Looking to the future PATRAM 2010

TRANSPORT CRITICALITY ASSESSMENT METHODOLOGIES FOR THE RWMD SPENT FUEL DISPOSAL CANISTER TRANSPORT CONTAINER

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ABSTRACT

Over the past four decades or so, the UK has operated a number of reactor systems, including Magnox reactors, AGR and PWR. The UK's Nuclear Decommissioning Authority is looking at several options for the disposal of spent fuel (SF) to a Generic Disposal Facility (GDF). One concept is based on the KBS-3 design by SKB. In this the SF would be packed into copper canisters, each containing an integral cast-iron insert. The canisters would be transported to a GDF in a transport container and at the GDF, the copper canister and SF would be unloaded and disposed of, with the transport container being re-used. The transport container, referred to as the "Disposal Canister Transport Container" (DCTC), is currently being designed.

Under the IAEA Regulations there are several ways to ensure the nuclear criticality safety of a package. The purpose of this paper is to report initial findings on the transport criticality safety issues that may arise in the assessment of the DCTC concept. The following design variants have been examined:

- Restricting the payload of the package.
- Amending the package design to include neutron absorbing materials in the insert or flux traps in the package.
- Incorporating multiple water barriers in the package.
- Taking credit for fuel irradiation ("burn-up credit") in the criticality assessment.
- Hybrid approaches.

The paper describes the work method and summarises the nuclear criticality safety issues, together with the arguments for and against each option.

1. INTRODUCTION

The role of the Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority is to provide the UK with safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials.

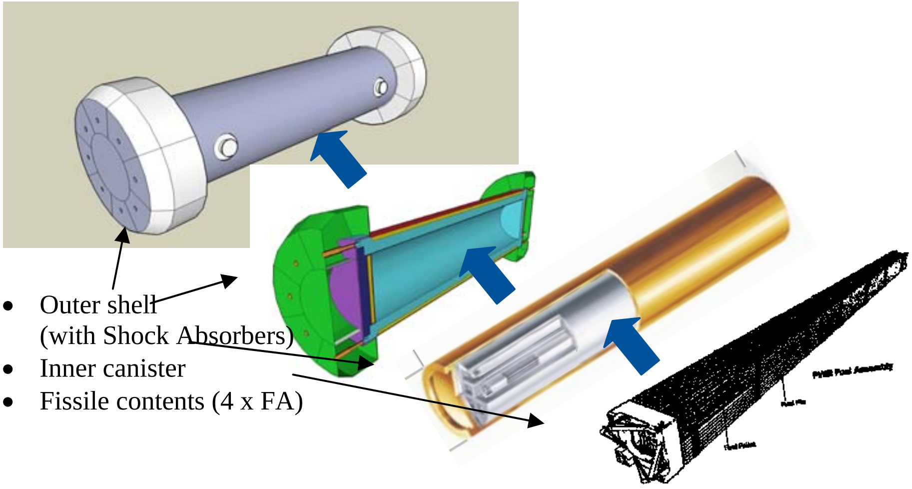
This role covers not only intermediate level radioactive wastes (ILW) and some low level wastes (LLW), but also high-level wastes (HLW) and potentially spent fuel (SF), should the UK Government decide to declare spent nuclear fuel a waste material.

Currently RWMD is developing a range of concepts for the potential direct geological disposal of some of the UK's SF. One such concept is based on the KBS-3 design, developed by SKB in Sweden, in which the SF is packed in copper canisters with a cast iron insert. A conceptual Disposal Canister Transport Container (DCTC) has been designed for the shipment of the copper disposal canisters.

2. THE DISPOSAL CANISTER TRANSPORT CONTAINER

As shown in Figure 1, the main body of the DCTC is a cast-steel cylinder, overall approximately 0.9 m internal diameter and 6.625 m in length. The steel walls are 150 mm thick, to provide gamma shielding, structural integrity and containment. An external 50 mm of Kobesh will provide neutron shielding. Shock absorbers at the ends of the DCTC will afford protection against collisions.

Figure 1: Arrangement of DCTC



The design is at the conceptual stage and factors other than criticality safety (for example operability, heat transfer, shielding) may affect the package.

3. FUELS

The DCTC is being designed to carry standardised disposal canisters which may contain for example:

- up to four Sizewell, AP 1000 or EPR PWR fuel assemblies (FA) – up to 5% U235 initial enrichment to allow for modern fuels. An irradiation of up to 65 GWD/tU.

- up to sixteen or twenty consolidated spent AGR fuel bundles - typically up to 2.3% U235 initial enrichment and a lower irradiation of up to 18 GWD/tU.

AGR bundled fuel consists of AGR fuel pins that have been removed from their elements, consolidated into a bundle and placed in a can. The can has drainage holes. All graphite is removed from the fuel.

4. IAEA REGULATIONS AND CRITICALITY SAFETY

Ensuring the nuclear criticality safety of packages during transportation is a major aim of the IAEA Transport Regulations. Currently for the UK, the basic principles of transport criticality safety are described in paragraph 671 of [1] and the principal requirements for packages carrying fissile materials are listed in paragraphs 673-682 of [1]. Reference [2] provides advice on the interpretation of these regulations.

In summary, in applying to a Competent Authority for a package approval, the applicant must define and justify a criticality safety criterion and show that under normal and accident conditions, both a single package and an array of packages would satisfy the criticality safety criterion.

Usually, for the massive packages used to transport SF, there is no significant difference in the neutron multiplication factor of a single package and an array of packages because of the neutron attenuation provided by the packaging. Neutron reflection for individual packages and arrays, at least as effective as 20 cm of full density water, must be assumed, but for massive packages this also usually has little effect for the same reason. Unless special features (multiple high standard water barriers) are present, the applicant must consider the effects of water ingress into the single package, irrespective of whether it is believed that this could credibly occur. Thus, for SF in a massive package, the acceptable payload can usually be determined from criticality calculations on a single, damaged, flooded package. The calculations, described later on, are based on a single fully water reflected DCTC.

5. BASIC SKB & POSIVA CRITICALITY ASSESSMENT

A complete transport criticality assessment (TCA) of the DCTC with UK fuels is not currently available, but basic criticality results from a SKB plant assessment have been obtained [3, 4] and these can be used to infer the most important results for a TCA. For a typical 17x17 PWR fuel assembly (FA) containing fresh (unirradiated) UO_2 fuel of 4.2% U235 enrichment, the key results from [3, 4]are:

Table 1: Key Results

Model	Neutron Multiplication factor		Comments
	Keff+/-σ	K+3σ	
Models containing unirradiated fuel: 4 x PWR FA in canister.			
(1). Planar infinite array of packages reflected by 60 cm water saturated bentonite clay. No water in FA.	< 0.5	< 0.5	Typical of the K+3σ that would be expected in a DCTC having a multiple water barrier.
(2). As (1) – water fills the spaces in the canister.	1.055+/-0.0012	1.059	These are not quite the models that would be used in a TCA, but are similar enough to draw conclusions about a single package in isolation and an infinite array of packages under normal conditions. A consideration of transport accident states could add a few % to the values of K+3σ.
(3). Infinite array of air spaced packages – otherwise, as (2).	1.0868+/-0.0012	1.091	
(4). As (3), FA displaced towards centre of package.	1.0903+/-0.0012	1.094	

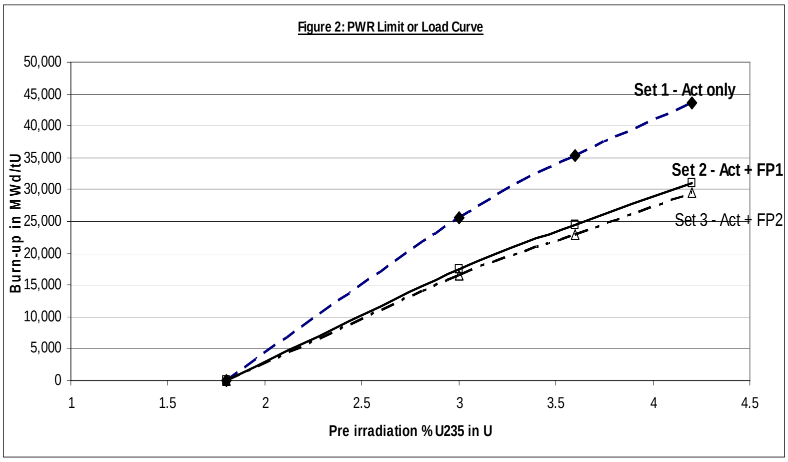
A typical UK TCA safety criterion is K+3σ =0.94 or 0.95. Except for the model which assumes that the DCTC incorporates a multiple water barrier, these results are clearly far too high to meet the safety criterion. Reference [3] also considers the benefits that might be obtained for the criticality assessment by taking account of fuel irradiation; the results from three "burn-up credit" approaches are reported. These are shown below where:

- **Set 1:** uses an "Actinide-only" approach, modelling the U234, U235, U238, Pu239, Pu240, Pu241, Pu242 and Am241 in the fuel.

- **Set 2:** uses an "Actinides + fission products1". As Set 1 + Am243, Np237, Nd143, Nd145, Sm147, Sm149, Sm150, Sm151, Sm152, Eu151, Eu153 and Gd155.

- **Set 3:** uses an "Actinides+ fission products2". As Set 2 + Tc99 and Rh103.

Figure 2 shows the "loading-" or "limit-curve", which relates the initial pre-irradiation enrichment to the burn-up necessary for the SKB models to meet K+3σ = 0.95.



These results must be considered to be very approximate for UK spent PWR fuel because, for example, they have not accounted for accident conditions and they depend on the irradiation histories of Swedish PWR reactors. Nevertheless, they give an indication of the fuel irradiation that would be necessary to safely transport a full DCTC in the UK.

Noting that many PWR and AGR UK fuels exceed 2% initial enrichment, the results suggest that the DCTC concept would need to be modified to be suitable for transporting UK fuels of low irradiation.

Also it can be seen that assuming actinides only (Set 1 – the simplest approximation) carries a significant penalty over the assumption of Set 2 and 3 (actinides + fission products). For example, to meet the safety criterion for fuel of 3% pre-irradiation enrichment, a burn-up of 25,000 MWd/teU would need to be demonstrated. In contrast, the results suggest a far less onerous 15,000 MWd/teU would be needed if taking credit for fission products (Sets 2&3).

6. POTENTIAL CRITICALITY ASSESSMENT METHODOLOGIES

The following options for demonstrating nuclear criticality safety of the transport of the UKs fuels in a DCTC were examined:

- Restricting the SF payload to one, two or three FAs.
- Amending the package design to include neutron absorbers, either in a conventional arrangement for a SF flask (ie flux traps - neutron absorbing plates in a wet package) or by adding absorber uniformly to the iron insert (eg including boron in the iron).
- Filling the void space in the package by sand to reduce the density of any water that would be present.
- Incorporating multiple water barriers in the DCTC.
- Taking credit for fuel irradiation (“burn-up credit”) in the criticality assessment.
- Hybrid approaches, based on combinations of the above.

With these options in mind, a generic model of a DCTC, copper canister and fresh fuel was designed, which was suitable for demonstrating compliance with the IAEA Transport Regulations. In the model, water was assumed to pervade the FAs; in other words the system is a simple configuration of FAs (fuel & cladding), insert, canister and water. There was a 20cm thickness of water reflector surrounding the canister.

In order to gain an understanding of the trends and sensitivities of the DCTC concept with respect to variations and uncertainties in basic parameters (enrichments, insert materials etc), approximately 30,000 criticality calculations were carried out.

An automated procedure was used to systematically survey the effect on the neutron multiplication factor of variations in a number of parameters. The criticality model consisted of a fully water reflected single canister containing between 1 and 4 FA. The parameters and variations were:

- Fresh (unirradiated) fuel of enrichments = 3.0, 3.5, 4.0, 4.5, 5 and 6% U235 in U (as UO_2 pellets).
- 17 x 17 fuel pins per assembly – based on the Sizewell B PWR.

- Various insert materials, including: cast iron, void, water and boronated stainless steel and at various densities.
- A range of separations between fuel assemblies (1, 5, 10, 15 & 20cm).
- Flooding of the void space by a range of water densities (0 to 1 gcm^{-3}) to represent void, water mists and full flooding.
- The lodgement walls (the structures contain the FA) were generally modelled as boronated stainless steel at various thicknesses and with various levels of Boron (0.8% to 4% in steps of 0.2% - the industry norm is for about 1.2%), although other materials were also considered.
- Adding flux traps (water + slabs of boron, boronated stainless steels and some other material) to the DCTC.

All criticality calculations were carried out using the MONK8 criticality code with JEF2.2 nuclear data [5,6]. Automated parameterisation routines, available within the MONK code, were used to set up the surveys. Submission of the criticality models to a Beowulf (a cluster of about 100 CPU cores) was handled by Codemore [7]. Each criticality calculation took about 5 minutes to run, allowing about 2000 models per hour to be calculated – the entire set of models can be calculated within about a day or so (although this neglects the considerable time needed for model development, checking and result processing).

7. CONCLUSIONS

Clustered PCs and automated criticality codes can provide a valuable aid for assisting in the design of transport packages – ideas can be tested thoroughly and quickly.

The complete analysis shows that none of the options are completely free from one sort of difficulty or other; a synopsis is provided in Table 2. In summary only the following options appear to be capable of accommodating all of the fuels of current interest (though all of the options can accommodate some of the fuels):

- **Multiple water barriers**: The approach is appealing in that it largely excludes a factor with large safety impact (water) from consideration, thus greatly simplifying the criticality assessment. Another advantage would be that the criticality assessment would be largely independent of fuel parameters (eg fuel rod diameter), except for the pre-irradiation U235 enrichment. Also consideration of fuel damage states (eg birdcaging, fuel debris), which are often difficult areas of study, would probably be unnecessary.

- **Adding conventional flux traps** Amending the package design to include neutron absorbers in a conventional arrangement (ie neutron absorbing plates in a wet package) is a likely strategy for success. However, this would require major changes to the design of the copper canister and DCTC.

The remaining options, by themselves, do not appear to be capable of accommodating the full range of fuels of current interest. (Further work is needed on the use diluents to establish whether they would be effective on their own).

There are a number of hybrid approaches – that is making use of two options simultaneously – with the potential to allow the transport of the full range of fuels of current interest:

- sand + burn-up credit,
- sand + boron in the insert
- sand + a reduced payload
- boron in the insert + burn-up credit

8. REFERENCES

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Table 2: Summary of DCTC Criticality Analysis

(The success criterion is to be able to make an application for 4 x FA up to about 5% enrichment)

Success?	Option	For	Against
X	**Reduced payload** (one, two or three FAs)	• Use existing SKB canister without modification. • Effective for some fuels.	• Even 1 x FA per package is likely to exceed the safety criterion for some fuels. • Would greatly increase the number of transports – cost and public acceptability issues. • Operational controls would be needed – unless insert is modified • **On its own this option is not sufficient to guarantee criticality safety for all UK fuels (see Section 1) of current interest.**
✓	Amending the package design to include **conventional flux traps,** ie fixed neutron absorber plates and moderator (eg water or resins)	**Could probably be used for the transport of all fuel types.** • Conventional and uncontroversial approach to criticality safety. Very safe– “engineered-in”	• Complete redesign of DCTC and canister. • Relatively expensive? • Unknown implications for cost, package performance etc. • Environmental problems for disposal?
X	Amending the package design to include **neutron absorbing materials in the insert,** eg boron uniformly mixed with the iron.	• Conventional and uncontroversial approach to criticality safety. Very safe– “engineered-in. • Would be effective for some fuels depending on boron content.	• Design changes to insert • Unknown implications for cost, package performance etc. • Environmental problems for disposal? • **On its own this option is not sufficient to guarantee criticality safety for all fuels of current interest.**
X	Amending the package design to include diluent materials (eg **sand**) in the void space to reduce the density of the water considered in the criticality assessment.	• Minimal changes to existing concept. • Probably avoids consideration of fuel debris, birdcaging etc. • Would be effective for all fuels up to about 4% initial enrichment, and perhaps greater enrichments. • Might be more effective if diluents included with neutron absorbers	• There may be insufficient reduction in K to meet the safety criterion for some fuels – this will depend on the density of water in the models. This value needs to be established. • Operational controls would be needed • Unknown implications for cost, package performance etc. • Retrieval issues? • **On its own this option may not be sufficient to guarantee criticality safety for all fuels of current interest.**

Table 2: Summary of DCTC Criticality Analysis

(The success criterion is to be able to make an application for 4 x FA up to about 5% enrichment)

Success?	Option	For	Against
✓	Including **multiple water barriers** in the DCTC design.	**Could be used for the transport of all fuel types**. • Small change to existing design ? • Relatively inexpensive? • Simplified criticality assessment - probably avoids consideration of fuel debris, birdcaging etc. • Very tolerant to increases in fuel enrichment. • Independent of fuel types.	• New approach to criticality safety in the UK - Potential regulator resistance • Design change • Design criteria currently unclear. • Possibly enhanced testing requirements.
X	Taking credit for fuel irradiation (“**burn-up credit**”) in the criticality assessment.	• Use existing SKB canister design. • Established criticality methodology. • Tolerant to increases in fuel enrichment. • Would be effective for some fuels depending on initial enrichment, irradiation and BUC methodology.	• Insufficient reduction in K to meet the safety criterion for some fuel burn-ups • Increased criticality assessment costs. • Potential regulator resistance - little experience of BUC in UK. • Additional operational controls on loading and monitoring requirements. • Assessment gains may be offset by additional pessimisms. • Little use for low burn-up, high initial enrichment fuels. • Current methodologies only defined up to 5%U235 enrichment, 50,000 MWd/tU. • **On its own this option is not sufficient to guarantee criticality safety for all fuels of current interest.**
✓	**Hybrid approaches**	**Could be used for the transport of all fuel types, namely**: • sand + burn-up credit, • sand + absorbers in the insert and • sand + a reduced payload • boron in the insert + burn-up credit	• More complicated criticality safety assessments. • Issues as above (but to a lesser degree).