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A Criticality Perspective on Multiple Water Barriers for Fissile Material Transport Packages

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Abstract: *New packages have been identified and are under development by INS to facilitate the re-disposition of fissile materials under the NDA's programme of managing the UK's historic nuclear legacy. The development of new fissile material transport packages is an increasingly complex and costly business, and much time is spent on 'future-proofing'.*

The IAEA regulations stipulate performance requirements for the behaviour of the package under both normal and accident conditions. According to Paragraph 677 of the IAEA transport regulations (2009 Edition), for fissile material package designs, the criticality safety assessment must assume that water leaks into or out of all void spaces within the single package. This is irrespective of the integrity of the package following the IAEA standard tests, unless 'special features' to prevent such leakage of water are incorporated into the package design. These special features include Multiple high standard Water Barriers (MWB).

Water is an efficient moderator of neutrons, i.e. it possesses the ability to reduce the energy of fast neutrons down to thermal energies, which will then have an increased probability of causing further fissions. Hence the requirement to assume the addition of 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. If water ingress can be prevented, criticality safety will be guaranteed for the particular package design.

The new packages developed by INS for irradiated and unirradiated fissile materials will feature MWB technology which will enable safe transport of optimised payloads. The paper presents, from a criticality viewpoint, examples of the advantages of package designs incorporating MWBs for transport of a variety of fissile materials.

Keywords: *Criticality, Transport, Multiple Water Barrier*

INTRODUCTION

Internationally, the transport of radioactive materials is carried out in accordance with the IAEA Regulations. These are a set of rules and regulations which provide safety standards for transport in the public domain for packages containing radioactive materials. The IAEA Regulations have been agreed internationally and demand a very high standard of safety. So much so that there has never been a criticality accident involving a certificated transport package.

Development of fissile material transport packages is multifaceted and requires consideration of many different safety aspects, e.g. , criticality safety, thermal analysis, shielding analysis/dose uptake, structural integrity/impact performance, radiological safety/containment, etc, the requirements of these different disciplines can often compete, with fine tuning often required to optimise the design of a package.

If one or more of the speciality safety areas can be simplified this could potentially condense the overall process. For some packages it may be possible to establish criticality safety through passive engineered features which provide robust protection. (e.g. intrinsic properties of fissile material - safe by mass and/or enrichment). It is more likely that packages will require engineered protections by design (e.g. spacing of fissile masses within package, fixed neutron poisons, limitation of intimate moderation – i.e. Multiple (high standard) Water Barriers (MWB)). The use of a MWB would undeniably simplify the criticality safety case for a package. The reasons and benefits are explored herein.

The IAEA regulations stipulate performance requirements for the behaviour of the package under both normal and accident conditions. According to Paragraph 677 of the IAEA transport regulations (2009 Edition), for fissile material package designs, the criticality safety assessment must assume that water leaks into or out of all void spaces within the single package. This is irrespective of the integrity of the package following the IAEA standard tests, ***unless*** 'special features' to prevent such leakage of water are incorporated into the package design. These special features include MWBs.

This paper explores the advantages of the inclusion of a MWB on criticality safety of a package – it does not justify principles of design, i.e. the definition of what a MWB should include from an engineering viewpoint. In addition the presence of residual water in the packages prior to transport, or that which could be present due to minor in-leakage as a result of immersion testing as required by TS-R-1 #729, 730 and 733, is neglected. For the purpose of this paper it is assumed that the package is completely dry with the exception of any moisture present within the fissile material as stipulated by any conditions of acceptance (e.g. a moisture content of $\leq$ 3.2 w/o moisture is typically cited for PuO_2 powders)

The examples included herein are not necessarily for authentic package designs, i.e. the package design may exist but without the inclusion of a MWB. Nevertheless the examples do demonstrate the real advantages of how MWBs can improve criticality safety and payload capacity.

The benefits of a MWB may also depend strongly on the size and make-up of the packaging outside the confinement area. For lightly constructed packages, with less outer package shielding, the potential for neutron interaction between fissile packages in arrays is enhanced. For this package type, and depending on the particular fissile material, the benefits of a MWB may be less significant. For heavier packages – such as those used in the transport of irradiated fuel assemblies there is little neutron interaction between packages in arrays, in this case k-effective for an infinite array of packages is analogous to that for a single Fully Water Reflected (FWR) package – and often the single package calculations form the bounding case in terms of criticality safety.

CRITICALITY CONSIDERATIONS

Criticality safety is based on the control of one or more of the key factors which affect the neutron balance, e.g. mass of fissile material, enrichment, geometry, poisons, moderation, reflection, interaction/isolation between packages in arrays.

The criticality of a system is often discussed in terms of the effective 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 less < 1.0. A safely subcritical system can be maintained by ensuring adequate control of the parameters that affect the neutron balance.

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.

MODERATION AND FISSILE MATERIALS

Neutrons are released from fission with substantial kinetic energy. Collisions between neutrons and the nuclei of the surrounding material can cause the neutrons to lose energy and slow down. This process is known as moderation and has a vital influence on criticality safety.

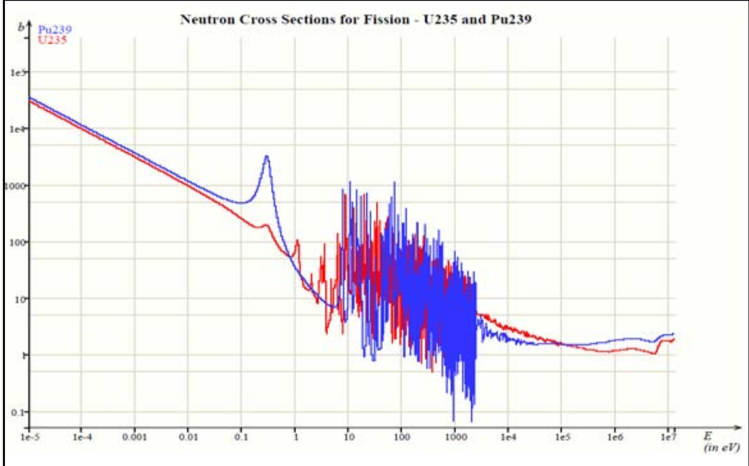


Figure 1: Neutron Cross Sections for Fission - Pu-239 and U-235

The amount of neutron energy lost in a collision depends on the mass of the nucleus involved; a large nucleus, such as that of uranium, would cause negligible energy loss, the neutron would simply 'bounce off' after collision.

Light nuclei, such as deuterium and carbon, are especially efficient in slowing down or moderating neutrons by scattering reactions. Hydrogen is particularly effective at reducing incident neutron energies as its mass is comparable to that of a neutron. On average, a neutron will lose half its energy in a collision with a hydrogen nucleus , thus hydrogen is an example of a good moderator. Eventually after repeated collisions with nuclei (if not absorbed) the neutron's speed will reach equilibrium with the particles in the surrounding material – this is a "thermal neutron".

Fissile nuclei are those which can fission after absorbing neutrons of any energy. The probability of a fissile nucleus undergoing fission (known as the fission cross section) varies both with the type and form of the fissile material and also depends on the energy of the incident neutron – with thermal neutrons increasing the likelihood. The critical mass of fissile materials is lowest in a well-moderated, thermal system. It so follows that the addition of a good moderating material can significantly increase the reactivity of a 'dry' system and reduce the mass of fissile material required to form a critical assembly.

Water is an excellent moderator due to its high hydrogen content. Depending on the fissile concentration potential increases in k-effective can be significant due to water ingress or loss and the common occurrence of water in nature makes it the major moderating material of concern in criticality safety.

The optimum ratio of moderator-to-fissile nuclei defines the minimum mass of a fissile material that can be made critical in a finite system. This mass generally occurs due to hydrogen moderation.

This effect can be well illustrated for the case of a fissile isotope, first dry, and then dissolved in water at progressively increasing dilution. e.g. for Pu-239 the critical mass falls from several kilograms of unmoderated metal to less than half a kilogram at optimum moderation. The extent of moderation can be expressed in terms of fissile concentration for fully water saturated materials.

REGULATORY REQUIREMENTS AND ASSESSMENT OF THE SINGLE PACKAGE

Additional requirements imposed by the IAEA Transport Regulations for fissile packages necessitate the design and transport to be in such a way that an accidental criticality is avoided.

The transport criticality safety assessment must consider various parameters to ensure the package will remain safely subcritical in both normal and accident conditions of transport. The analyses must depict the packaging and contents to be in the most reactive configuration consistent with the chemical and physical form of the fissile material.

Water has a significant effect on the reactivity of fissile material. Current regulatory requirements for damaged conditions demand that the criticality analysis for the single package must assume water can leak into or out of all free space within the package (including partial/differential flooding). This includes the space within the confinement system, to ensure the maximum credible k-effective is determined.

The assumption of water ingress is regardless of Regulatory test results - unless the package design particularly incorporates ‘special features’ to prevent leakage of water into or out of void spaces. Special features are defined to include Multiple Water Barriers (MWB), at least two of which would remain watertight under the IAEA prescribed tests .

Provided that Regulatory test results demonstrate a package to remain leak tight there are no specific requirements to assess ‘bulk’ water ingress for package arrays, bulk water ingress is required for the single package only in the absence of a MWB.

There are obvious financial and operational benefits in having higher package payloads and higher numbers of packages in a consignment for both the facility and transport phases of operation. Design options that depend on limiting mass, dimensions or concentration are often needed for safety, but are often a low priority design option because of payload reductions. Similarly, control by separation of fissile material takes too much valuable package space.

Hence the design option to provide special features to prevent water in-leakage (i.e. MWB) is an attractive alternative, as this eliminates the need for consideration of water ingress into the package during the criticality safety assessment.

Nevertheless, requirements stipulated by TS-R-1 #729, #730 and #733 of IAEA Transport Regulations still need to be addressed for MWBs. In the accident condition water is assumed to have penetrated the first barrier and filled the outer containment vessel, or secondary containment; the seals on the primary containment will have been demonstrated to a certain standard of leak tightness in the accident condition. If, for example, this is a gas pressure-drop test, the results can be converted to an equivalent water leakage rate, and factored according to the time and external pressure to calculate a volume of water inleakage.

ADVANTAGES OF A MULTIPLE WATER BARRIER DESIGN FISSILE PACKAGE

For a high proportion of fissile packages, leak tightness is usually demonstrated following impact testing. As such any actual ingress of water into the package cavity is highly unlikely.

For a package which is under normal conditions transported dry, water ingress is the single most significant damaged package 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 effectively insignificant in terms of presenting a criticality safety hazard. Without the addition of a moderating material into the package cavity, the fissile material will generally remain relatively unreactive. Hence it is the addition of water into the 'damaged' system which presents the criticality hazard and not the alternative condition resulting from an independent accident.

Therefore results signifying the effects of damage other than water ingress are actually a consequence of multiple accident scenarios, the principal damaged condition being flooding. Since all additional damaged conditions normally take fully water flooded packages as the basis for further analysis they are enormously pessimistic and fully bound any real accident conditions.

Sensitivity of neutron interaction between packages in arrays varies with the package design. Small, lightweight packages are more susceptible to high neutron interaction than large, heavy packages.

Hence the principal benefit for a package design taking credit for MWB is gained where the most significant increase in k-effective is as a result of water ingress. Particularly for a heavy package where the neutron interaction between packages is insignificant and the single package provides the "bounding" case.

SPECIFIC EXAMPLES

- ***The effect on criticality safety of no water ingress for Pu and U metals***

  For a limited moderation system, fissile material at a higher density provides the minimum critical mass, the mass being significantly higher than that which would occur in a well moderated system when lower fissile density provides the bounding case.

  The safely subcritical mass for limited moisture systems increases sharply as density reduces. For lower density materials (e.g. powders) the safely subcritical mass becomes considerably larger – and typically more than could physically be transported in a single package with a MWB. Conversely, the safely subcritical mass for a fully saturated system reduces as density reduces and the corresponding moisture content increases. Similar trends occur for most fissile materials.

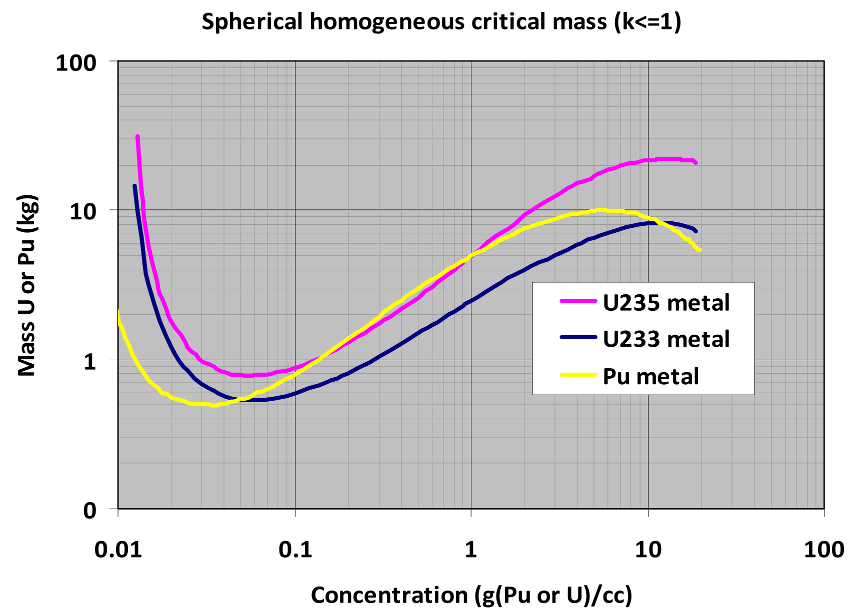


Figure 2: Critical mass curves for Pu239, U235 and U233 metal (with varying moderation) (Data for uniform, homogeneous, fully water saturated, fully water reflected spheres

- ***The effect on criticality safety of no water ingress for unirradiated UO$_2$ fuel assemblies – differential flooding***

Some packages lend themselves to the possibility of "differential" flooding. Water may leak out from one part of the package yet remain in others. This may result in the efficient moderation of the fissile material content of a package but also the removal of interstitial water, which may be contributing to the neutron absorption process between discrete regions of fissile material. This effect is most significant within individual packages.

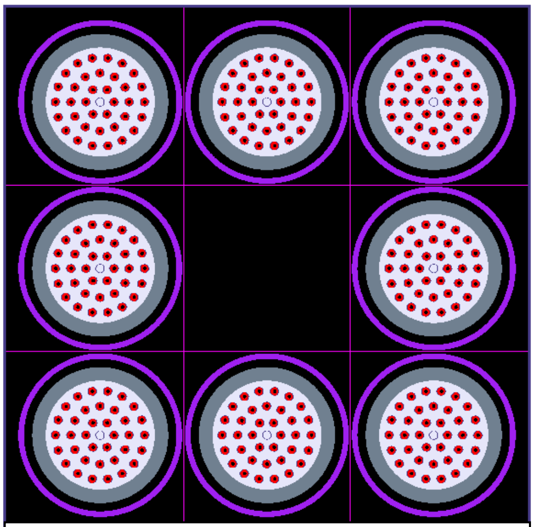


Figure 3: Differentially flooded AGR FA's

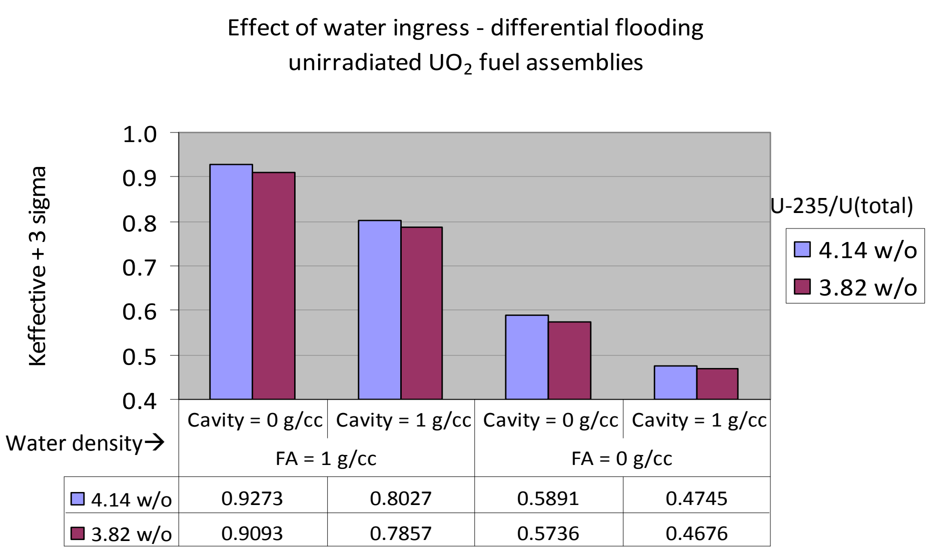
For example AGR fuel assemblies comprise enriched UO$_2$ fuel pins housed within a graphite sleeve. It is feasible that during transport accident conditions the free volume within the graphite sleeve could be fully water flooded such that the fuel pins are well moderated, with the space around the fuel assemblies i.e., the remainder of the package cavity, drained.

Although it is extremely unlikely that the graphite sleeves in each of the eight fuel assemblies would retain water simultaneously within each package in an array it cannot be unconditionally dismissed and hence is given consideration within the analysis.

Differential flooding creates the most onerous condition for the assemblies within packages as both the single fuel assembly reactivity and the neutron interaction between adjacent assemblies is maximised.

If the possibility of the ingress of water is eradicated through design, by including a MWB, the scenario of differential flooding can also be eliminated.

As a result the payload (in terms of number of fuel assemblies and/or enrichments/fissile content) and package numbers in a consignment could potentially be increased.



Water density→	Cavity = 0 g/cc FA = 1 g/cc	Cavity = 1 g/cc FA = 1 g/cc	Cavity = 0 g/cc FA = 0 g/cc	Cavity = 1 g/cc FA = 0 g/cc
▨ 4.14 w/o	0.9273	0.8027	0.5891	0.4745
▨ 3.82 w/o	0.9093	0.7857	0.5736	0.4676

Figure 4: Varying degrees of flooding for AGR fuel assemblies

- ***The effect on criticality safety of no water ingress for irradiated UO_2 fuel assemblies***

During the transport of irradiated UO_2 Light Water Reactor (LWR) fuel assemblies, an impact accident could feasibly lead to rupture of the fuel pin cladding and subsequent release of fuel particulate due to cracked/damaged pellets.

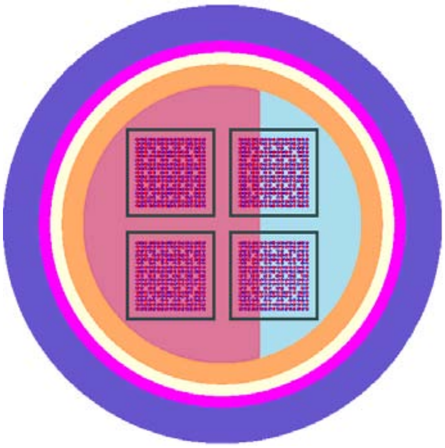


Figure 5: Ruptured fuel modelled as homogeneous sludge

In transport criticality safety assessments for irradiated fuel packages it is typically assumed that a proportion of damaged pins lose some of their fuel. The released fuel is then assumed to be liberated within the package cavity and amalgamated as the most severe conceivable accumulation. Position within the package (i.e. the largest unpoisoned volume), credible orientation (e.g. a sphere, ungula etc) and the fissile concentration are adjusted to maximise k-effective.

A pessimistic value for the fissile mass of fuel which could be released from damaged pellets within ruptured pins is usually derived based on the results of the package impact testing and finite element analysis[*].

For some heavy packages carrying irradiated fuel assemblies it can be challenging to demonstrate that the fuel assemblies 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 is may be necessary to assume a large proportion of the overall fuel mass is released. With a high mass of ‘free’ fissile material and water ingress modelled, it is unlikely that an adequate margin to the applied criticality safety criterion would be demonstrated.

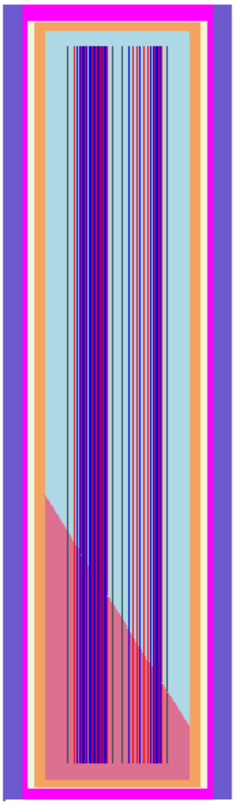
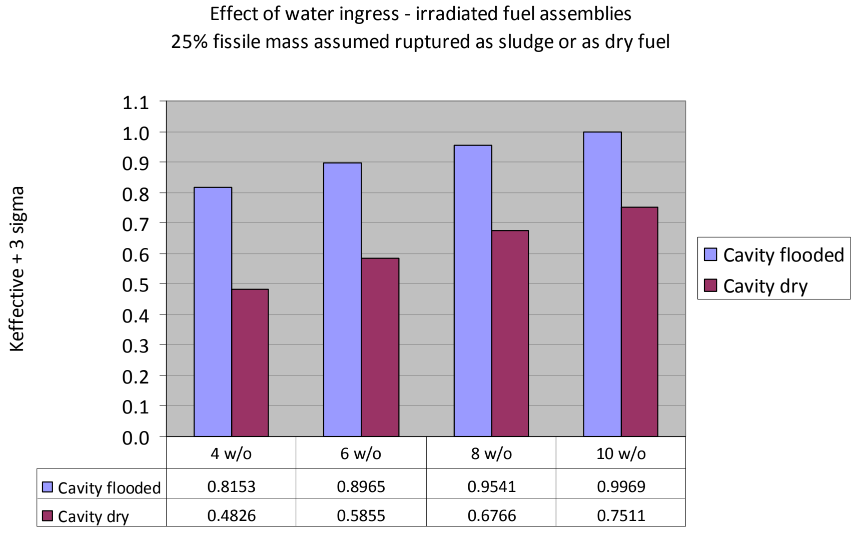


Figure 6: Ruptured fuel modelled as homogeneous sludge



	4 w/o	6 w/o	8 w/o	10 w/o
Cavity flooded	0.8153	0.8965	0.9541	0.9969
Cavity dry	0.4826	0.5855	0.6766	0.7511

Figure 7: Flooded v dry package cavity with ruptured fuel

Whilst it may be demanding to prove a highly irradiated fuel assembly is not badly damaged, the use of a MWB could allow the ultimate consideration that the fuel assemblies are completely destroyed. All the fissile material assumed to have escaped the assembly and be liberated within the package cavity in the most optimised geometrical arrangement. With a lack of moderation, the package cavity void from water due to presence of the MWB, the criticality safety margin could be maintained.

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[*] It is feasible that the residual space within pins in an assembly from where fuel has been released could be taken up by water. LWR fuel assemblies are typically undermoderated by design, hence a secondary effect of fuel release is a possible enhancement in moderator:fissile ratio over a limited region which could potentially increase the assembly reactivity within a flooded cavity.

- ***The effect on criticality safety of limited moisture content for unirradiated LWR MOX fuel assemblies***

Depending on the fissile material to be transported, the possibility of differential flooding can be engineered out of most packages during the early design stages.

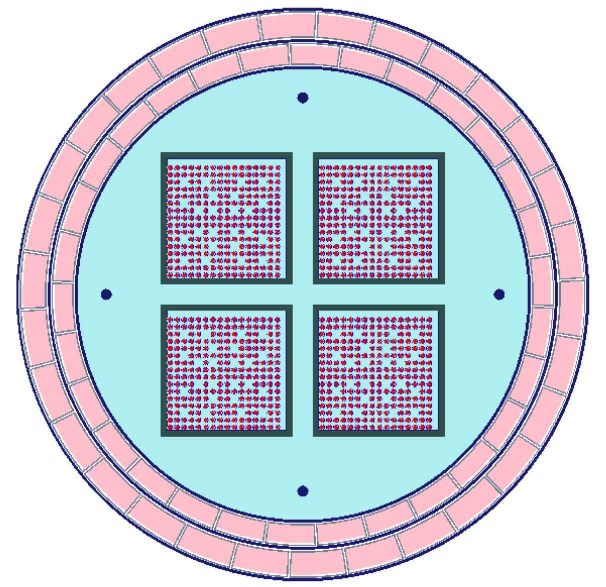


Figure 8: Flooded package cavity with MOX fuel assemblies

Features such as water circulation holes to provide adequate drainage between the different regions internally can be incorporated. In this case full water flooding presents the most onerous credible scenario with regard to the ingress of water. The reactivity of a partially flooded package would be bounded by that of a fully water flooded package.

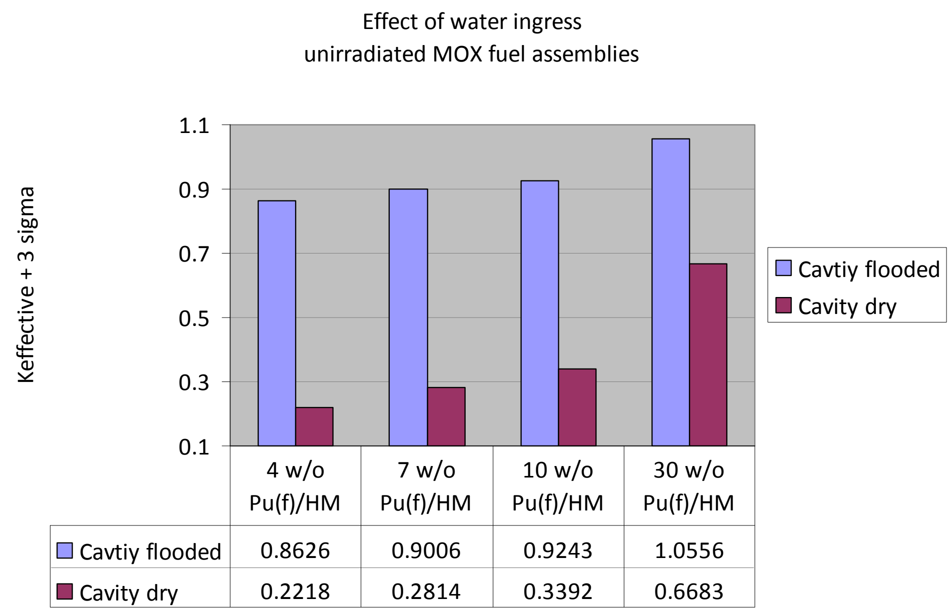
For packages which are in the normal condition transported dry – i.e. the cavity void of water – the largest credible increase in k-effective, when compared with normal conditions, can be attributed to the ingress of water into the package cavity alone.

The increase would be far in excess of that which could occur as a result of any other single damage condition.

As LWR fuel assemblies are undermoderated by design, any ingress of water into a normally dry package will increase k-effective and potentially lead to a breach of the criticality safety criterion.

If the package is designed with a MWB full water flooding need not be considered.

For LWR MOX transport this could conceivably allow the fissile material payload to be greatly increased in terms of the fissile loading of the fuel assemblies.



	4 w/o Pu(f)/HM	7 w/o Pu(f)/HM	10 w/o Pu(f)/HM	30 w/o Pu(f)/HM
Cavtiy flooded	0.8626	0.9006	0.9243	1.0556
Cavity dry	0.2218	0.2814	0.3392	0.6683

Figure 9: Effect of full water flooding for MOX fuel assemblies with varying enrichment

CONCLUSIONS

It is evident that the use of MWBs for fissile packages has enormous advantages during the criticality consideration of single package calculations.

However the discussion and examples included herein assume the complete absence of water ingress. It is likely that minor in-leakage as a result of seal prolonged exposure to external water pressure will need to be considered. In addition the potential for water ingress due to operational fault, (e.g. insufficient drainage), human error etc. will be required. It should be borne in mind that any limited volume of water ingress identified will bring about an erosion of the criticality safety margins to some extent.

Perhaps conversely, the assumption of no bulk[†] water in-leakage should be considered as an exemption that is appropriate only in those instances in which its benefits clearly outweigh the additional risk. Justification of this assumption will generally necessitate an increase in design margin and a substantial effort in package evaluation, operating procedures, acceptance testing, maintenance and quality assurance programs. Nonetheless, from a criticality viewpoint MWB's are essentially well ace.

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[†] 'Bulk' is used to differentiate between - minor in-leakage as a result of seal prolonged exposure to external water pressure (e.g. immersion) which is determined by the Standard Leakage Rate (SLR) determined for the seal in the activity release assessment in the PDSR – and gross in-leakage as a result of containment failure