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Method To Evaluate Limits Of Lattice Expansion In Light Water Reactor Fuel From An Axial Impact Accident During Transport

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Abstract

Packages transporting Light Water Reactor (LWR) fuel in the public domain must comply with IAEA Transport Regulations, which state safety standards for both normal and accident conditions. Hence, an impact accident which causes deformation to the fuel may influence package safety and hence this must be analysed to demonstrate compliance with regulatory standards. For example, an impact event that causes fuel pin lattice expansion can increase the overall reactivity of the system.

A limited length of lattice expansion is typically analysed in the criticality assessment of the package under impact accidents but to consider lattice expansion over the full fuel length may be pessimistic. To ensure undue pessimism is not used, analytical methods, described in this paper, have been developed to estimate bounding limits to the length over which the fuel assembly lattice can expand due to an axial impact. These methods use both static and dynamic analysis techniques, based on the results of impact tests involving both complete fuel assemblies and individual fuel rods. These tests demonstrate that virtually all fuel rod deformations induced from an axial impact are due to interactions between the end of the fuel rod and the deformed nozzles. The static analysis method estimates the response of a single fuel rod to imposed end conditions whilst taking into account the effects of lateral constraints imposed by adjacent fuel rods, spacer grids and compartment walls. This method estimates a deformation profile resulting from end loading conditions which is translated to changes in lattice geometry and subsequently applied to the criticality safety analysis on the package contents.

The dynamic technique achieves a similar objective but can also take in to account pellet specifications and the influence of plenum springs when determining the resulting mode of deformation along the rod length.

Results, directly comparing static and dynamic methods are good, as are comparisons with actual fuel rod drop test data.

Introduction

Shipments of new Light Water Reactor (LWR) fuel, routinely take place throughout the world and ultimately, after irradiation, the fuel is transported to a storage or reprocessing facility. When shipments pass within the public domain, approval must be given by the authorised Competent Authority (CA), subject to demonstrating the package and transport system is compliant with the relevant IAEA Transport Regulations..

With both new and irradiated fuel, CA approval requires that package safety is demonstrated following specified accident conditions, which include impacts from 9m

height on to a rigid target. For the package to comply with IAEA regulations, the influence of such impacts on the reactivity of the payload must be assessed, this will include consideration of any potential expansion to the fuel pin lattice.
This is because most LWR fuels are designed under moderated, hence an impact event which increases the pin pitch can result in a general increase in reactivity. Furthermore it has been observed that end impacts on PWR fuel assemblies tend to cause lattice expansion adjacent to the end, whilst in several BWR designs of fuel, the lattice may contract near the impacted end but expand slightly in the adjacent inter-grid length. Irrespective of the fuel design and its mode of response, it is becoming increasingly necessary to have a means by which the extent and proximity of lattice expansion can be determined.
The purpose of this paper is to describe methods developed for the purpose of determining bounding limits for the extent of lattice expansion resulting from end impacts, these methods being applicable to a wide range of LWR fuel designs.

General Discussion

In practice, lattice expansion may have an influence on the overall reactivity of the payload, potentially leading to a lowering of the allowable enrichment that can be transported.

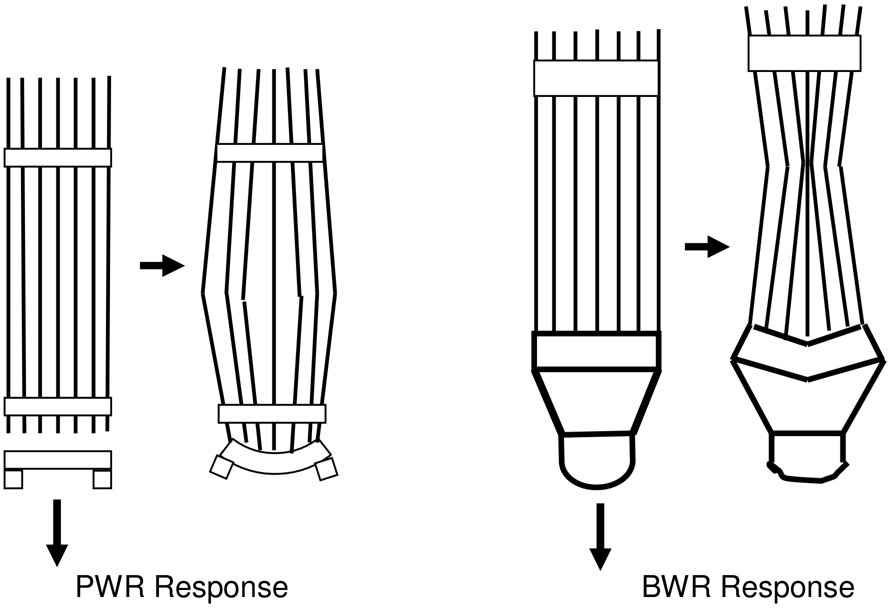


Figure 1 Typical Response Modes Of PWR and BWR Fuels To Axial Impacts

Typically, on PWR fuel designs, an axial impact causes lattice expansion, whilst with many BWR fuel designs, the lattice near to the end is contracted with associated lattice expansion above the next grid, see Figure 1.
In some current PWR package safety cases, the criticality analysis 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, see Figure 2. In the case of BWR fuels, competent authorities can not accept credit for any reduced reactivity due to lattice contraction as this represents an apparent benefit from an accident condition, which is not generally permitted.

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

However, more recently, competent authorities have challenged these assumptions 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.

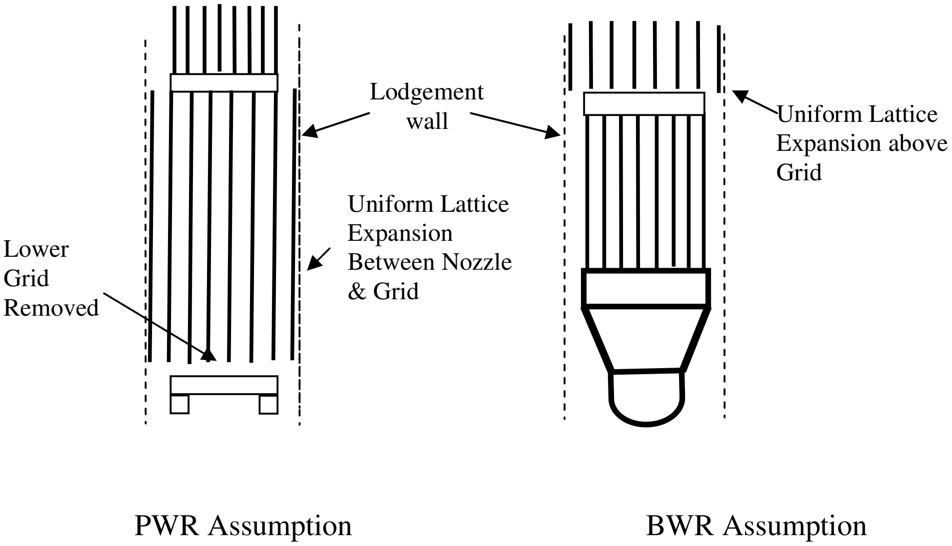


Figure 2 – Typical Deformation Modes Assumed In Criticality Safety Case

Recognising that competent authorities are challenging the validity of the assumptions shown in Figure 2, International Nuclear Services (INS) have developed analytical methods, specifically to underpin assumptions applied in the package criticality analysis.

Static Analysis Method

There have been a number of controlled axial drop tests on packages carrying new LWR fuel assemblies which have demonstrated deformation modes on the fuel as shown in Figure 1. Furthermore, accidental drops of irradiated fuel have also shown corresponding deformation modes, where the lower nozzle had suffered distortion. Conversely, axial impact tests on individual fuel pins dropped from 9m height directly on to a rigid target, resulted in very little deformation and none being evident beyond approximately 600mm from the impacted end, despite the severity of the impacts, corresponding to approximately 800g acceleration, Ref 1.

Additionally, analysis of fuel rods under end impacts has also confirmed that plastic deformation should not occur on individual pins at the typical acceleration levels measured from axial impact tests on packages ie 100g to 350g. This has also been demonstrated from the analysis of data obtained from a series of quasi static axial load tests on fuel pins, Ref 2.

It is therefore concluded that, fuel pin deformations leading to lattice expansion on LWR fuel assemblies under axial impacts in packages, result from the interactions between the ends of the fuel rods and the deforming nozzles. Based on this conclusion, it was decided to develop a quasi static analysis method to estimate deflection modes along the length of a single fuel rod subject to lateral movements and rotations imparted to one end.

The method uses conventional static analysis processes for structures subject to elastic deformations with sufficient built in flexibility to allow a wide range of dimensional and mechanical properties to be accommodated. An important feature of the method is the ability to apply bounding constraints to the lateral deflection of the fuel rod being evaluated.

Parameter	**Min**	**Max**
Rod OD -mm	8	14.5
Cladding Thickness Th - mm	0.5	1.0
Young Modulus GPa (cladding)	65	100
Yield Strength MPa (cladding)	240	600
UTS MPa (cladding)	290	750
Elongation (cladding)	10	30
Deflection Limit At mid Span Above Lower Nozzle - x mm	0	20
Angular Rotation On End - Deg	0	30
Lateral End Deflection - mm	5	50
Grid Pitches (a- h on Fig 4) mm	450	650

Table 1 – Range Of Parameters – Quasi Static Method

The analytical model was developed by Ove Arup and Partners using the computational computer programme MathCad, Ref 3, being based on the configurations presented in Figures 3 and 4 and a task specification prepared by International Nuclear Services (INS). Results for each set of parameters are given by the analytical model within a few seconds in both graphical and tabular format.

In order to ensure the method can be applied to most cases, the analytical model was designed to cover the range of parameters given in Table 1.

Depending on the example being assessed, an angular rotation and/or a lateral displacement can be imposed on the end plug of an individual rod whilst a constraint

can be introduced to limit resulting lateral deflections mid way between spacer grids, this representing movement restrictions imposed by the lodgement walls.
For any combination of parameters the analytical model gives outputs in both graphical and tabular formats of the following;

a. Lateral deflections over the total rod length
b. Bending moment in cladding over the total rod length
b. Shear stress in the cladding over the total length
c. Lateral force imposed by the rod at each grid position

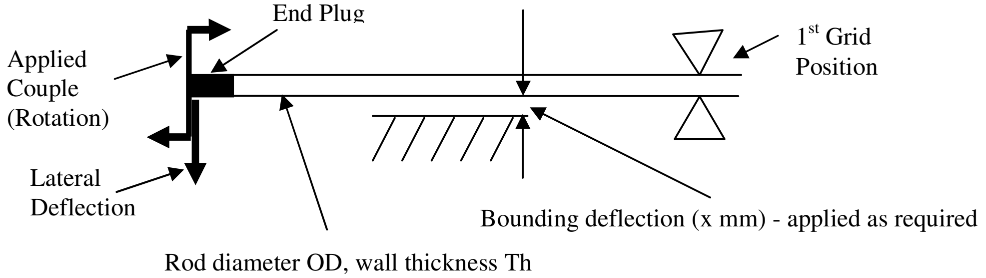


Figure 3 – Parameters For Quasi Static Method

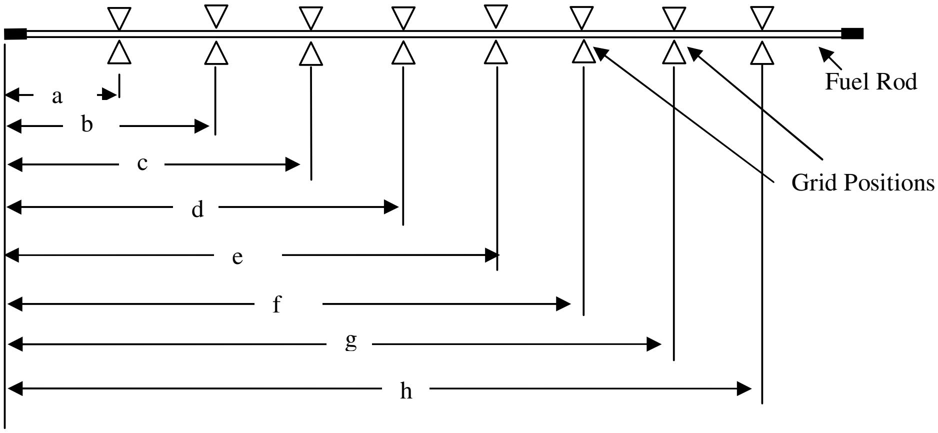


Figure 4 – Identification Of Grid Positions

It is evident this method relies on the user determining the initial deformations imposed to the end of the fuel rod. At first sight this may appear to be a major stumbling block but it is one that can be sufficiently resolved by examining the design of the end nozzle at the impacted end. Provided the impact accelerations are below approximately 350g, it is feasible to pessimistically estimate the potential deformations of the end nozzle. In some fuel designs this process being assisted by test data which show the relationship between loading on nozzles and consequent deformation, Ref 4.
Nonetheless, it is not usually necessary to have precise data on nozzle deformations because the analytical model readily allows deformation parameters to be considered

ranging from the likely to the highly pessimistic, thereby allowing a sensitivity study of the system response to be carried out.
The principal objective being to demonstrate that severe deformations imposed on the end of a fuel rod can not result in significant lateral deformations at locations remote from the end, ie further than approximately one spacer grid pitch.

Results Derived From Quasi Static Model

One of the most pertinent results from the quasi static analysis is the profile of the lateral deflection along the length of the rod. This depends on the magnitude and direction of the displacements imposed on the end of the rod and the mechanical properties of the cladding, these in turn depend on the fuel design. In many PWR fuel designs the end of the fuel rod stands off from the nozzle, but under an axial impact the rod slips through the grids and contacts the deforming nozzle which tend to displace the end rod end. Hence, when examining a PWR case it is usual to only impose a lateral displacement to the end of the rod.

Figure 5 is a typical result from an example where a PWR fuel rod is subject to a 50mm deflection at the end and no lateral restrictions to displacement has been imposed.

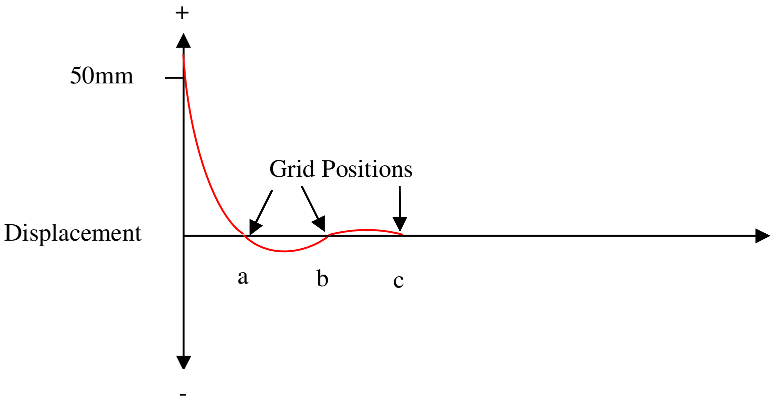


Figure 5 - PWR – Typical Rod Displacement

Although a 50mm displacement to the end of a fuel rod is highly pessimistic, the resulting lateral displacements for subsequent inter- grids is much less and soon negligible. In the case of PWR fuel designs, as shown in Figure 1, the inward displacement on the end of the rod causes lattice contractions between grids a and b.

Conversely, Figure 6 is a typical example of a BWR fuel assembly in which the lower end plug of the fuel rod is positioned in a socket in the lower nozzle. In this design, collapse of the nozzle under impact imparts a bending couple to the end of the rod and a small lateral deflection. This example represents a case where the rod end is displaced inwards by 5mm and a bending couple of 20 degrees is imposed on the end plug. Figure 6 shows these pessimistic conditions cause lattice contraction up to the first grid (a) followed by minor lattice expansion between grids a and b, further along the deformation is negligible.

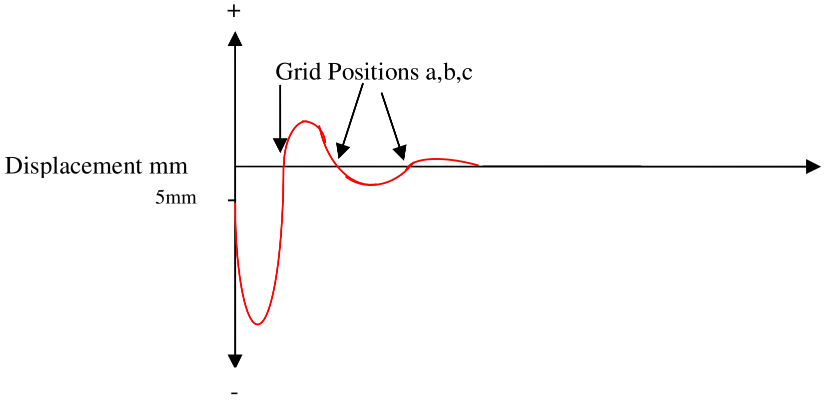


Figure 6 - BWR – Typical Rod Displacement

Application of Quasi-Static Method To Fuel Assembly

Because this method considers the consequences of end deflections acting on an individual fuel rod, the results may not appear applicable to an actual fuel assembly, where complex interactions between adjacent fuel rods would occur. However, the key objective of this method is to assess the bounding limits of lattice expansion along the assembly, which is pessimistically demonstrated from the response of an unrestricted individual rod. Where deflecting fuel rods interact, the mean result is to reduce the potential for uniform lattice expansion despite the complex entanglement of fuel rods that would probably occur.

Deformations derived from the quasi-static method must be taken as deviations from their original position and not as changes in pitch. Hence if the maximum rod deflection between grids a and b is Y mm then the change in lattice pitch, as applied to the criticality analysis, can be estimated by the following formulae;

Pitch Change = (Y mm x 2)/Number of Pin Pitches per side.

The factor of 2 is because deflections occur in opposite directions either side of the fuel assembly centre line.
Hence a deflection of 15mm on an 8 x 8 BWR assembly gives a mean lattice pitch change of (15 x 2)/7 = 4.29mm.

Dynamic Analysis Method

In order to verify the accuracy of results from the quasi static method as described above, a dynamic analysis method was developed in parallel, Ref 5. This was undertaken by Arup using the finite element code LS-DYNA version 970. The objective was to apply LS-DYNA models to analyse the response of a single rod falling from 9m on to both flat and inclined targets, the latter being to induce lateral rotations and displacements to the end. A range of fuel rod parameters were assessed with a typical result shown in Figure 7, this is for a BWR fuel rod with 14.5mm OD, 1.0mm cladding thickness and a total mass of 3kg, material properties being set mid way between the max and min range in Table 1.

The dynamic analysis method gave excellent correlation with the static method, confirming that dynamic deformations imposed at the end of the rod did not cause significant deflections beyond the first grid position.

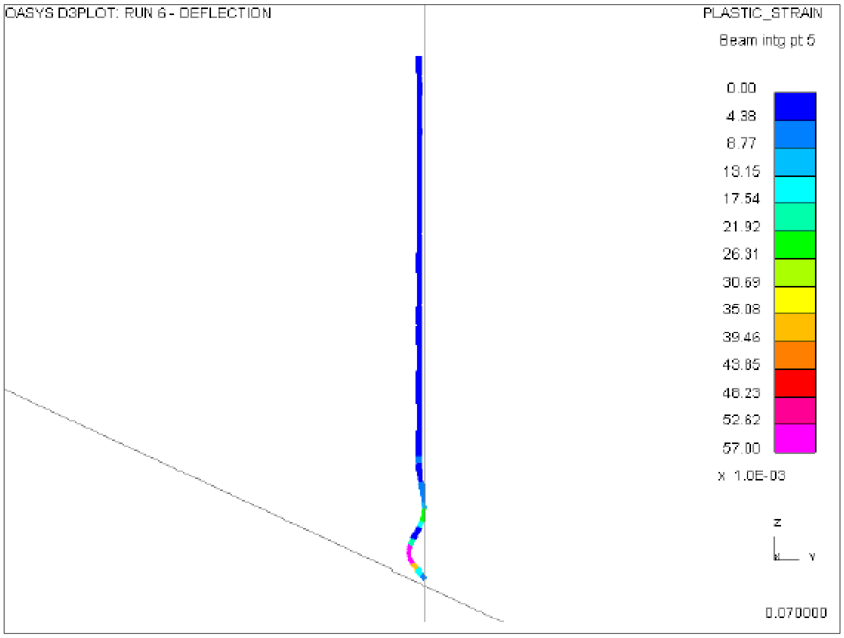
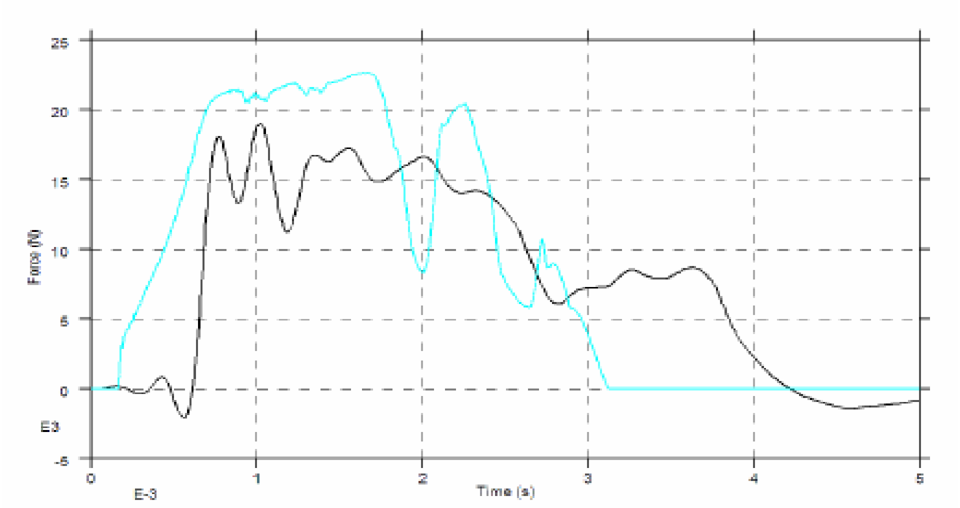


Figure 7 Dynamic Analysis – Runs 6 – Plastic Strain Distribution

Run6 = 5mm displacement, 20^{o} Rotation & 450mm grid pitch



________ Dynamic Analysis – LS Dyna

_______ Test 6.2 – PWR rod – 9m impact on to rigid target

Figure 8 – Impact Force-Time History – Dynamic Model and Actual Test (6.2)

The dynamic method using LS-DYNA was applied to an actual impact test on a PWR fuel rod. Test 6.2, from a series of dynamic tests conducted on PWR and BWR fuel rod was the test that was selected for modelling. Test 6.2 parameters were input to the LS DYNA FE analysis to yield results that compared well with the measured results from the test, an example is given in Figure 8 comparing dynamic force/time characteristics of the system following impact.

Overall, the dynamic analysis was shown to give acceptable correlation to an actual test and dynamic deflection results compared very well with those from the static method. Because the dynamic analysis method, using LS-DYNA, is best suited to the FE specialist, it is recommended, for most cases, the quasi static method is preferred, being sufficiently accurate and straightforward to use.

Conclusion

Usually, the application of a quasi static analysis method to a dynamic system is questionable, but this becomes less so when the method applies parameters having implicit derivation from dynamic events, ie deflections and rotations of the end plug.

Dynamic analysis on identical models has demonstrated this to be the case and confirms the static analysis method described in this paper can be used to underpin assumptions on impact induced pin lattice expansion applied in criticality safety analysis.

Axial drop tests on complete fuel assemblies have demonstrated that lattice deformations are limited to the proximity of the impacted end. This has been confirmed by the methods described in this paper and consequently validated current modelling assumptions.

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