EFFECTS OF IMPACT ACCIDENTS ON TRANSPORT CRITICALITY SAFETY CASES FOR LWR PACKAGES – A NEW APPROACH

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ABSTRACT

Transport criticality safety cases for packages containing Light Water Reactor (LWR) fuel assemblies assess reactivity under normal and accident conditions. Depending upon the particular packaging design it may be necessary to consider the fuel assemblies in a variety of states. This approach can result in a combination of pessimisms that are in extreme cases unrealistic, thereby resulting in design limits that are unnecessarily restrictive. Furthermore, due to the international nature of transporting such fuel assemblies, there are variations in the assumptions made in safety cases, which are country dependent. These variations reflect the domestic experience of the country and development of their analytical techniques. This situation can result in additional analysis and assessment time by Competent Authorities when considering international transports. To rationalise this aspect of the package safety case, a two–year Fuel Integrity Project (FIP) has been initiated between BNFL and Transnucleaire Paris (TN) which is scheduled for completion in 2002.

This paper explains the project structure adopted and the scope of the work undertaken together with information relating to the intended deliverables from the project.

The objective of the FIP is to develop a common method to assess the nature of impact response of a LWR fuel assembly when subjected to the decelerations associated with the BNFL and TN fleet of transport packages. A variety of structural analysis routes will be identified together with confidence levels to enable the package designer to demonstrate the appropriateness of the assertions and assumptions used in a package criticality safety case.

The FIP is being undertaken in consultation with the Competent Authorities of France (DSIN, IPSN) and the UK (DTLR) and their support is being sought at key stages throughout the project programme. The French and UK Competent Authorities are therefore being given the opportunity to peer review the scope, content and direction of the FIP to provide assurance that the developed method can be adopted into transport safety cases in the future.

A programme of mechanical testing will begin in 2001 and include unirradiated and irradiated fuel assembly components. This will provide a basis for extending the method developed thus far for unirradiated fuel, to cover additional fresh fuel applications and also spent fuel.

INTRODUCTION

If a LWR transport package is subjected to an impact accident, there is the potential for damage to the structure of the fuel assemblies. Since water flooded LWR assemblies are typically undermoderated, changes in geometry could cause an increase in the reactivity of the fissile material **potentially** giving rise to a criticality hazard Notwithstanding this, the engineering of the packages is such that they will still retain their protection.

Impact testing of package designs can be undertaken to demonstrate the structural integrity of the Multi-Element Bottle (MEB) or fuel frame design, not of the fuel itself. The resulting distortions of the package are incorporated into the transport criticality safety cases as appropriate. The consensus of opinion, endorsed by the Regulators, was that conservative assumptions, together with reduction in modelling uncertainties and improvements in nuclear data libraries, resulted in an envelope of criticality safety within which the effects of fuel disruption were considered to lie. It is now recognised that such an approach may be not be sufficient in some cases and that the effect of an impact upon the structural design of the fuel assemblies, in a water flooded package, needs to be quantified. It is therefore timely to consider the issue of fuel integrity under impact conditions as it relates to modern fuels. To this end, BNFL and TN initiated the Fuel Integrity Project (FIP).

The FIP will deliver a Technical Guide as output, which can be used systematically during the development of package design safety cases for both existing and new packages to ensure that effects of a regulatory transport impact is adequately considered in the criticality safety case. As such it will attract periodic review and revision as appropriate to accommodate fuel designs as they are nominated for transport.

This paper explores the potential damaged states resulting from an impact accident and describes the method used to differentiate between those that are insignificant from a criticality perspective and those requiring Finite Element Analysis and/or mechanical testing to complement the criticality analysis. In all cases, the criticality analysis assumes that the package is water flooded. One specific damage condition, that of deformation giving rise to changes in pin pitch within a damaged fuel assembly, is described in detail.

PROJECT OBJECTIVES

The commitment made by BNFL and TN is to confirm that the safety margins presented in criticality safety cases, under impact accident conditions, are based upon substantiated assumptions.

At the start of the project the key objectives were defined:

- To obtain French and UK Regulator acceptance of the agreed methodology
- To improve the level of confidence in safety by better identification of the existing margins
- To confirm criticality calculation assumptions on mechanical behaviour of fuel are conservative with respect to:
  - changes in geometry
  - rupture of fuel pin(s)
- To develop a Simplified Impact Methodology (SIM) for the mechanical analysis of LWR fuel assemblies by:
  - Qualifying the method for unirradiated fuel, on the basis of analysis and test data;
  - Identifying the data needed for the application of the method to irradiated fuel;
- To utilise existing mechanical test data or if unavailable to develop a series of mechanical tests to establish the mechanical properties and/or the mechanical responses of the LWR fuel assembly components which significantly influence its performance in an impact accident.
- To develop a system to categorise the various LWR fuel assembly design parameters into a small number of generic fuel assembly models for impact analysis and criticality (recognising these will be different for each discipline).
- To identify the engineering design principles which could mitigate the criticality consequences of any changes to the LWR fuel assembly configuration, if necessary.

The ultimate deliverable of the project will be a Technical Guide, which is scheduled for completion by Q2/2002.

PROJECT STRUCTURE

The Fuel Integrity Project and the Collaboration Agreement between BNFL and TN was established in Q1/2000. Four components to this project were agreed, namely: collation and review of existing data, criticality calculations, impact calculations and mechanical testing of representative LWR fuel assembly components.

The Project is segmented into six phases:

FIP Phase 1	Project Management	FIP Phase 2	Interface with Regulators
FIP Phase 3	Impact Testing	FIP Phase 4	Impact Analysis
FIP Phase 5	Criticality Analysis	FIP Phase 6	Evaluation of Results and Final Report.

To date, against a backdrop of regular meetings with the Regulators, efforts have been focused on Phases 4 and 5. This has resulted in the development by TN of the SIM, which is nearing completion for unirradiated material. Efforts are now being directed towards the translation of this approach to irradiated material, which will involve mechanical testing of both unirradiated and irradiated materials.

Criticality analysis of the potential failure modes has been continuing. All the factors which could have a bearing on the criticality safety of the fuel in an impact accident have been identified and discussed with the Regulators, in order to provide an appreciation of the risks of failure.

A series of static and dynamic tests has been devised and Test Specifications issued to prospective Test Houses. The scope of these tests and any associated analysis has been presented to the French and UK Regulators for their comments. It is intended that future LWR fuel designs, i.e. fuels outside the scope of the FIP could be incorporated into the impact and criticality methods developed by the FIP, this may necessitate additional analysis and testing in the future.

CRITICALITY ANALYSIS

Due to the international nature of transporting fuel assemblies, there are country dependent variations in the assumptions made in criticality safety cases. These variations reflect the domestic experience of the country, the differences in analytical codes and also the development of these analytical techniques. Such differences in analytical techniques were addressed in a BNFL/TN code verification exercise discussed later.

The assumptions used by BNFL and TN in criticality safety assessments have also been compared and reviewed to determine whether these assumptions adequately encompass all credible contingencies arising from an accident. This has resulted in the creation of a reference set of assumptions for use in criticality safety cases for water flooded transport packages. The reference set of assumptions can be collated into two categories:

a) 'Safe independent of mechanical design', i.e. one in which the worst possible conditions are assumed and no criticality hazard is created.
b) 'Credible assumptions' in which criticality safety relies upon a level of deformation that is within the physical boundaries of the package design and consequently require substantiation; such substantiation being the purpose of the FIP.

VERIFICATION OF CRITICALITY CODES

Efforts are focussed on developing a harmonised criticality methodology. To achieve this it is necessary to understand the effects due to differences in criticality calculational techniques. In particular, limitations within the geometry modelling options and the nuclear data libraries, employed by the various codes, should be quantified. TN and BNFL have benchmarked their codes to determine whether any bias is present in the results. TN uses APOLLO/MORET, Reference 1, BNFL uses MONK, Reference 2, and in addition TN and BNFL both have access to MCNP, Reference 3. The benchmark was carried out using all three codes employing an abstract model of fuel in an MEB/Open Frame with fuel released and settled into the region below the fuel assemblies.

Generally there was good agreement using APOLLO / MORET, and MCNP. MONK showed a conservative bias, which was tracked back to the data library (UKNDL) Reference 4. Use of JEF2.2 data library, Reference 5, aligned MONK results with the results of other codes. Good trending agreement was identified between all three codes, changes in control parameters resulted in similar changes in the predicted results for all three codes.

Both BNFL and TN utilise fully validated computer codes and therefore it is not intended to undertake any validation of the codes as part of this project.

CRITICALITY HAZARDS IN HYPOTHETICAL ACCIDENT CONDITIONS

In the event that a transport package containing fissile material is involved in a significant accident (defined by the tests described in Reference 6), it is possible that the loads imparted to the fuel could damage the fuel assembly. If the fissile material is or can become moderated then it is necessary to assess the criticality safety of the fuel under such conditions. The transport packaging could also incur damage from such an accident although it is assumed that the packaging would retain the fuel within the MEB cavity, or the flask cavity if an open frame were being used. Damage to the transport package is considered in the criticality analysis for each specific package and as such is not a generic feature of this project

A review of hypothetical impact accidents was carried out by qualified mechanical and criticality experts from BNFL and TN and damage that is potentially significant from a criticality perspective was recorded. From this review it was apparent that the three principal types of damage that are important in criticality safety are deformation, slippage and rupture (See Figure 1).

The importance of these three types of damage is,

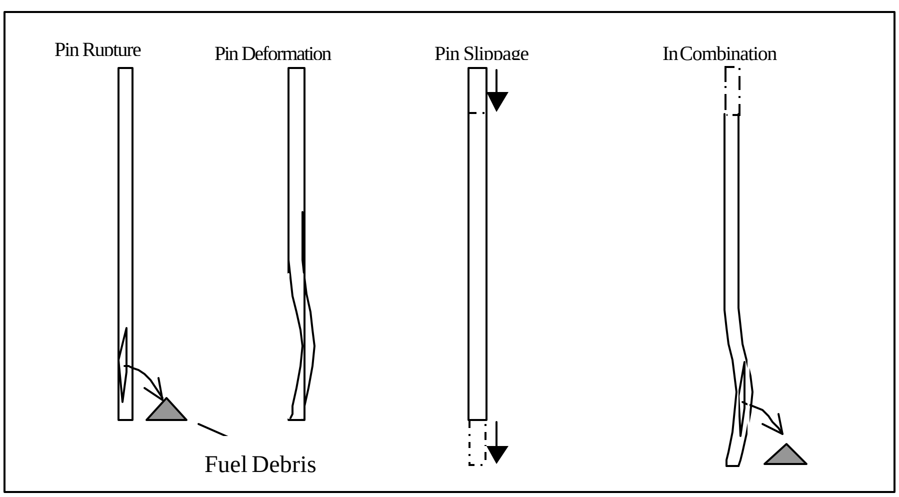
Slippage allows pins to move from their normal locations possibly into regions where there are no neutron poison materials to control reactivity. They can also slide and change their pitch relative to each other and since water flooded LWR fuel assemblies are typically undermoderated it is possible to give rise to regions of optimal pitch, thus increasing the neutron multiplication factor, $k_{effective}$.

Deformation of fuel pins allows the pitch between adjacent fuel pins to be changed. As noted above changes in pitch could change the fuel to water ratio and hence the $k_{effective}$.

Deformation of non-fuel components (e.g. the collapse of the end fittings) could increase the space available to the fuel components. The potential for changes in the geometry arising from this could give rise to changes in $k_{effective}$.

Rupture of the fuel pins could allow fissile material to escape into the MEB or flask cavity. Fuel debris could collect in an optimised configuration (in terms of geometry and density) in unpoisoned regions and this could influence $k_{effective}$.

Figure 1 Potential Damaged States



The review identified a number of distinct mechanisms by which the types of damage listed previously could arise as a consequence of either an axial (or near axial) impact or a horizontal impact, these are listed in Table 1.

Table 1– Postulated Damage that Could Affect Fuel integrity of Fresh and Spent Nuclear Fuel

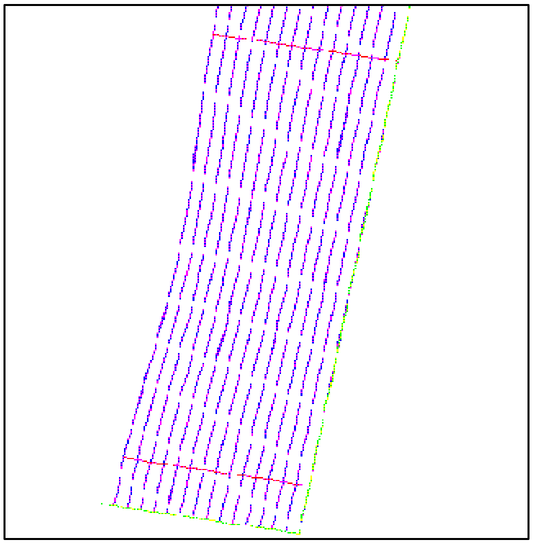
Item	Damage	Consequence
AXIAL IMPACTS		
A.1.	Pins slip axially.	Pins slide to region below or above poison plates, and/or to more optimum pitch arrangement.
A.2.	Rupture of pins caused by impact with end fittings.	Possible release of fissile material. Release could be at the end plugs.
A.3.	Penetration of the end fittings by the fuel pins.	Pins slide to more optimum pitch arrangement. (possibly through the water circulation holes in PWR end fittings)
A.4.	Pins pass around the end fittings.	Pins slide to more optimum pitch arrangement/ into an unpoisoned region
A.5.	Pins rupture while passing around the end fittings.	Pins slide to more optimum pitch arrangement, possible release of fissile material.
A.6	The spacer grids rupture pins.	Possible release of fissile material.
A.7.	Deformation of the pins and the top/bottom fitting leading to rupture.	Deformation of pin array, possible release of fissile material.
HORIZONTAL IMPACTS		
H.1.	Lateral movement of the BWR top/bottom fitting relative to the fuel pins causes shear at the pin/end fitting interface.	Possible release of fissile material due to shear at the pin/end fitting interfaces- occurs only for BWR
H.2.	Shear and bending interaction between the pins and the spacer grids.	Possible release of fissile material.
H.3.	Interaction between pins or between the pins and the lodgement wall.	Possible release of fissile material.
H.4.	Interaction between the fuel pin end plug and the lodgement walls.	Possible release of fissile material.

From this review, it was possible to produce a focussed programme of criticality analysis to support the aims of the fuel integrity project. The precise response of the fuel to an impact accident has not yet been quantified and will probably only be partially quantified at the conclusion of the project. Therefore, the criticality analysis will consider bounding cases so that comparisons with test results or impact analysis can be made at a later date. It should then be possible to quantify criticality safety margins. From the work completed to date it has been concluded already that deformation of pins, other than leading to fuel pin rupture, will not present a significant criticality hazard; the logic behind this conclusion is presented.

PIN DEFORMATION – PROPOSED PATTERNS OF DEFORMATION

It is assumed that pins deform in an axial impact accident and the pitch between adjacent pins will change in a manner that could increase the reactivity of the fuel, i.e. by an increase in pin pitch. Although in most impact accidents, it is anticipated that the fuel pins would tend to move in the same direction (See Figure 2, produced by Finite Element Analysis) and reduce the reactivity of the fuel.

Figure 2– Beam Element Model of a Fuel Assembly



Since at this time it cannot be demonstrated that the conditions in Figure 2 occur for every impact orientation, it is necessary to perform criticality calculations using abstract and pessimistic geometry.

The following schemes are proposed for the analysis in support of the fuel integrity project.

Undamaged Fuel
The fuel pins are in their original position. In this case a 7x7 array, centred in the lodgement cavity, see figure 3.

Damaged State A
The pins have become distorted such that they are evenly spaced across the entire lodgement cavity. There is only one pitch to model, see figure 4.

Damaged State B
The fuel pins have spaced evenly but continue to buckle after meeting the lodgement wall. The lodgement wall has restrained the outer layer of pins and all the inner layers have increased in pitch evenly until they contact with the outer layer. There are two regions with different pin pitches. The interface between the two regions creates a number of other pin pitches, see figure 5.

Figure 3 –Undamaged Fuel

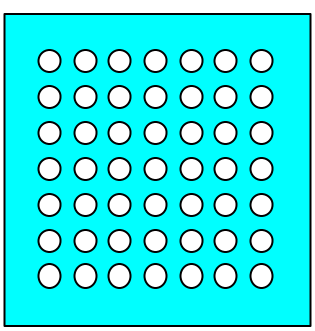


Figure 4 – Damaged State A

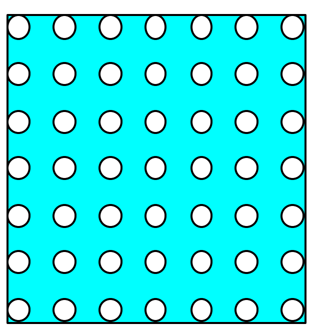
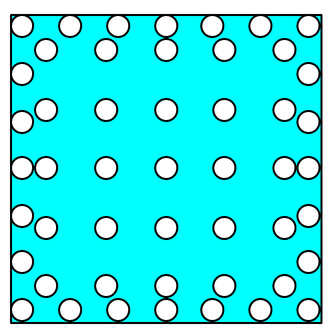


Figure 5 - Damaged State B



Reactivity from highest to lowest is from Damaged State B to the Undamaged State. This assumes that the most optimised central region drives the reactivity of the fuel assembly. However, the layer of bunched fuel pins around the outer edge may also be contributing to the reactivity of each assembly by acting as a more efficient neutron reflector or by increasing the interaction between adjacent assemblies when part of an array within a package.

It is possible to derive further models with more zones each having a progressively smaller central region, but having a larger pitch. Each in turn may be progressively more reactive but would require progressively more deformation of the fuel pins. However, a point may be reached where the central region, although having near optimum pin pitch, and hence moderation, could be of too small a volume and enclose too small a mass of fuel to influence the reactivity of each fuel assembly. Reactivity will also be strongly influenced by the axial length of the fuel subject to deformation.

Pin Deformation – PWR fuel
For PWR fuel assemblies, a conservative assumption will be made with respect to the amount of damage to the fuel.

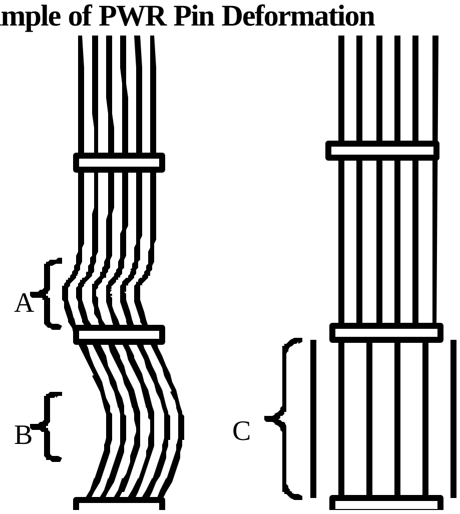
Assumption 1: Deformation of fuel assemblies is bounded by modelling a ~500mm axial section of fuel between two spacer grids as having increased pitch such that the fuel assembly in this region just fills the MEB lodgement with even pitches between pins.

This deformation is considered to be sufficiently conservative to cover requirements of Reference 6 and is based on the following considerations :-

- Fuel assemblies bend in arcs whereas Assumption 1 described above uses a step change in pin pitch over a length dictated by the distance between the spacer grids. This is typically a length of about 500mm whereas in a real impact accident, the deformation may only come close to an optimum pitch over a significantly reduced length.
- It is not considered credible to have a perfectly axial impact and therefore there will be a tendency for fuel pins to bend in the same direction rather than opposing directions. This would not increase the pitch of the fuel assemblies (See Figure 2).
- In many cases, the size of the MEB/basket lodgement is optimised thus the gap between the fuel assembly and the lodgement wall is minimised, restricting the amount by which pins may deform.

It is noted that deformation may not occur in such a regular pattern. In an impact accident, there may be more than one region along the axial length of the assembly where the pin pitches are increased, this is shown in Figure 6 below. Also shown in figure 6 is the approximated model used in the criticality analysis.

Figure 6 – Example of PWR Pin Deformation

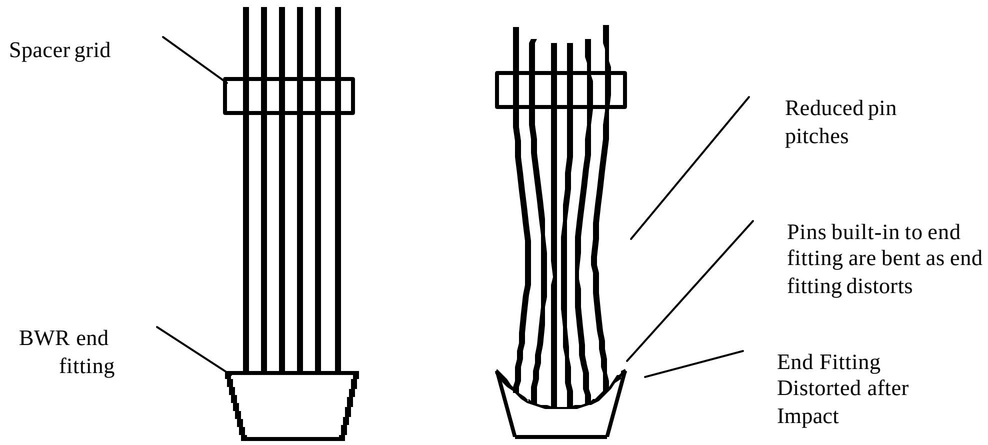


However, it is judged that modelling a single region “C”, 500mm long with increased pitch is a conservative approximation if the total axial length where pin pitches are increased (A + B on Figure 6) is much less than 500mm. Impact analysis will be required as part of the FIP to determine whether this occurs and over what axial length.

Pin Deformation – BWR fuel

Results from drop tests carried out by TN, indicate that BWR fuel distorts in such a way as to reduce the average cross section of the fuel rather than increase it. This is due to the fact that the design of the BWR assemblies is such that fuel rods are connected into the top and bottom end fittings. As these end fittings distort in a severe impact, the pins move down with the end fitting and are bowed inwards. Figure 7 demonstrates this phenomena.

Figure 7 – Example of BWR Fuel Pin Deformation



This preceding discussion of fuel pin deformation enables us to make some preliminary criticality analysis assumptions for **BWR fuels**.

Assumption 2: All BWR fuel pins have their ends built-in to both end fittings and any movement of the end fitting will result in movement of all the fuel pins.
This will be substantiated as part of the Fuel Integrity Project by a review of BWR fuel assembly designs.

Assumption 3: Provided it can be demonstrated that the results of the existing tests on BWR fuels are applicable to all BWR fuel assemblies that BNFL and TN expect to transport then there will be no need to consider deformation of BWR pins in the criticality analysis. The value of $k_{effective}$ in such an impact can be stated as being bounded by the results for the undeformed fuel assembly.

The above does not preclude the requirement to consider fuel pin rupture or other forms of damage for BWR fuel.

These assumptions, and others from the reference set mentioned earlier, are dependent on the results from the supporting programmes of work identified for the other specialist areas involved in the Fuel Integrity Project.

SUMMARY

The preceding Sections indicate that there are different conditions that could arise as a result of an impact accident. In each case some substantiation is possible, either by examination of the existing package and fuel designs, mechanical or impact analysis or even testing. The following table provides an example of how that substantiation could be carried out for unirradiated fuels for a number of the accident conditions described in Table 1.

Table 2– Analysis to Substantiate Postulated Fuel Damage for Unirradiated Fuel Assemblies

Damage	Examine Package/ Fuel Design	Criticality Analysis	Simple Mechanical Analysis	Finite Element Analysis	Testing
Axial Slippage of Pins	✓	✓	✗	✓	✗
Rupture of Pins Caused by Impact with the End Fittings	✗	✓	✗	✓	✓
Penetration of the End Fittings by the Fuel Pins	✓	✓	✦	✗	✗
Pins Pass Around the End Fittings	✦				
Lateral Movement of the BWR Top/Bottom Fitting	✓	✓	✓	✗	✗
Shear and Bending Interaction Between the Pins and the Spacer Grids	✗	✓	✓	✓	✓

✓ Analysis to be carried out.
✗ Analysis not required.
✦ Existing analysis/test results to be used

All potential impact accident conditions have been addressed in this manner for both fresh and irradiated LWR fuels. The resulting programme of analysis and testing to support the Fuel Integrity project is scheduled for completion in 2002.

The indications from analysis to date are extremely positive. The level of confidence in safety has been significantly enhanced by better identification of the existing margins. Although the FIP is not complete the results are promising and should be beneficial to the nuclear industry, its regulators and other interested parties in improving understanding in this area.

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