route to be followed whilst also allowing the purchase of uranium in the chemical form necessary to fabricate the fuel elements.

The fuel inventory policy was changed, from 10 years of full power equivalent to 3 years full power equivalent, thus reducing the financial charges by more than 75% (nearly US $2400/kg U used).

This decision on core replacement made it possible to send 207 discharged HEU fuel elements to the USA and recover approximately 90% of the storage pool capacity for interim storage, and deferment for 10 years of the erection of a new storage facility, assuming normal operation of the reactor at 10 MW. The financial impact was to defer the US US $3 000 000 investment for the same period.

The achievement of these goals allowed the continued operation of the reactor, and associated research and development plans, whilst saving 33% in the fuel cycle costs over the pre-conversion situation, worth approximately US $350 000 per year.

In order to make further improvements to the costs of the fuel cycle additional studies are being performed. The new strategy is based on increasing the fuel density by changing the dispersed fuel to silicide types with a density of 4.8 g U/cm^3. This change will reduce the number of fuel elements used per year and further delay the need for extra capacity in the storage facility. The savings expected as a result of this change today are about 12% on present fuel cycle costs (US $85 000 per year at the time of the analysis (2006).

7.3. AUSTRALIAN CASE STUDY: CONVERTING THE HIFAR RESEARCH REACTOR FROM HEU TO LEU FUEL

A case study by the Australian Nuclear Science and Technology Organisation (ANSTO).

7.3.1. Introduction

The Australian Nuclear Science and Technology Organisation (ANSTO) began operating the High Flux Australian Reactor (HIFAR) in 1958. HIFAR was a DIDO class research reactor operated at a thermal power of 10 MW. The reactor core was cooled by heavy water which also acted as the primary neutron moderator. HIFAR was originally designed as a materials test reactor and used very highly enriched fuel.

HIFAR is primarily used for:

- Neutron scattering science: neutrons are supplied to a number of neutron beam instruments, most of which are located close to the biological shield inside the containment building;
- Irradiation services: the major usage being for neutron transmutation doping (NTD) of silicon ingots;
- Isotope production: both medical and industrial isotope products are generated in HIFAR, with medical ^{99}Mo the dominant product.

In 2000 a contract was signed for the construction of a 20 MW multi-purpose research reactor to replace HIFAR. The replacement research reactor, which was later named the OPAL reactor, was planned to be fully operational by late 2006. This defined a nominal end date for operation of HIFAR for the end of 2006.

Over the nearly 50 year operating life of HIFAR a variety of fuel designs have been used. After the 1970s, fuel enrichment was reduced in stages from over 90 per cent to 60 per cent. The reactor core contains 25 fuel assemblies, and for the last 25 years has used a design consisting of concentric rings of uranium dispersion fuel clad in aluminium. The highly enriched uranium (HEU) fuels used U–Al dispersions. For the 60% enriched fuel the nominal fresh ^{235}U mass was 170 g per fuel assembly.

HIFAR operated continuously at nominal full power between refuelling periods, which were planned on the basis of four and later five week cycles and typically involved the replacement of three to four fuel assemblies.

Consistent with international efforts to introduce proliferation resistant low enriched uranium (LEU) into research reactors, analyses were performed in the late 1980s to investigate the options for converting HIFAR to low enrichment fuel. The analyses involved various enrichments and uranium loadings. From a technical point of view the results showed that relatively minor changes could be expected in nuclear characteristics of the reactor. However, for LEU fuelled cores with uranium loadings resulting in similar reactivity levels for HEU fuelled cores, the analyses indicated that reductions in thermal neutron flux levels between 5 and 15 per cent could be expected. The evaluations also involved financial and scientific output considerations, which were complicated by the uncertainty of how long HIFAR might continue to operate.

7.3.2. Planning for the end of HIFAR operation & beginning of OPAL operation

The decision by the Australian Government to replace HIFAR with OPAL, subject to compliance with strict environmental and safety legislation, prompted key decisions regarding nuclear fuel for HIFAR operation. Specifically, it was important for ANSTO to procure sufficient fuel to operate HIFAR until OPAL was fully commissioned. Additionally, to allow for scientific, production and financial continuity, ANSTO sought assurances from the nuclear regulator, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), that for a limited period HIFAR and OPAL could operate in tandem. With a limited number of years now remaining before HIFAR was to close, the case for converting from HEU to LEU was altered. Based on the inventory of fuel at the time, ANSTO needed to procure new fuel assemblies to achieve operational objectives for the next five years. ANSTO initiated discussions for purchase of the final HIFAR fuel order with a long standing fuel supplier.

At about this time, the RISO national laboratory in Denmark announced the closure of its research reactor called DR3, which was a PLUTO type reactor, being of similar design to DIDO reactors. There were 61 unused LEU silicide fuel assemblies left after the closure of DR3, and this presented ANSTO with an opportunity to acquire and use the fuel. Working closely with staff from RISO, design and safety documentation was translated into English and it was concluded that the remaining LEU fuel was compatible with the HIFAR design, subject to modifications to non-fuel portions of the fuel assemblies. After negotiations, ANSTO contracted to purchase these remaining LEU fuel assemblies. If approved for use the RISO LEU fuel could be obtained from the nuclear regulatory authority (ARPANSA), then full power operation of HIFAR would be possible until the 3rd quarter of 2006.

Factors considered for continuing operation with LEU fuel

To firstly achieve and secondly optimize the extended operating period for HIFAR, the following factors were considered:

Licensing — ARPANSA approval for use of the RISO LEU fuel in HIFAR was the first and most important step in the process. This entailed development of a detailed and rigorous safety case. A summary of the technical requirements contained within the safety case is given in Section 2.2. The associated financial costs included several person-years of effort from a range of professional staff. A consultant from RISO national laboratory was engaged to assist with development of the safety case.

Measurement programme — A detailed measurement programme formed part of the safety case presented to ARPANSA. This entailed programming fuel reactivity, control rod reactivity and neutron flux measurements at low power. This caused extension of some of the normal shutdown periods by up to half a day, resulting in loss of irradiation time and revenue for customers. Over the 18 month period where the core was progressively converted from HEU to LEU, the total loss of irradiation time was approximately 4 days.

Continuity of staffing — It was particularly important to ensure that sufficient numbers of trained and authorized operations, maintenance and utilization personnel were available to enable continued operation. This coincided with demanding requirements for OPAL staffing, and consequently one of the biggest challenges for ANSTO was to ensure adequate staffing for both HIFAR operation and planned OPAL commissioning and operation. The financial costs entailed normal staff employment salaries and overheads, short term contractor costs to fill in employment gaps, specialized training costs, and specialized but limited retention offers to HIFAR operational staff.

Continuity of supply of products to customers — Once the above factors were realized, this made possible the provision of important products to customers via the continuing operation of HIFAR.

Fuel management strategies — A number of different fuel management strategies were considered, but after approval to use RISO LEU fuel the most cost-effective strategy was to maintain a shutdown period of about 4 days per 5 week operating cycle and aim to maximize reactor availability.

Penalties introduced by conversion of HEU to LEU — The flux penalty introduced due to the conversion of HIFAR from HEU to LEU fuel was calculated to be approximately 5% for the irradiation facilities within the core and approximately 10% for facilities located in the reflector region. Analysis of the measurement programme was not completed at the time of writing of this case study.

The full conversion from HEU to LEU was achieved in May 2006.

Technical requirements for using the RISO LEU fuel in HIFAR.

Prior to loading the LEU fuel into HIFAR, approval for its use was required from ARPANSA. To support the consideration for approval a substantial safety case was prepared by ANSTO.

The Danish Regulatory Authority approved the use of RISO type 18A LEU silicide fuel assemblies in 1988. DR3 operated with a mixed core of HEU and LEU from 14 October 1988 to 28 March 1990 (28 operating cycles), and continued operation with a full core of type 18A LEU silicide fuel assemblies after that. DR3 was also operated at 12 MW for periods of time with a full LEU core to confirm safe operation at this power level. DR3 safely operated for 10 years with a full LEU silicide core without any safety concerns or fuel failures. In September 2000, the board of governors of RISO National Laboratory decided to permanently shut down DR3 due to technical problems (not caused by LEU fuel) and anticipated increasing operating costs.

The LEU silicide fuel assemblies are a very similar design to the Mark IV/23 fuel assembly design that was successfully used in HIFAR for many years. Each fuel assembly consists of four concentric tubes made from welding 3 individual fuel plates per tube. Each fuel plate consists of uranium silicide/aluminium dispersion (U_3Si_2_Al/Al) sandwiched and hot rolled in aluminium cladding. The four tubes are held in place by four aluminium combs at the top and four at the bottom of the tubes. This fuel section is then welded by the combs to an unfuelled outer aluminium tube. A guide nose is attached to guide the coolant inlet flow and a diffuser section to guide the outlet coolant flow. Each type 18A fuel element contains 180 g (+0/–2%) of ^{235}U enriched to 19.75% with a uranium density of 3.3g/cm^3.

The fuel assemblies were modified in the following ways:

— The addition of 24 holes to allow coolant flow from irradiation rigs which may be located inside the central tube of the fuel assembly. These coolant holes are present in the MTR mark IV/23 fuel elements and are used to facilitate free coolant flow from the rigs without creating excessive wave action on the D_2O surface.
— The addition of 16 emergency core cooling holes to provide emergency cooling to the fuel plates in the event of a loss of coolant accident (LOCA) involving a large breach downstream of the primary coolant system non-return valves.
— The outer aluminium tube was shortened to the required length and the fuel assembly guide nose replaced with the same design as used in the mark IV/23 fuel assembly.

A safety analysis report was prepared to assess the safety aspects of operating HIFAR with the LEU fuel. The report included assessments of the following topics:

— Criticality;
— Reactor physics;
— Fuel handling and ever-safe times;
— Mixed core operation;
— Thermal hydraulics;
— Emergency cooling;
— Reactivity insertion accidents;
— Thermocouple position;
— ATWS;
— HIFAR reference accident;

— Steam explosions;
— Fuel management computer code;
— Use of type 14A fuel elements — (2 special elements).

Impact of OPAL construction on HIFAR operation

Early in the construction period of OPAL, several geological features were exposed during excavations which indicated that geological faults had occurred in the past through the site where the facility was being constructed. A halt was placed on construction of the facility while investigations by geological experts attempted to determine the age of the faults. Those investigations demonstrated that the faults were indeed millions of years old, and the site was essentially stable. ARPANSA subsequently gave approval to recommence construction, but a four month delay to the construction schedule had resulted. This in turn meant that if the schedule delay could not be recovered, it was unlikely that OPAL commissioning would be completed before HIFAR fuel supplies were exhausted.

By early 2005 it was increasingly likely that OPAL commissioning would not be completed before the last quarter of 2006, and ANSTO began considering in what ways HIFAR operation could be extended.

ANSTO's considerations during this period are set out below.

Extended operation — For the purpose of investigating options for extended operation the required operating time for HIFAR was assumed to be until 31st December 2006. This was the limit of a regulatory licence condition on HIFAR operation. To achieve this date, fuel supplies needed to be conserved. A primary constraint was to minimize effects on customers due to changes in HIFAR operation. The following options were considered:

— **Purchase more LEU fuel** — Considerations included length of time to purchase fuel, how many fuel elements would be required, the cost of fabricating only a small number of fuel elements and what to do if there was any new fuel remaining after HIFAR shutdown.
— **Shut down HIFAR during periods of low molybdenum demand**, e.g. Christmas or Easter. This was considered unsatisfactory for other customers, including those related to silicon production and neutron beams.
— **Remove unused reflector rigs from HIFAR** — Only a one-off gain in excess reactivity would have occurred.
— **Irradiate less material in the reactor core** — This would lead to a reduction in yield for radioisotope customers. Some materials might have been able to be irradiated in self-service reflector rig facilities.
— **Shuffle fuel at fuel changes** — Calculations with fuel management codes indicated that if limited fuel shuffling were employed, 2 to 3 fuel elements could be saved per year. Offsetting this saving were cost penalties incurred due to extra shutdown time and extra radiation dose to staff who performed the fuel shuffling.
— **Extend shutdown period** — This would lead to a reduction in yield for all customers. A return to a 4 week (28 day) operating programme could be implemented. In this case, the reactor would be at power for 24.4 days, leading to 9.4 less days at power per year over the current 5 week (35 day) cycle.
— **Operate HIFAR at lower power** — This would reduce the yield for all customers. As an example, if HIFAR was operated at 8 MW for 6 operating programmes (each of 5 weeks duration), sufficient fuel could be saved to enable HIFAR to operate for 1 extra operating programme when compared to similar operation at 10 MW. However, yields or irradiation times would have been about 20% lower or longer, respectively.

Ultimately, it was decided to purchase more fuel and a contract was signed with a fuel supplier for a limited number of new LEU fuel elements for HIFAR. Some fuel shuffling was also performed and reactor power was reduced by ½ MW for a few operating cycles. The second supply of LEU fuel for HIFAR arrived at ANSTO in July 2006. Approval to use the fuel was obtained from ARPANSA in August 2006.

7.3.3. Summary and conclusions

ANSTO operated HIFAR as a national facility and therefore in any considerations related to operations there are a range of both financial and non-financial factors that need to be considered. For the conversion of HIFAR to LEU fuel the situation was primarily driven by the need to keep HIFAR operating until the OPAL reactor was commissioned and ready for operation. While this affected almost all subsequent decisions, costs in terms of safety, science and national interest had to be considered alongside the financial situation. The situation and considerations were complex and dynamic. Ultimately it required an integrated and strategic management approach to implement the changes successfully. HIFAR was eventually shut down on 30 January 2007. OPAL was officially opened in April 2007.

Appendix

CALCULATION OF DISCOUNTED VALUES AND NET PRESENT VALUE METHODOLOGY

A.1. Discounted values

The discounted cash flow method allows future revenues or costs to be expressed in current money values, by taking into account the 'time value' of money. There is an expectation that money invested today will be worth more after some period of investment, or conversely, that returns on investment at some point in the future should be reduced, or 'discounted', by that expected growth rate to calculate their equivalent value at the present time. The discount rate is usually chosen to reflect the cost of money to the reactor operators, in essence the costs of borrowing or otherwise obtaining the needed investment funds.

For example, if the receipt of a given amount of money P_t is delayed to a given time period, the value of the money at the end of that time period P_{t+1} is smaller than the initial value, so P_{t+1} / P_t is a constant number smaller than 1. This constant number is usually called a discount number and can be written as $1/(1+r)$ where r is the discount rate. The present value is defined by:

$$P_t = P_{t+1} \times \left(\frac{1}{1+r} \right)$$

If the time period is one year, the discount rate is called the annual discount rate. It can easily be shown that the present value of a given amount of money (P_n) n time periods in the future could be written as:

$$P = P_n \times \left(\frac{1}{1+r} \right)^{n}$$

The present value method can be applied to both future revenues and future costs, and is fundamental to any economic model because it allows money flows in different years to be aggregated and compared.

A.2. Net present value methodology

The net present value (NPV) is the comparison of revenues and costs from future years to determine if investments will be justified by the income that they generate, or whether for financial provisions invested over a period of time an appropriate interest rate will be sufficient to cover eventual liabilities (for example for spent fuel management and disposal or decommissioning).

As a first step the relevant future cost and revenue items must be identified for each year. Next the values of these items must be determined to build a picture of the annual cash flows.

The net present value of this series of costs is then determined by discounting each cash flow entry (see above) at the appropriate interest rate to a reference year (this may be the current year, or the year that an investment is made). The sum of all entries produces the total NPV which is the typical figure of merit for measuring the economic merit or viability of the project or enterprise. Most computer spreadsheet programmes have inbuilt functions for calculating an NPV.

To illustrate this basic technique, take an example where the initial capital investment for a facility is 100 currency units paid in a reference year (2009). The annual operating costs of 5 currency units are incurred every year thereafter for 10 years, and decommissioning costs of 7 currency units are incurred in each of the subsequent 2 years and 10 currency units are incurred in each of the subsequent 2 years. During operation the facility generates revenues of 25 currency units each year.

The NPV of these costs and benefits at a real discount rate of 4.9% (that is, net of adjustment for inflation) is 35.19 currency units, as shown in Table 8.

TABLE 8: SAMPLE CALCULATION OF NET PRESENT VALUE

Year	Annual costs	Annual revenues	Annual cash flows	Net present value of annual cash flows (discount rate: 4.9%/a, reference year 2009)
2009	100		(100)	(100.00)
2010	5	25	20	19.07
2011	5	25	20	18.18
2012	5	25	20	17.33
2013	5	25	20	16.52
2014	5	25	20	15.75
2015	5	25	20	15.01
2016	5	25	20	14.31
2017	5	25	20	13.64
2018	5	25	20	13.00
2019	5	25	20	12.40
2020	2		(2)	(1.18)
2021	2		(2)	(1.13)
2022	2		(2)	(1.07)
2023	2		(2)	(1.02)
2024	2		(2)	(0.98)
2025	7		(7)	(3.26)
2026	7		(7)	(3.10)
2027	10		(10)	(4.23)
2028	10		(10)	(4.03)
Totals	194	250	56	35.19

A.3. Levelized unit cost

Another useful concept for comparing the economics of different projects is the levelized unit cost. This simply means calculating the present value of all of the costs during the project lifetime, and dividing this figure by the total output of the project during the same period. For example, if different fuel fabrication processes were to be compared, the total costs over time can be reduced to a single, comparable levelized cost, and divided by the number of assemblies produced in the fuel facility, to give the levelized unit cost per assembly.

This reduces a very complex calculation to a single figure, and thus simplifies the comparison of the merits of different alternatives.

The output parameters chosen for calculation of the unit cost should be selected appropriately for the purposes of the comparison. In the fuel fabrication facility example, if the assemblies from different facility options are not comparable, perhaps one option produces uranium silicide fuel meat and another uranium molybdenum fuel meat, the generated power in the research reactor, or the average neutron fluxes in the reactor might be better parameters with which to determine the levelized unit cost.

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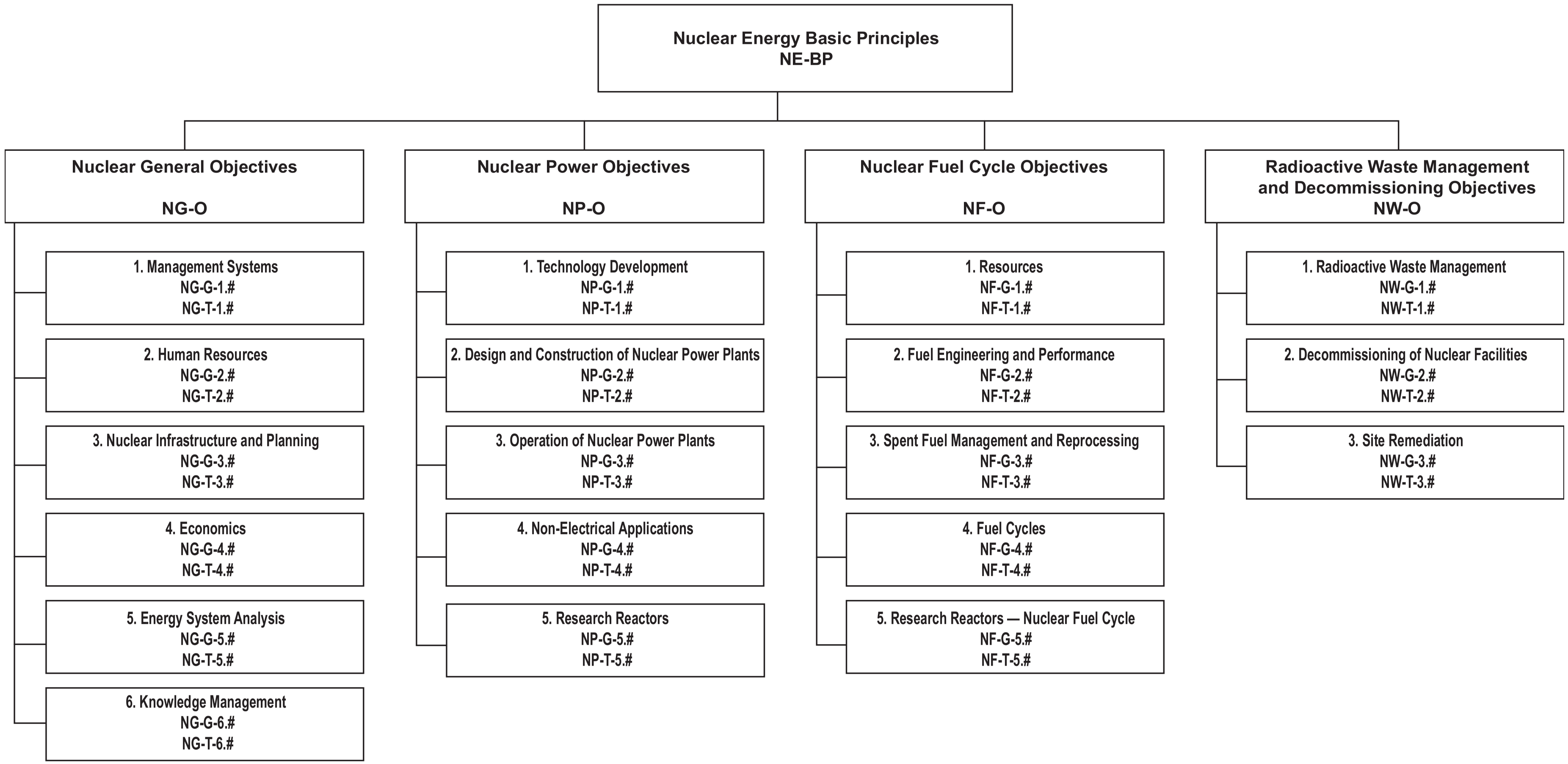

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