ISSUES IN RESEARCH REACTOR SPENT FUEL MANAGEMENT

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Many countries have operated research reactors safely for many years. The scale and design of these reactors varies considerably according the objectives of the research programs that they were intended to support. The amount of spent fuel arising is relatively small, compared to that linked to commercial and military reactors. However, in countries which do not have commercial or military programs, only research reactors, the management of the spent fuel presents a significant challenge. It is also the case that research reactor fuel does not present a single set of characteristics relevant to its management. Coupled with other regional and local factors as widely disperse as geography, regulatory framework and policy, this means that no single solution is likely to emerge that is effective in all cases. This paper reviews those issues and provides some illustrative discussion and conclusions.

I. INTRODUCTION

The International Atomic Energy Agency (IAEA) Research Reactor Database records 247 operational research reactors worldwide including 159 in developed countries and 88 in developing countries [1]. A further 19 are under temporary shutdown, while 6 are under construction and an additional 12 are planned. Their combined operation entails a substantial and continuing inventory of spent fuel arisings which have also to be managed safely. In addition, another 481 research reactors have been shut down and the associated spent fuel management programs, including completion of disposal of waste, have not been fully completed in many cases.

The scale and design of these research reactors varies considerably according to the objectives of the research programs that they were intended to support. The power output varies substantially, from zero or very low power, e.g. the 3 kW Graphite Low Energy Experimental Pile reactor (GLEEP) in the UK, which ran from 1946 until 1990 [2], through those of moderate power, e.g. the 5 MW(th) training and research reactor being constructed in the Hashemite Kingdom of Jordan [3], up to about 100 MW(th), as in the case of the Canadian National Research Universal reactor which has a maximum rating of 135 MW(th) [4]. Apart from the fuel and reactor designs, the operational histories can also vary significantly. In combination, this means that spent fuel from research reactors has widely varying characteristics.

Among these countries, Norway has a long history of safe research reactor operation. The first commenced in 1951 and today there are still two in operation, run by the Institute for Energy Technology. The larger of the two is the Halden Boiling Heavy Water Reactor (HBWR), which is run as part of a co-operation program with organizations from 19 countries through the Nuclear Energy Agency (NEA-OECD). The HBWR reactor is used for safety-focused research into materials, fuel burn-up, and fuel behavior in prolonged operating conditions. Spent fuel from these reactors has been held in store for some years in purpose built facilities. The inventory, though very small compared to that arising from typical nuclear power programs, demonstrates a wide range of physical and irradiation characteristics, see table 1. It includes uranium metal and aluminium clad fuel as well as oxide fuel. Work is also on-going which will likely give rise to small quantities of thorium spent fuel [5].

TABLE I. Norwegian spent fuel characteristics and amounts [6], [7], [8] and [9]

Reactor	JEEP I and NORA	JEEP II	HBWR 1st charge	HBWR
Fuel type	Metallic U	UO_2	Metallic U	UO_2
Initial ^{235}U (%)	natural	3.5	natural	6
Burn-up (MWd/t initial U)	1 to 1,000	10,000 to 15,000 (average)	12	30,000 to 40,000 (average)
Irradiation period	1951 to 1967	1966 to present	1959 to 1962	1962 to present
Residual thermal power at 30 y (W/t U)	< 50	200 to 350 (average)	< 1	650 to 900 (average)
Fuel rod diameter	25.4	12.8	25.4	10.5

(mm)				
Fuel length (mm)	1.90E3	900	2.38	748 - 811
Cladding material	Al alloy	Al alloy	Al alloy	Zr alloy
Total mass of SF (kg of initial U)	3.1E3	2.0E3	6.7E3	3.5E3

Note: the table does not include further smaller quantities of other spent fuel materials.

Following initial investigations, work on defining methods for continued management of the Norwegian research reactor spent fuel (RRSF) was firmly established with the setting up of a Committee in 1999. This Committee was given a mandate to "develop a national strategy for disposal of high active, spent nuclear fuel". Several reports have been issued since with evolving recommendations, notably the report of a Technical Committee in 2010 [6].

In the case of Norway, RRSF is the only spent fuel arising. Obviously, other countries like the USA have much larger commercial and/or military spent fuel inventories to manage, alongside those from research reactors. In such cases, the research reactor fuel could arguably be considered a side issue; not to be ignored, but managed within a wider program. However, the characteristics of RRSF, by the very nature of research activities, result in a range of non-standard features, which suggest that special management consideration may be needed. This is reflected in the UK Nuclear Decommissioning Authority (NDA) program for management of so-called *exotic* fuels as illustrated, for example, in Ref. [10] which discusses options for management of spent fuel from the Dragon research reactor. A further example of non-standard spent fuel could be fuel arising from damaged reactors or which has degraded during inadequate storage [11].

Experience with management and storage of RRSF from countries with different scales of nuclear program has been shared though the International Atomic Energy Agency (IAEA), see Ref.12]. Noting the above, the following sections review the factors relevant to a RRSF management strategy, illustrate how they can affect decisions, and discuss how they might be analyzed to support a decision.

II. FACTORS RELEVANT TO RRSF MANAGEMENT STRATEGY

The development of and justification for a strategy needs to include an analysis of options. Keeping an open mind so as not to foreclose some options without due consideration, with respect to RRSF, these options can be summarized as:

- Direct disposal with no treatment.
- At other extreme, indefinite safe storage with no further plan at the current stage than to take further action on the basis of future developments.
- Intermediate options, taking into account alternatives for treatment, transport and further interim storage, but leading to final disposal.

The middle option of the above three could arguably be considered as an incomplete strategy since it is open ended as regards disposal. However, if the future developments include participation in an on-going program to investigate radioactive waste disposal, then the strategy could be considered complete.

Relevant factors which, upon analysis, could be used to support selection of the preferred option can include:

Technical factors:

- Engineering feasibility, ease of application.
- Existing/tried or new/untried technology.
- Access to technology (e.g. for reprocessing).
- Transport logistics.

Safety factors:

- Risks in planned operations, to people, workers, the environment and property, in the short and longer term.
- Accident risks to people, workers, the environment and property, in the short and longer term.
- Does the option readily meet safety standards?

Security factors:

- Scope for loss of control, due to actions of malevolent entities.
- Does the option readily meet security standards?

Status of wider national radioactive waste management strategy:

- Existence of a clear strategy and an established framework for its implementation.
- Existence of a clear regulatory framework and basis for demonstrating compliance with standards.

Cost considerations:

- Availability, sufficiency and reliability of funding on timeframes consistent with strategy implementation.

Constraints arising from wider policy issues:

- Policy limitations on the application of technology, e.g. for reprocessing.
- Policy limitations on international transport and transfer of materials.
- Process for and role of engagement with stakeholders.

The above list may not be complete, but, to the knowledge of this author, it is comparatively unusual to see parallel and proportionate consideration of security and safety within a single options analysis, or within a safety analysis use to support a specific option.

Factors relevant to RRSF management include all the factors relevant to radioactive waste management generally. The important question is, what makes RRSF different so as to require special attention.

III. ILLUSTRATIVE OBSERVATIONS

Based on on-going practice and experience, the following observations are offered.

Concerning disposal, direct disposal of U metal and Al clad fuel from research reactors has been effectively ruled out on the basis of its chemical reactivity in Ref. [5], while elsewhere a comprehensive safety case for direct disposal of much larger inventories of U metal spent fuel with higher burn-up has been provided. Section 1.5 of the safety assessment for a repository at Yucca Mountain notes that most U.S. Department of Energy (DOE) spent fuel (approximately 98% of the heavy metal) is {to be} shipped to and handled at the repository in sealed canisters that are suitable for co-disposal in waste packages with High Level Waste (H LW) {primarily commercial spent fuel} without being opened [13]. Specific consideration of relevant features, events and processes which support this contention are provided in Ref [14]. This includes the comment, “the oxidation of the uranium metal fuel will not adversely affect radionuclide release because the {assessment} model uses a bounding instantaneous degradation rate”. Further inventory information about the DOE and other US spent nuclear fuel is provided in Ref. [15].

While the case for direct disposal of U metal and Al clad fuel appears to have been made in the USA, Savannah River Nuclear Solutions reportedly has recently started a multi-year campaign to process aluminum-clad used nuclear fuel from both foreign and domestic research reactors at the Savannah River Site [16].

The direct disposal of significant amounts of U metal spent fuel is similarly planned in the UK. As an example, in the case of the low burn-up GLEEP fuel, the proposal [17] includes packing of the fuel into stainless steel 500 l drums which ultimately will be infilled with cement grout to form disposable waste packages. Following grouting, the drums will be stored pending the availability of a geological disposal facility. In reaching this strategy, an assessment was made against intermediate level waste (ILW) packaging standards and specifications derived from the geological disposal concept. As regards U metal with higher burn-up, for Magnox reactor spent fuel has routinely been reprocessed. However, it might not be possible to reprocess some of the remaining Magnox spent fuel prior to closure of the currently operating reprocessing plant. The contingency plans include interim storage, and conditioning and packaging suitable for disposing without the need for reprocessing [18]. However, the need for further work on the appropriate conditioning and packaging is acknowledged.

It is apparent that reprocessing can be convenient if the technical option is already accessible, and especially if RRSF reprocessing is consistent with, but marginal to, wider reprocessing operations at the plant. It may also be appropriate in the case that existing designs for disposal of other spent fuel do not address the specific features of the RRSF. This is given as the reasoning behind reprocessing of the Sweden R1 spent fuel in the UK, rather than disposal with other spent fuel in Sweden [5]. It may be noted that although the reprocessing has already occurred, the disposition of the ‘product’ Pu is still, at the near time of writing, being negotiated as part of a wider reprocessing arrangement [19].

The possible distinction emerges from these examples between fuels with low and high burn-up. This is acknowledged in the UK program in Ref. [20], where it is said that, “Small quantities of relatively low irradiation spent fuel that are not planned to be reprocessed have already been designated as waste and are reported in the radioactive waste inventory. These comprise spent fuels from the Windscale Piles, GLEEP, the Dragon and Zenith reactors, and small quantities of mainly prototype commercial fuels.”. Fuel from the Windscale Piles and GLEEP is U metal. Note that one of the Windscale Piles was the site of a major accident in 1957. It is also relevant that the management strategy does not revolve around where the fuel comes from, but confirms with what is appropriate according to its characteristics, notably in this case the heat output of the fuel.

As an illustration of the heat output issue, it may first be noted that according to international recommendations [21], HLW requires management that takes account of the decay heat. For example, it is noted under discussion of HLW disposal that “Heat dissipation is an important factor that has to be taken into account in the design of geological disposal facilities.” By contrast, intermediate level waste (ILW)” may contain long lived radionuclides, in particular, alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal.” The determination of how much heat output is enough to distinguish HLW and ILW may need to take account of local factors such as the thermal conductivity of the intended host rock and other factors.

In the UK, in the absence of a specific host geology, ILW waste packaging requirements have been developed so as not to delay the making safe of various waste streams while, at the same time, not foreclosing on disposal options. The requirements are given in Ref. [22] and the justification for them in Ref. [2 3]. The requirement on heat output [22] specify "The heat output from all sources withi n the waste package (including radiogenic, chemical and bi ological sources) shall be limited to a value that will prevent excessive temperature rise within the waste package during all the phases of {management}." This is th en quantitatively specified as, "The heat output from a 500 litre Dru m waste package should not exceed 50W for transport and 25W at the time of vault backfilling." Note that these requirements independent of the geological environment, but that hard rocks, for example, tend to have a higher heat conductivity than other rocks, which might therefore allow further leeway for a hard rock site. See Ref. [23] for further discussion of how these limitations have been derived, and, by implication, how the requirements could be evaluated in different conditions and contexts. Overall, this provides a clear b asis for safe and non-prejudicial treatment of the GLEEP and other RRSF as ILW prior to the availability of a disposal route. It is also u seful to recognize that not all spent fuel is high active.

While it can clearly b e inappropriate to delay implementing an option to make a waste safe on the off-chance that a b etter option may turn up later, hurried intervention can also be a mistake. Careful planning alongside a cl ear regulatory path is of great importance. While this may sound a truism, and it is, i t is still worth emphasizing. Scope should also be left to allow for new options. In this context, a recent U.S. DOE study [24] concluded that "Sm all waste fo rms are potentially attractive candidates for dee p borehole disposal. Those wastes forms include…{…}, and DOE-managed spent fuel that has not yet been packaged." Said DOE-managed spent fuel includes more than 2000 tonnes of U metal and/or Al clad fuel, of a variety of types which appears to encompasses, and generally exceeds, the range of fuel burn-up seen by RRSF.

I

IV. ANALYSIS OF OPTIONS

There is a long history of options analysis for matters nuclear [25], including radioactive waste management [26]. There is a corresponding history of their criticism, typically concerning the set of factors considered as relevant and more especially the weightings applied to different factors when they are not directl y comparable. Whether you value three apples over two p ears is very subjective.

If the scope of an analysis is li mited to a few highly technical matters, then a technical approach and some form of bal ance and an effective process could be developed. It is may be appropriate to consult a patient as to whether they should undergo brain surgery to remove an otherwise fatal tumor, but it do es not make sense to consult on which type of scalpel to use. The process devolves to some sort of expert elicitation.

However, the distinction between technical and not-technical is not always obvious. Some factors, suc h as assumptions for long-term future human actions are probably only addressable through consideration of a range of credible alternatives, as in Ref. [27]. By contrast, we can rely on the banks to tell us reliable values of long-term discount rates in order to determine the current net present value of investments needed to meet future liabilities.

In our enthusiasm, any of us fall into the trap of believing the results of our careful, thoughtful and well informed analyses gives us the a nswer, falling for a "computer says" fallacy. It would be well to remember Arrow's "impossibility" theorem—or "general possibility" theorem, as h e called it, wh ich answers a very basic question in th e theory of co llective decision-making. Say there are some alternatives to choose am ong. They could be policies, public projects, candidates in an election, distributions of income and labor requirements among the members of a society, or just about anything else. There are some people whose preferences will inform this choice, and the question is: what procedures are there for deriving, from what is known or can be found out about their preferences, a collective or "s ocial" ordering of the alternatives from better to worse? The answer is startling. Arrow's theorem shows m athematically that there a re no such procedures whatsoever; none, anyway, that satisfy certain quite reasonable assumptions concerning the autonomy of the people and the rationality of their preferences. This is well known in welfare economics, but, for this author, seems not to have been recognized in the current context.

The point of the analysis is not to provide answers to questions which mathematics has t old us cannot be answered. This should not be taken as an argument for not thinking: available information that you do have should be considered in su ch a way as t o point in a direction which at leas t appears to meet with your or other objectives. Multi-attribute approaches at least provide mechanisms for structuring the information and identifying the factors which appear at least to be driving the decision. Those who object in principle to albeit austere cost benefit a nalyses would presumably rather leave things to chance. A common mistake would appear to be th e over-interpretation of results, not just by those commissioning them, and i n other cases, a lack of willingness to publish t he full results a nd conclusions, because to do so would it make clear what the real policy is.

Given the above, it is fortunate that procedures and tools are continuously being developed to help in the analysis of multi-factorial problems involving as many issues as i dentified above. The approach exemplified in Ref. [28] uses an a nalytical hierarchy approach. This involves identification of goals and a subsequent hierarchy of criteria for evaluation. Alternatives are evaluated with respect to criteria in a series of pairwise comparisons. This leads to early recognition of the factors affecting the decision. Ref. [29] from the Dalton Institute, Manchester University, provides some critique of conventional Multi-Attribute Decision Analysis methods and proposes a so-called Generic Feasibility Assessment which focusses on identifying the benefits of each alternative relative to a reference system. Ref. [30] describes a system for structured analysis of complex decisions with uncertain evidence, based on Evidence Support Logic (ESL). The method is designed to assess the confidence that can be placed in a decision, taking account of the amount of uncertainty or conflict in the supporting evidence. The focus here is on understanding why the decision is not easy to make and addressing that uncertainty.

V. CONCLUSIONS

The above observations and discussion reflect only a personal background and experience. Nevertheless, the following conclusions are offered.

- One technical solution will not likely be th most appropriate for all RRSF. The characteristics and the related hazard range very widely indeed. In particular, not all spent fuel is high active.
- Nevertheless, different technical solutions are available for all the different RRSF.
- A clear regulatory basis set within a wider national strategy for managing radioactive waste is extremely important.
- Development of a RRSF management strategy in one country can be supported by international cooperation and engagement, at technical, regulatory and institutional levels. This can be bi-lateral as well as through organizations such as the IAEA and the NEA-OECD.
- Specific and overall strategic issues for RRSF are similar to and could be addressed alongside issues associated with other nonstandard fuel.
- Advanced methods and techniques for evaluation of options, more broadly based than cost benefit analysis and conventional multi-attribute techniques, can support analysis of options.
- Such methods do not provide the answer, but support the intelligent application of information so as to inform a decision.
- A set of factors which might need to be included in an options analysis has been offered. They are very broad, ranging from the highly technical to social and political matters. Since the relevance of these factors is bound to range widely in different contexts and countries, it is likely that what might be considered appropriate in one country may not be in another, even for similar types of RRSF.
- The factors to be assessed and the scope of an options analysis should be defined clearly from the beginning. A balance is needed between completeness and "making the model of the forest as complex as the forest". It should also be made very clear from the beginning what is not included in the scope.
- Any process should avoid early foreclosure of options. In this respect, further investigation of deep borehole disposal appears warranted

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