

**Proceedings of the 15th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2007 -
October 21-26 2007, Miami, Florida, USA**

**An Industry Initiative to Facilitate the Criticality Assessment and Subsequent
Licensing of Transport Packages**

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ABSTRACT

The World Nuclear Transport Institute (WNTI) set up an Industry Task Force in 2005 to explore the possibility of developing an Industry Knowledge Base on Criticality Assessment. The objective of the Knowledge Base is to provide a philosophy and source of technical data to assist applicants in the preparation of criticality safety cases with a view to achieving, where practicable, worthwhile harmonisation.

The initial focus has been on new and spent fuel assemblies; the intention is to consider the full range of nuclear fuel cycle materials eventually.

Currently, when considering hypothetical accident conditions, the underlying assumptions can differ widely from application to application. One stage of the Task Force process has been to increase understanding of the basis for approaches to identifying and justifying realistic and achievable configurations of nuclear materials following an impact accident. A challenge for industry is to see if it can arrive at a more common understanding of realistic worst cases, i.e. those which have most effect on the approach to criticality, based on sound engineering principles and analysis, coupled with experimental evidence.

The importance of reaching a consensus on the content and style of the Knowledge Base was recognised and a way forward has been agreed which successfully addresses the above issues.

Good progress has been made. Sections of the Knowledge Base addressing fuel lattice expansion and fuel pin cladding failure have been drafted; abstracts of relevant and supporting information have been prepared in support and areas requiring further substantiation have been identified.

At the most recent workshop, earlier this year, sections of the Knowledge Base covering e.g. enrichment mapping, water ingress and burn-up credit were considered and are now in preparation.

INTRODUCTION

The World Nuclear Transport Institute (WNTI) was founded in 1998 to represent the collective interests of the radioactive materials transport Industry and also those who rely on safe, effective and reliable transport. WNTI, together with criticality experts from its member companies, is currently embarked on a major project to explore the possibility of defining a set of methodologies and data, a Knowledge Base, to

assist applicants in the preparation of criticality assessment of transport packages in submissions to Competent Authorities.

Although there is a single set of regulations governing the transport of radioactive materials (the IAEA Regulations [2, 3]), there can be major differences in the way both criticality assessors and regulators make assumptions and use models. This can lead to inconsistencies between international assessments, sometimes, overly pessimistic assumptions as well as duplication of work and inefficient use of resources.

The remainder of this paper more fully explains the background to this project, associated issues such as Intellectual Property Rights, and progress to date, particularly with respect to new and spent fuel assemblies.

THE ISSUE

With regard to criticality safety modelling, the IAEA Regulations require the assessment of a fissile transport package under both normal and accident conditions of transport. The accident conditions of transport are very challenging and include: water immersion, highly energetic impacts onto unyielding surfaces and the effects of prolonged and very hot fire.

In practice, accident modelling generally depends upon the analyst making a credible set of assumptions (e.g. on the degree of fuel break-up, pin displacement). Of necessity, these can be highly subjective because of the lack of test data to adequately describe the performance of a package and its contents under accident conditions. It is the subjectivity which can lead to difficulties.

For example, in assessing impacts involving transport packages carrying fuel pins, because of budgetary and time constraints, it is practically impossible to completely describe the state of the fuel assemblies after the accident in a form which would allow highly accurate criticality modelling. There are so many fuel pins, each with its own 3-D damage state that it is also impracticable to accurately represent the damaged fuel in a criticality model. What often happens is that the greatest pin displacement from a highly idealised, but limited, test on a similar fuel assembly would be applied to all fuel pins in the package, together with highly pessimistic representations of the fuel debris and moderation state. In most cases this requires a degree of interpretation of the experimental results, with large safety factors being applied to allow for uncertainties. This is one example of many.

It can be appreciated that this state of affairs encourages different approaches to modelling an accident-state. There is a tendency to construct hypothetical models of accident-states, some of which, although bounding or conservative, have an unduly large reactivity (K_{eff}). Criticality evaluations, of potentially identical situations, can then lead to radically different conclusions depending upon the assessors conducting the study. In the past, this has led to transport assessments collecting conflicting and inconsistent reviews from Competent Authorities, with the final submission being based on the “worst of the worst”.

HOW CAN A CRITICALITY KNOWLEDGE BASE HELP?

It is obvious that a completely common approach would not be feasible because of differences in the design of the packages, and also the fuel assemblies. However WNTI believe that a wider industry understanding may be achieved based on consistent methods, reliable data and realistic assumptions. The benefits are considered to be in the areas of

- sharing of knowledge and methods

- education and training
- provision of detailed guidance to assessors
- minimisation of unnecessary pessimism.
- Improving the efficiency and reducing costs to both applicants and regulators.

The WNTI Industry Task Force is structuring the Criticality Assessment Knowledge Base to function as a basic resource for transport criticality assessors. The specific aims are to provide:

- a combined source of information for criticality assessors in support of applications
- guidance to industry assessors on which realistic accident-states to assess
- guidance to industry assessors on how the accident-state may be assessed
- an explanation of the issues surrounding each accident-state
- where possible, a list of all relevant sources of data (indicating where there is a paucity of data).

The Knowledge Base is not intended to be prescriptive. In other words, industry assessors will exercise discretion and decide to use the information (or not) as appropriate. From the outset it was acknowledged that all the various possible accident conditions depend strongly on the detailed design of the package and also the fuel elements. So, if the design is such that a particular scenario is not possible, then some information in the Knowledge Base would not be deemed relevant; on the other hand, if the scenario is possible then the information given could be helpful.

It is recognised that there is not a common ‘best method’. For example the assessment could be based on pessimistic assumptions which would allow a simple safety case to be made but increase the cost or reduce the capacity of the package. Alternatively the assessment could be based on an accurate and validated model which would involve a more complex safety analysis but lead to a more cost effective package design. The optimum will depend on the particular circumstances.

The basic layout of the Knowledge Base is shown in Table 1, i.e. a listing of issues to be considered including accident conditions with relevant supporting information for a safety case.

This supporting information, which could be material already available in the public domain or, subject to Intellectual Property rights (IPR), will be referenced and briefly described. Where appropriate, comments on its use, applicability, etc. will be provided. The “pedigree” of the data will be considered to ensure a reasonable level of confidence for all data included in the Knowledge Base.

No IPR is referenced without owner’s consent and the owner’s willingness to consider its use by others if terms can be agreed; for example, by purchase, or information exchange. When the supporting information in the Knowledge Base is in the form of IPR, the owner will include an abstract giving sufficient detail to allow others to assess its applicability and value – the shop window.

A specific, but simplified, example of the Knowledge Base is provided in Table 2, for the following fault-state:

- Unirradiated and irradiated LWR fuel in an axial impact accident resulting in a change in fuel pin lattice pitch.

MODELLING OF ACCIDENT CONDITIONS IN A CRITICALITY SAFETY CASE

It can be seen from Table 2 that there are various ways to model a specific accident condition (in this instance lattice expansion), ranging from no damage to a significant degree of damage with several

options in-between. The degree of damage modelled is a function of the performance of the transport package and the fuel assemblies in an impact accident plus the data available to support the assumed damage condition.

Lattice expansion (also known as “birdcaging”) is of concern for criticality safety because in most LWR fuel elements, the as-manufactured fuel configuration is significantly under-moderated. This means that any expansion of the lattice in a flooded package will lead to an increase in moderation. A significant increase in reactivity might occur, depending on the degree and length of the expansion. In contrast, lattice contraction is of no concern because of the decrease in moderation in these sections of the fuel assembly. Generally in BWR fuel assemblies the fuel pins are attached to the end fittings and in PWR fuel the pins are unattached (however, there are exceptions to this). This determines the nature of the impact damage and this is described below.

BWR Fuel - Birdcaging can occur in BWR fuel assemblies, although because of the nature of the end-fitting (usually the pins are built-in), significant lattice expansion is not expected. As illustrated in figure 1, the end fitting/tie plates would distort in a severe impact; the pins would move down with the end fitting and bow inwards. This lowers reactivity in the first inter-grid because of the decrease in the moderation in this region of the fuel assembly. Some birdcaging could occur in the next region (2nd intergrid), but generally the fuel pin deflections (and ones in subsequent intergrids) would be small in magnitude, and would not produce a significant change in K_{eff} . This is discussed further below.

PWR Fuel - In a PWR fuel assembly, the pins are usually not attached to the end-fitting and deformation of the fitting has the potential to cause lattice expansion, as shown in figure 2. Birdcaging needs to be considered only when the design of the PWR fuel assembly/package is such that a degree of expansion can credibly occur. Not all PWR elements would experience birdcaging, because this phenomenon is a direct result of the interaction between the fuel pins and the bottom end-fittings, and these latter items differ between designs.

Figure 1

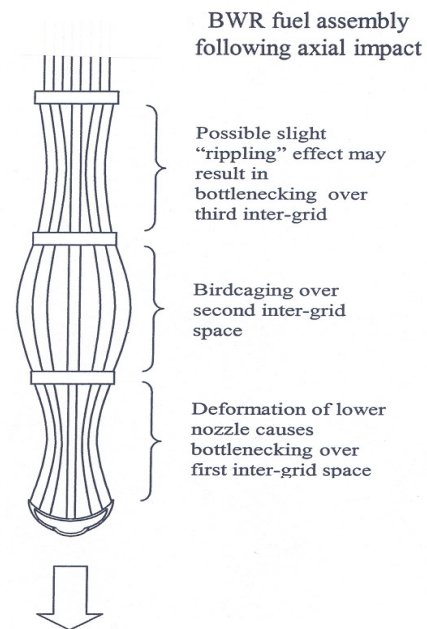
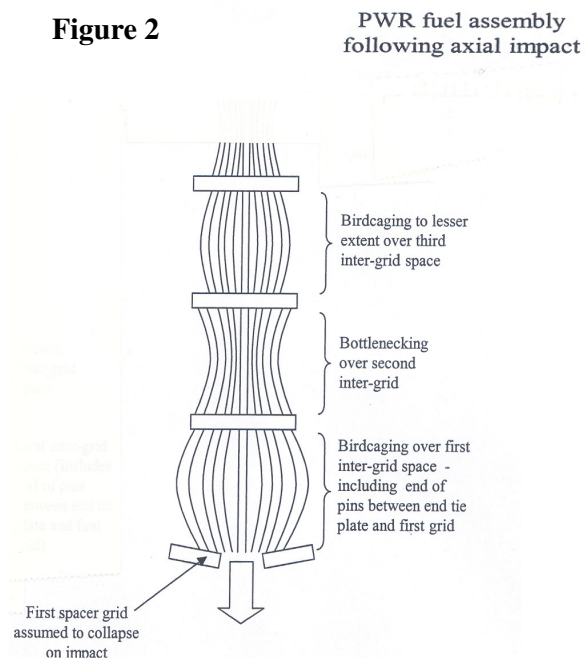


Figure 2



Typically, in current PWR package safety cases, the criticality analyst will assume the lowest grid has effectively burst and the lattice has expanded laterally up to the limits of the fuel lodgement, or to optimum pin pitch if this occurs first. Usually, the lattice expansion is assumed to occur over a length of approximately 500mm, or up to the first remaining grid whilst in the adjacent inter-grid length the lattice pitch is unchanged. By contrast, for BWR fuel, the criticality analysis may ignore lattice contraction near the end but consider uniform lattice expansion for a short length above the next grid; in some instances change in lattice pitch is not modelled at all.

Overall, this is a convenient and pessimistic approach for both PWR and BWR fuels because it is relatively easy to model and usually gives a higher reactivity than would arise from the actual deformation patterns as shown in Figures 1 and 2.

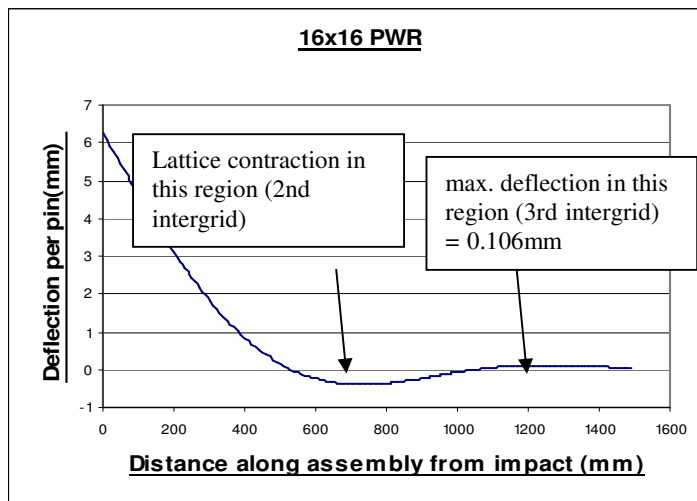
However, during the development of the Knowledge Base, it became apparent that these previously accepted modelling approximations, have been subject to challenge by competent authorities because they are specific to a limited length of deformation and do not consider the potential for lattice expansion to extend beyond one inter-grid length. They are aware that in some designs of LWR fuel, if lattice expansion were considered to act over more than one inter-grid length, then further increases in overall reactivity may result.

Recognising that competent authorities were challenging the validity of the assumptions, static and dynamic analytical methods have been developed, specifically to underpin assumptions applied in the package criticality analysis. These engineering methods are the subject of another paper, Reference 1, to be presented at this PATRAM symposium. The method, outlined in Reference 1, determines a deformation profile which translates to changes in lattice geometry which can subsequently be applied to the criticality safety modelling, this is discussed below:

PWR Analysis

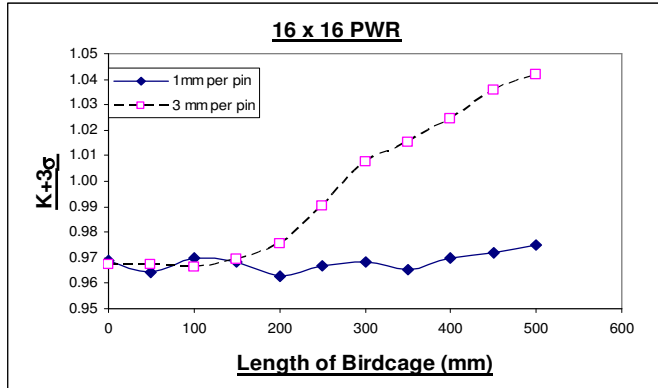
The principal objective of the static and dynamic analysis was to demonstrate that severe deformations imposed on the end of a fuel pin could not result in significant lateral deformations at locations more than approximately 500mm from that end.

The graph below is a typical result from an example where a PWR fuel pin is subject to ~ 50mm deflection at the end.



50mm deflection to the end of a fuel pin is far greater than could occur in practice because it exceeds most fuel lodgement sizes. From the graph, it can be seen that the 2nd intergrid region has contracted. Birdcaging has occurred in the 3rd inter-grid region, but the maximum displacement per pin is 0.11 mm. Subsequent expansions are smaller. Lattice contractions can be ignored because of the lower moderation state in these intergrids.

Specific criticality calculations were then completed to show that the reactivity effects of the small lattice expansions in the 2nd and subsequent inter-grids were insignificant in terms of K_{eff} . Criticality studies on a range of fuel assemblies were completed, results for a 16x16 fuel array are summarised in the graph below.



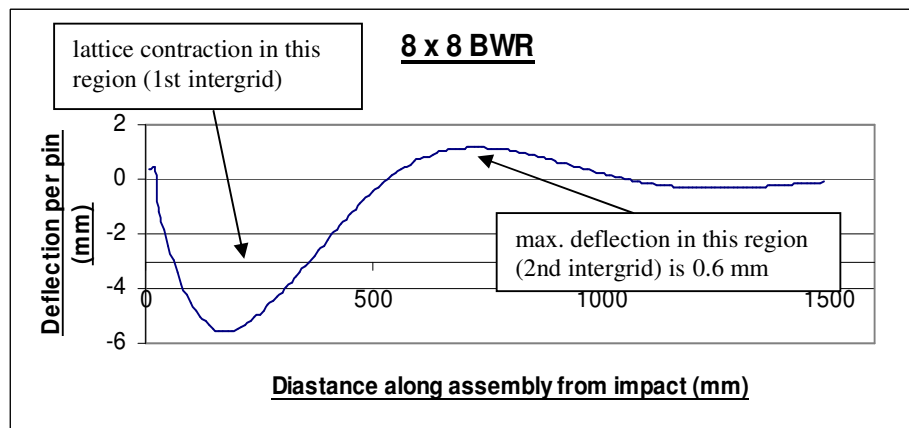
This shows the variation in K_{eff} as a function of birdcage length for two expansion values. The lower curve is the most relevant as it shows the variation in K_{eff} for a displacement of 1mm per pin, which is a factor of 10 greater than predicted in the engineering analysis. It can be seen that an increase in pitch of 1mm per pin over a 500 mm length has little effect on reactivity; the change in K_{eff} is approximately 0.008, this is barely statistically significant.

Thus in this PWR fuel assembly, birdcages in the 3rd and subsequent intergrids are of no concern for criticality safety. It would be appropriate to model this fuel assembly as undamaged, except for a bird-caged region in the first intergrid.

BWR Analysis

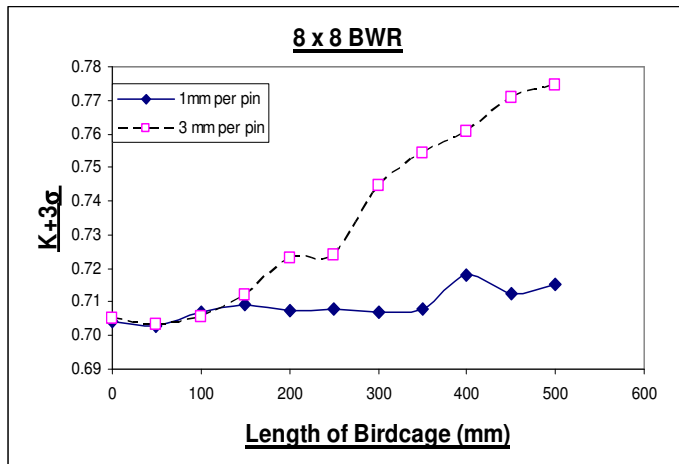
The principal objective of the static and dynamic analysis was to demonstrate that BWR assemblies (and those designs of PWR assemblies in which the lower end plug of the fuel pin is positioned in a socket in the lower nozzle) can be modelled as an undamaged fuel assembly after an axial impact accident.

The graph below represents a case where the pin end is displaced inwards by 5mm and a bending couple of 20 degrees is imposed on the end plug.



It can be seen that there is a significant contraction of the lattice over the first inter-grid. This is of no concern for criticality because of the decrease in moderation. In the 2nd intergrid, the maximum lattice expansion does not exceed 0.6 mm per pin. Subsequent expansions are negligible.

Criticality studies on a range of 8x8 fuel assemblies are summarised in the graph below.



This shows K_{eff} as a function of birdcage length for two expansion values. The lower curve is the most relevant as it shows the variation in K_{eff} for an increase in pitch of 1 mm per pin. It can be seen that this pitch increase (and smaller) has only a small effect on reactivity. The calculations show that change in K_{eff} is ~ 0.01 for a 500 mm length (an intergrid). Although, this is a statistically significant difference it is considered that for the pitch increases predicted by the engineering analysis (less than 0.6 mm per pin) there would be no criticality safety concern.

Therefore under impact conditions it would be appropriate to model these fuel assemblies in the undamaged state.

The results of both the engineering analysis and subsequent criticality analysis will be made available as reference data in the criticality Knowledge Base.

CONCLUSIONS

WNTI, together with criticality experts from its member companies, is currently embarked on a major project to explore the possibility of defining a set of methodologies and data, a Knowledge Base, to assist applicants in the preparation of criticality assessment of transport packages in submissions to Competent Authorities.

The major challenge for this project concerns hypothetical accident conditions and validation of the assumptions when modelling these conditions. Good progress has been made. Sections of the Knowledge Base addressing fuel pin lattice expansion, fuel pin cladding failure, moderator ingress and differential flooding have been drafted; abstracts of relevant and supporting information have been prepared in support and areas requiring further substantiation have been identified.

At the most recent workshop, earlier this year, sections of the Knowledge Base covering e.g. enrichment mapping and burn-up credit were considered and are now in preparation.

REFERENCES

1. Method to evaluate limits of lattice expansion in light water reactor fuel from an axial impact accident during transport. Peter Purcell, International Nuclear Services.
2. IAEA Safety Standards Series, TS-R-1, Regulations for the Safe Transport of Radioactive Material 2005 edition.
3. IAEA Safety Standards Series, TS-G-1.1 (ST-2), Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material

<p>Unique reference for fault and failure modes</p>				
A2	<p>Fault title. Full description of fault and how it can lead to an increase in K-effective. List of associated faults, conditions and issues.</p>			
	<p>Accident Condition/ Fuel Failure Mode</p>	<p>Supporting Information</p>		<p>Remarks and Additional Information</p>
		<p>Public Domain</p>	<p>IPR</p>	
A2.1	Failure Mode 1	Reference X provides data for xyz fuel.	Reference Y provides data for xyz fuel.	
A2.2	Failure Mode 2		
A2.3	Failure Mode 3		
<p>Readily available information – e.g. conference or journal papers, free reports.</p>		<p>Commercial Information available – Knowledge Base provides only a brief summary. Assessor would need to contact author of abstract to agree use/obtain further information.</p>		<p>Technical information / advice for the criticality analyst.</p>

Table 1: Layout of the Knowledge Base

A1	<p>Depending on package and fuel impact parameters:</p> <ul style="list-style-type: none"> An axial impact has the potential to change the spacing between individual fuel pins. For some fuels, this could lead to an increase in the neutron multiplication factor because light water reactor fuel elements are generally under moderated. 			
	<p>Accident Condition/ Fuel Failure Mode</p>	<p>Supporting Information</p>		<p>Remarks and Additional Information</p>
		<p>Public Domain</p>	<p>IPR</p>	
A1.1	No change in lattice pitch.	Reference A provides data/justification for XYZ fuel/package.	Reference B provides data for XYZ fuel/package. Reference C provides data for XYZ fuel/package. NB Reference B, C etc could include such as FIP, tests or experiments with TN, FS 69 type packages.	Criticality analysis of this particular accident condition would not be required in support of the Application, provided that the Reference data justifies no adverse change in lattice pitch.
A1.2	Increase in pitch over entire length of fuel assembly.	Not required.	Not required.	No justification required because this is the most conservative assumption for criticality analysis. Reference data would be needed to provide the necessary justification. (The Knowledge Base should say where no data are available).
A1.3	Increase in pitch over single inter-grid.	Reference D for *** fuel.	No data available.	Reference data would be needed to provide the necessary justification. (The Knowledge Base should say where no data are available).
A1.4	Increase in pitch over limited length over several inter-grids.	Reference E for *** fuel.	Reference C for *** fuel.	Reference data would need to provide the necessary justification.

XYZ, A, B etc are hypothetical (i.e. for the purpose of illustration)

Table 2: Axial impact: change in lattice pitch in LWR Fuels