CRITICALITY CONSIDERATIONS RELATING TO THE UKs FIRST LICENSED MWB PACKAGE (M4/12.UFC MK-III)

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Abstract: The NDA's programme of managing the UK's historic nuclear legacy includes the re-disposition and/or consolidation of fissile materials. The paper is based on a real project.

This paper discusses aspects of legacy fuels which can be important to the transport criticality safety case and how they differ from fuels from thermal reactors. The legacy fuels are predominantly from experimental and/or fast reactors. The issues addressed include inventory determination and uncertainty, fuel damage from impact and corrosion and validation of the criticality calculations.

Use of an existing previously licensed 'conventional' Single Water Barrier (SWB) package with modifications to enable a Multiple Water Barrier (MWB) design has been employed to transport the materials.

This has involved extensive collaborative work from various organisations and disciplines to gain the UKs first MWB approved package.

The criticality aspects of the MWB design are discussed.

Keywords: Criticality, Transport, Multiple Water Barrier

1. INTRODUCTION

The Nuclear Decommissioning Authority's (NDA) programme for managing the UK's historic nuclear legacy includes the re-disposition and/or consolidation of fissile materials. The inventory includes unirradiated fast reactor fuels and an assortment of 'miscellaneous' fissile materials from mainly UK nuclear establishments. The unirradiated material was originally intended for irradiation in the Prototype Fast Reactor (PFR) or destined for reprocessing, however due to the closure of the PFR and reprocessing facilities the material was placed in short term storage.

M4/12.UFC MWB package

The existing 'M4/12 package', previously licensed to transport PWR and PFR MOX fuel, has been modified to enable the licensing of the UKs first Multiple Water Barrier (MWB) design package.

The paper is based on a real project and discusses the challenges associated with the criticality safety aspects of the MWB Package. It is not intended to provide a definitive interpretation of IAEA Transport Regulations or guidance on the design/use of MWBs. Neither a complete description of the package/materials transported nor the consequential improvements to operational and plant safety is discussed. Two further papers presented at PATRAM 19 discuss the engineering [1] and licensing [2] of the MWB package design.

2. INTERNATIONAL NUCLEAR SERVICES (INS)

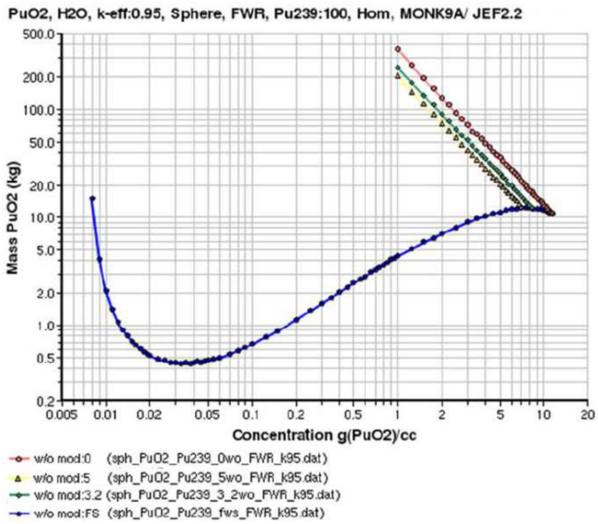
INS is a wholly owned subsidiary of the NDA who specialise in providing a complete nuclear transport system. INS' Engineering Technical Team have a wealth of experience in the design and licensing of Radioactive Material (RAM) Transport Packages and were commissioned to adapt the M4/12 to enable a MWB design package.

3. A DEFINITION OF CRITICALITY SAFETY

Fissile materials (defined in Para. 222 of SSR-6 as U-233, U-235, Pu-239 & Pu-241,) are capable of supporting a 'nuclear chain reaction' which may leading to a criticality accident and consequential high radiation level/dose rates.

The criticality of a system is often discussed in terms of the effective neutron multiplication, or 'k-effective'. K-effective is defined as the ratio of neutron production to neutron loss; for a system to remain subcritical, k-effective must be < 1.0. A safely subcritical system (typically with k-effective <0.95) can be maintained by ensuring adequate control of the parameters that affect the neutron balance (the mass of fissile material, enrichment, fissile material geometry, neutron poisons, moderation/neutron energy, neutron reflection, etc.).

If water is present the mass of fissile material needed for criticality is reduced, for example, a sphere of less than 10 kg of dry plutonium will not be critical, if water is added the "critical mass" reduces to around 0.5 kg.



PuO_2 safe mass vs moderation

The geometry in which the fissile material can accumulate also affects the potential for criticality (e.g. fissile material which is safe with cylindrical geometry may be unsafe with spherical geometry) IAEA Transport Regulation [1] requirements for fissile packages necessitate the design and transport to be in such a way that an accidental criticality is avoided.

4. THE 'PROBLEM' - REGULATORY REQUIREMENTS RELATING TO CRITICALITY ANALYSIS OF THE FWR SINGLE PACKAGE

The IAEA transport regulations [3] demand specific requirements for packages containing fissile materials. Sub-criticality must be maintained during routine, normal and accident conditions of transport (NCT/ACT) (Para. 673 [3]). Specifically, where the chemical/physical form, the isotopic composition, the mass/concentration, moderation ratio or geometric configuration is not known, assumptions in the criticality analysis have to assume that the unknown parameters have values to maximise k-effective consistent with the known conditions for the fissile material (Para 676.).

In addition, for the single package water leakage into (or out of) all void spaces, including those within the containment/confinement system, must be assumed in the criticality analysis. This is regardless of the integrity of the package following the standard Regulatory tests, unless *special features* to prevent the leakage of water are incorporated into the package design. The special features include Multiple high standard Water Barriers (MWB) (Para. 680 [3]), at least two of which would remain watertight under the prescribed IAEA tests .

In effect, for ACT the criticality safety analyses must depict the packaging and contents to be in the most reactive configuration consistent with the worst credible chemical and physical form of the fissile material. In addition if the package is a single water barrier (SWB) design the moderation state of the fissile material should be such that the maximum credible k-effective is determined.

There is a Regulatory requirement to address the potential movement of water across each of the distinct barriers, even with a MWB design. For ACT water must be assumed to penetrate the first barrier and 'border' the second inner barrier. Though not being able to intimately mix with the fissile material, this has the potential to provide increased neutron reflection and augment k-effective.

5. CRITICALITY ASSESSMENT FOR TRANSPORT PACKAGES & THE ADVANTAGES OF A MWB DESIGN

For transport packages the key aim of the criticality safety assessment is to identify a set of parameters which allow a reasonably economical method (in terms of payload) of transporting the intended fissile material but which also provide sufficient fault tolerance for accident conditions to ensure inadvertent criticality is avoided. For a SWB design package, where the fissile mass and geometry are well defined (e.g. fuel assemblies held in lodgements, powder held in tins), it is more typically the moderation state of the fissile material that effects the reactivity of the system. If the fissile material can be guaranteed to remain dry then it may be easier to demonstrate a system remains safely sub-critical even if the geometrical configuration is subject to change.

For a package which under NCT is transported dry, water ingress is the single most significant damaged condition, in terms of causing an increase in k-effective. For an unmoderated system, other solitary damaged conditions, e.g. fuel damage, collapse of spacing between fissile regions, etc., are relatively inconsequential in terms of presenting a criticality safety hazard. Addition of a moderating material into the package cavity, particularly if the fissile geometry is undermined, can substantially increase reactivity and cause the greatest criticality hazard.

6. THE M4/12 TO TRANSPORT PWR MOX FAs (ORIGINAL SWB DESIGN)

INS have access to a previously licensed SWB 'dry' (as presented for transport) package; the M4/12. In regulatory test (as specified in SSR-6), the M4/12 was demonstrated to suffer no significant damage and to remain leak tight.

The M4/12 was originally designed and licensed to transport unirradiated Pressurised Water Reactor mixed oxide (PWR MOX) fuel assemblies (FA) in the UK and Europe.

M4/12 package for PWR fuel assemblies

The four lodgements of the existing fuel basket within the M4/12 are square in cross section, with walls manufactured from boronated aluminium to maintain criticality safety during assumed water ingress for ACT as necessary for a SWB package.

A single, square pitched PWR MOX FAs can be housed within each of four lodgements. The known integrity of the fresh FAs coupled with the package design, ensure criticality safety can be demonstrated for all NCT & ACT, including water ingress.

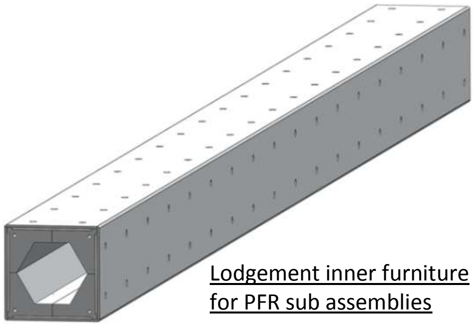
7. THE MODIFIED M4/12 TO CARRY PFR MOX SA'S (AS SWB DESIGN)

More recently, with some modification, the M4/12, as a SWB design, has been used to transport unirradiated Prototype Fast Reactor (PFR) MOX sub assemblies (SA) as part of the UK Government's strategic objective to consolidate fissile materials onto a single nuclear site.

Though both containing MOX fuel, PWR FAs are designed for irradiation in light water 'thermal' reactors, whereas PFR SAs are designed for irradiation in a metal cooled 'fast' reactor. Consequently, PWR and PFR assemblies are fundamentally different in design. For example; PWR FAs have a square cross section with pins arranged on a square pitch and an overall length of ~5 metres. PFR SAs have an overall smaller cross sectional area with pins of smaller diameter arranged on a triangular pitch surrounded by a wrapper, their overall length is ~4 metres. Additionally and possibly most challenging, PFR MOX has a significantly higher fissile content, of around 30 wo Pu/HM, compared to PWR MOX which is around 6 wo Pu/HM.

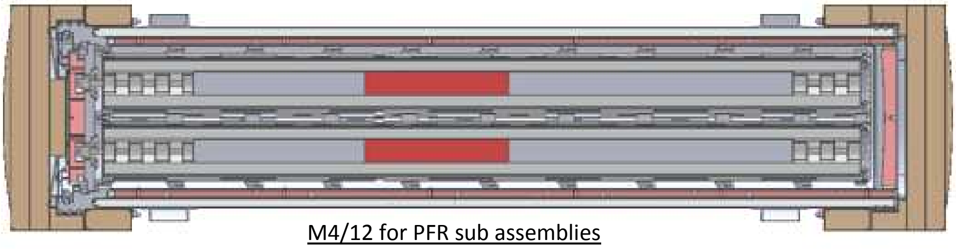
Modifications to the package, required to allow its use for the transport of hexagonally pitched PFR SAs, include provision of inner lodgement liners to restrict potential damage to the SA/pin array.

The M4/12 was originally designed such that each lodgement could securely accommodate a PWR FA, both cross sectionally and axially. As PFR SAs are smaller in both cross sectional area and length, each is housed within additional lodgement 'furniture', designed, by INS, comprising impact limiters within an aluminium liner, with square external and hexagonal inner profile. This effectively shortens and narrows each of the lodgements to accommodate the smaller PFR fuel assemblies.



Lodgement inner furniture for PFR sub assemblies

The PFR SAs are well characterised and their physical integrity intact, such that at the time of transport the fissile material could be demonstrated to be robust, by impact analysis, resulting in retention of fissile material within the pin cladding, i.e. there would be no release of fissile material into the package cavity. This was achieved by limiting the degree of deformation/damage to the SA array by restricting the available geometry within the lodgement liners.



M4/12 for PFR sub assemblies

For this specific case a MWB design package was not required.

8. INCENTIVE FOR MWB DESIGN – THE FISSILE MATERIALS

The material to be transported had been in storage for an extended period of time, ~30 years. An inability to justify the integrity of a large proportion of the fissile materials indicated an assumption of unlimited break-up in justifying criticality safety for ACT. This combined with water ingress would have the potential to increase package reactivity unacceptably.

INS judged the most favourable solution, in terms of timescale and package payload, to be a 'secondary boundary' which would be substantiated to remain leak-tight and maintain containment during all conditions of transport. This additional boundary the Mk-III Unirradiated Fuel Container (UFC) acts simultaneously with the M4/12 containment boundary to provide a high standard Multiple Water Barrier (MWB) system.

9. WHY DO WE NEED A MWB FOR THESE MATERIALS

The fissile materials are old and their physical state is unknown

As the fuel may be in poor condition there is a possibility that it could break up, releasing "free" fissile material from the pin cladding

The materials are packed into cylindrical containers (UFC), with bespoke internals. These provide some control over the geometry the fissile material can adopt. If the material were to escape from the pin clad it would be contained within the UFC/internals, designed to maintain a safe geometry for dry fissile material.

Without a MWB package, the payload for each M4/12 could be reduced from 600 kg MOX to 8 kg or less.

10. DETAILS OF THE MISCELLANEOUS FISSILE MATERIALS AND WHY THEY REQUIRE A MWB DESIGN

The legacy fuels are predominantly from experimental and/or fast reactors. They can be described as miscellaneous fissile materials comprising uranium and plutonium as mixed oxide, carbide or HM. The majority of the materials have a high fissile content and are in the form of pins and bars, held in containers and/or as ‘clusters’

Though un-used, the age and length of time in storage, compounded with the impracticalities associated with inspecting the unirradiated materials caused concern regarding the integrity of components. That is, it is difficult to confidently demonstrate the fissile material will remain within the pins. This has the potential to cause contamination and/or storage issues but also makes demonstration of criticality safety for transport extremely challenging.

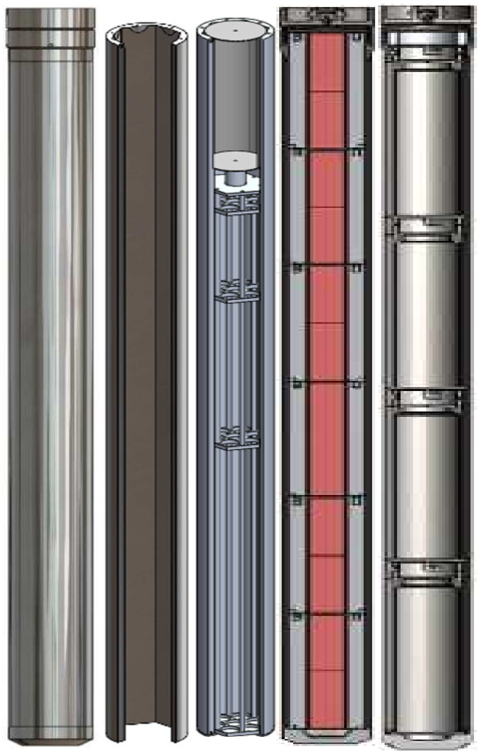
To enable the transport of high quantities of these materials with adequate margins of sub-criticality, it was necessary to demonstrate the exclusion of water from the proximity of the contents under all conditions of transport.

The miscellaneous fissile materials are different both physically and compositionally as they are derived from distinct locations and intended uses. However, with a total heavy metal mass of ~2,700 kg, they can be separated into five main categories for consideration in the criticality analysis:

- PFR mixed carbide SAs and MOX clusters (fixed physical form); with ~30 wo Pu/HM and U(nat)
- PFR MOX pins (held loosely in containers); with ~30 wo Pu/HM and U(nat)
- DFR Mixed carbide and MOX loose pins (held in containers); with ~30 wo Pu/HM and U(enr)
- MOX pins (held loosely in containers); with ~34 wo Pu/HM and U(nat)
- HM/MOX bars/pins (held loosely in containers); with ~1.5 wo Pu/HM and U(nat)

11. MWB: THE SECOND WATER BARRIER OR THE UNIRRADIATED FUEL CONTAINER (UFC)

The M4/12 flask has been demonstrated to meet the leak tightness requirement via drop testing for the original LWR MOX package. Design of an inner container, which externally is physically compatible with the a M4/12 PWR basket lodgement, can be demonstrated to maintain leak tightness distinctly from the M4/12 and can be adapted internally to house a large range of different fissile contents.



UFC inner furniture for miscellaneous fissile materials

This provides two high standard water barriers between the outside of the package and the contained fissile contents. The M4/12 transport package providing the first line of protection and the inner container or ‘Unirradiated Fuel Container’ (UFC) providing the second water barrier.

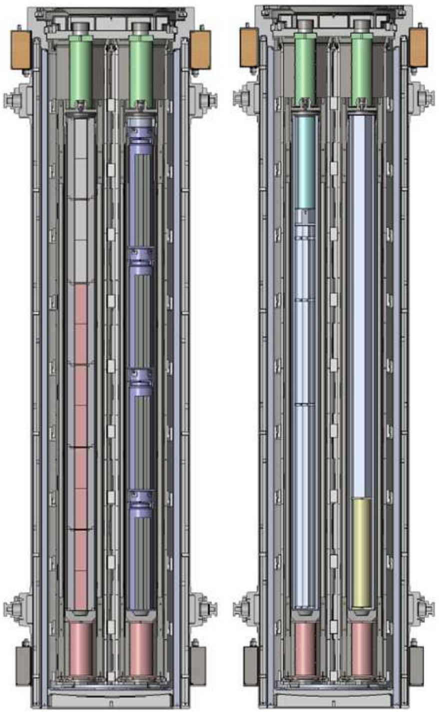
Each UFC provides a second barrier to water between the outside of the package and the fissile content. A UFC is, essentially, a four metre long/quarter metre diameter cylindrical stainless steel pipe with a thick chamfered base.

The UFC base is welded to the main body prior to loading and the lid welded to the opposite end following inventory loading.

Several different UFC internal furniture arrangements have been designed, to facilitate the shipment of different fissile contents. The UFC inner furniture comprises aluminium extrusions or items of welded stainless steel construction to support the various containers of materials, fuel pins and uranium bar material.

12. THE MODIFIED M4/12 TO CARRY MISCELLANEOUS FISSILE MATERIALS (AS MWB DESIGN)

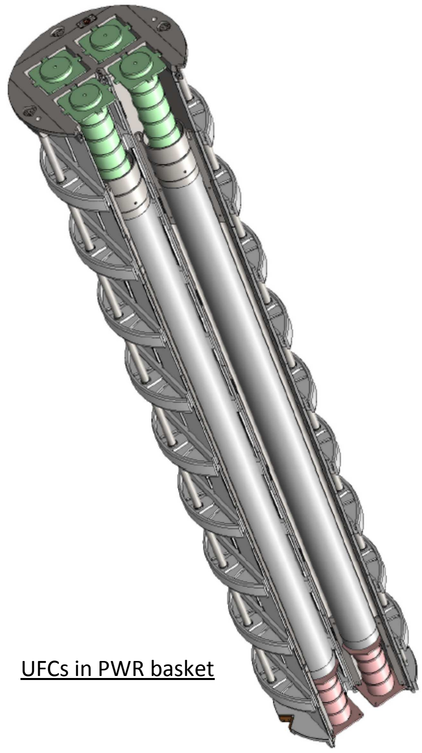
Release of fissile material becomes a problem in assessment of a single package for a SWB package. Unless a MWB package is utilised the assumption for demonstration of criticality safety must be one for full water flooding so that water intimately mingles with/around the fissile material to produce "optimised" conditions to enhance k-effective.



UFCs within M4/12 with alternative inner furniture

This would effectively indicate an optimised uniform mixture of fissile material and water "sludge" in any geometry in any location within the package cavity. This would restrict the fissile payload (at ~35 w/o Pu/HM) to approximately 10 kg MOX.

Uncertainties in fissile material damage/release may increase if the fissile material is present in a less well-defined or justifiably robust form, e.g. as loose miscellaneous items.



UFCs in PWR basket

The fissile material is transported in UFCs to reduce the potential for release of material into the package cavity during transport.

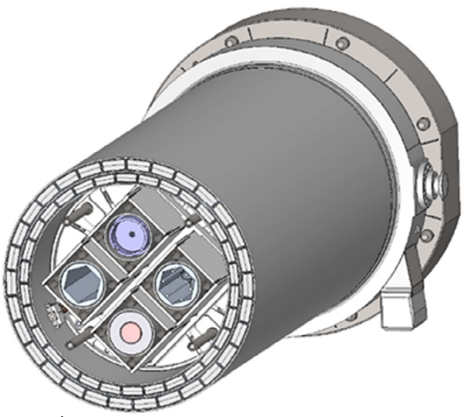
While the containers place some limit on the geometry the fissile material can attain within them, they cannot provide 'safe' geometry' (from a criticality viewpoint) for optimally moderated conditions given the physical dimensions of the materials to be transported (unless repackaged first which would incur other risks). In the absence of a MWB transport payloads may have been restricted. The UFCs are each able to be justified as providing a high integrity water barrier.

In combination with the flask this gave a MWB system for the fissile contents and the criticality assessment was able to be made without taking any credit for limited damage to fissile items.

M4/12.UFC MWB lid arrangement

13. THE M4/12 AND MODIFICATIONS TO FACILITATE ITS USE AS A MWB PACKAGE

The M4/12 package can still be utilised but more restraint is required for the geometry of fissile materials. In addition there is a requirement to eliminate the gross ingress of water into the regions occupied by the fissile material.

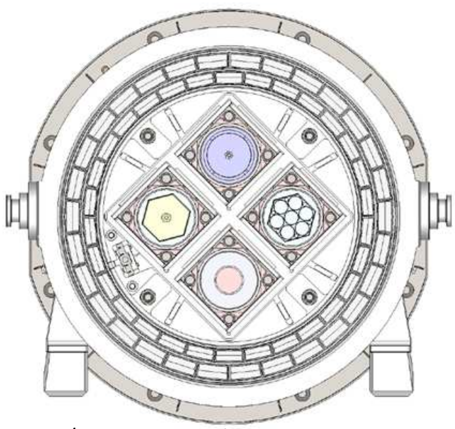


M4/12.UFC MWB alternative contents

So why use an existing package? Primarily due to the financial and operational benefits, both for the facilities involved and for the transport phases of the operation. Since there is previous experience and knowledge of handling the package and the associated equipment both on plant and during transport. In addition there is a valid package licence and an existing plant safety case.

INS' MWB package is justified using the M4/12 package (justified not to leak during NCT/ ACT via drop test and leak testing) to provide the first water barrier and the newly designed bespoke welded inner 'Unirradiated Fuel Containers' (UFC) providing the second barrier.

The M4/12 package remains as it was for transport of PWR FAs excepting the modifications made to accommodate up to four unirradiated fuel containers (UFC) each housing unirradiated fissile material.



M4/12.UFC MWB alternative contents

Lodgement 'furniture' designed to enable the UFC to be carried within the lodgements of the PWR basket also incorporates components to reduce the effect of impact loads in the event of an accident.

The UFCs provide some geometrical 'control' for the fissile contents. Further geometry limits are provided by UFC 'internal furniture' which further increases the capability to carry larger mass of fissile material. The design overall ensures criticality safety is maintained during normal and envisaged credible accident conditions.

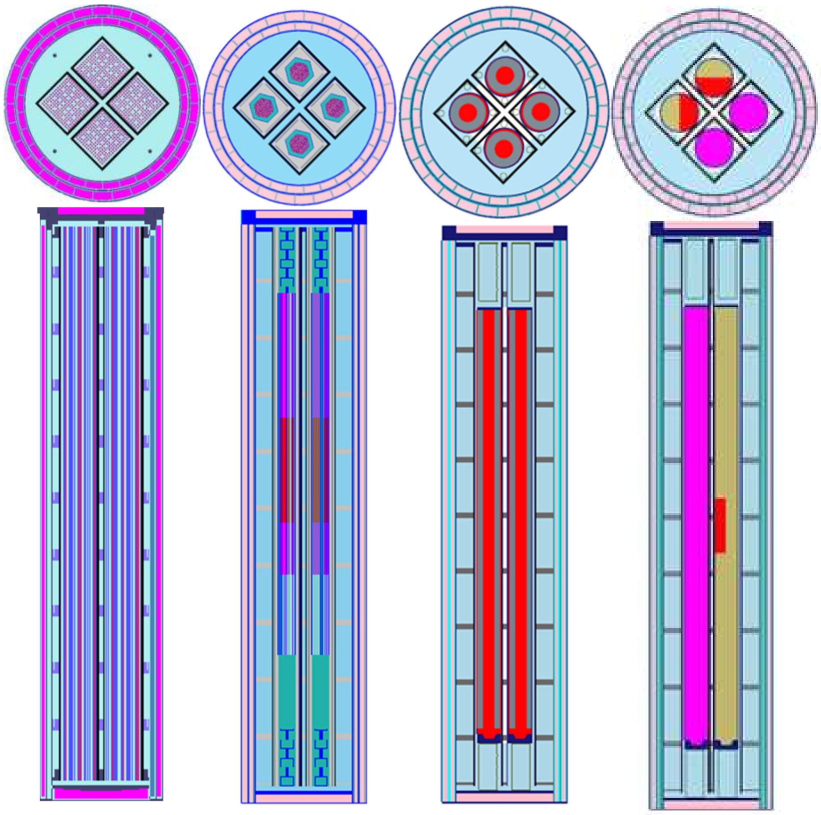
14. CRITICALITY SAFETY ANALYSIS FOR THE M4/12.UFC MWB PACKAGE

The criticality safety assessment for the M4/12.UFC MWB package was completed using the Monte Carlo neutronics code MONK 9A with the JEF2.2 nuclear data library. Survey calculations were performed using pessimistic values throughout to determine peak values for k-effective, the measure of criticality safety, to bound all transport conditions.

The requirement to assume the addition of bulk water into a "dry" package can significantly increase the reactivity of a system and reduce the mass of fissile material required to form a critical assembly. The primary effect on package limits is usually that of increased moderation of fissile material.

Though full water flooding into the fissile material need not be considered for the M4/12.UFC MWB package, partial flooding does need consideration. Water must be assumed to leak into the M4/12 flask cavity, though not into the UFCs. This may result in the efficient reflection of neutrons within a package back into the fissile material, thus augmenting reactivity.

For the MWB design package, partial flooding creates the most onerous condition for the fissile material within packages as the neutron interaction between adjacent assemblies is enhanced with less neutron leakage to the extremities of the package.



M4/12 SWB & MWB package alternative inner furniture. Criticality models

An impact accident could feasibly lead to rupture of the fuel pin cladding and subsequent release of fuel particulate due to cracked/damaged pellets. Due to the age and unknown condition of the fissile materials it is challenging to demonstrate that the pins are not significantly damaged as a result of an impact and so to justify a conservative value for released mass of fuel. Consequently, without sufficient plausible reasoning it is necessary to assume a large proportion of fuel is released into each of the UFC cavities. With a high mass of 'free' fissile material and water ingress modelled, it would be impossible to demonstrate an adequate margin to the applied criticality safety criterion.

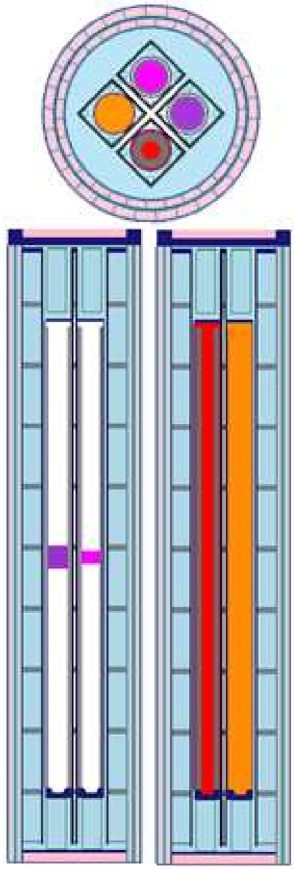
The MWB means there is no need to assess the effects of water crossing both barriers, e.g. from outside the package into the inner container.

For the single FWR package there is still a need to assess the effect of water crossing individual boundaries, e.g. from outside the package entering the package body (where it may provide reflection around the inner container) or moisture present within the package body when loaded entering the inner container.

The potential quantity of moisture needs to be justified; i.e. the mass of residual water for example from humidity in the air when fissile materials are loaded into the UFCs and UFCs into the M4/12.

The assumptions made in the criticality assessment provide a pessimistic representation of any potential real condition due to fracture and liberation of fissile material and for intimate mixing of water with the fissile contents during normal or damaged conditions of transport.

With the potential for water ingress to the UFCs removed, the use of the MWB package allows the ultimate consideration that the fuel pins are completely destroyed. All the fissile material is assumed to be liberated within the available volume within UFC/inner furniture cavity, in the most optimised geometrical arrangement. With a lack of moderation, since the package cavity is void from water due to presence of the MWB, the criticality safety margin is maintained.



M4/12.UFC MWB package alternative inner furniture. Criticality model

15. Conclusions

The use of MWB design packages for fissile materials has enormous advantages during the criticality consideration of single package calculations. The low values of K-effective for normal and damaged conditions due to impact accident demonstrate the large margin of criticality safety inherent in the package.

Even with extreme optimised conditions for dry fissile material, k-effective is well within the applied criticality safety criterion. The assumptions provide a pessimistic representation of any potential real damaged condition for the fissile payload.

M4/12.UFC MWB package for miscellaneous fissile materials

The M4/12 package was identified at an early stage in the programme as a solution to transporting these materials. The flask and fuel basket, originally designed for the transport of unirradiated LWR MOX FAs, were enhanced to include internal components, engineered to facilitate use of the UKs first MWB package. This has enabled the successful shipment and consolidation of fissile materials in line with the NDA’s programme for managing the UK's historic nuclear legacy.

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