DESCRIPTION OF FUEL INTEGRITY PROJECT METHODOLOGY PRINCIPLES

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ABSTRACT

TN International and International Nuclear Services (INS) have started the Fuel Integrity Project (FIP) in early 2000s, which goal is the development of a methodology to evaluate, as a safety requirement, the nature and the extent of fuel assemblies (FA) damage during accident drops of a packaging.

From TN International previous knowledge acquired from fresh FA behaviour during drop tests, a mechanical tests programme including testing on fresh and used fuel rod samples has been planned by both companies and executed by INS. Tests results analysis has led to the elaboration of FIP methodology by TN International.

Experimental knowledge on fuel was collected from the tests programme and the main mechanical phenomena arising from a drop have been identified and quantified. As a result, the FIP methodology, structured in flow charts, gives guidelines to study the effects of a lateral or axial drop of a packaging loaded with fresh or used FA of PWR or BWR types.

The flow charts of methods have the same philosophy: several pessimistic mechanical evaluations based on direct calculations or dimensionless comparisons with appropriate reference tests permit to determine FA damage, gradually increasing with acceleration. First, elastic models distinguish the null or slight damage cases; then, plastic models permit to rule out cases with extreme FA damage that lead to unacceptable criticality hypotheses; finally, other plastic models quantify the extent of fuel rods deformations in moderate FA damage cases.

FIP methodology application to a given case leads to the following output, used as criticality hypotheses for the safety analysis: existence or not of fuel rods rupture, their number, their location, the associated amount of released fuel material, and the extent of fuel rods array deformation and sliding.

All the knowledge arising from the FIP is synthesized in the Technical Guide, which presents extensively the methodology and builds up all background experimental data.

The methodology is applicable to fresh and used FA provided that brittle fracture risks are excluded.

1. INTRODUCTION

The absence of “multiple high standard water barriers” in a package implies considering water ingress in all void spaces of the inner cavity of a packaging. In this condition, to insure the sub-criticality of a package design in accident conditions of transport, it is necessary to master the radioactive content state in terms of deformations, displacements and fuel material release.

In addition, from the late 1990s, France and U.K. competent authorities (CA) began to have more and more questions about demonstrations related to both fresh and used fuel assemblies mechanical behaviour in transport conditions.

In the prospect of complying to regulatory requirements and answering CA questions, particularly on light water reactor (LWR) fuel assemblies (FA) state after 9-m drops, TN International (TNI) and International Nuclear Services started in early 2000s a joint programme, the Fuel Integrity Project (FIP), to better assess potential damage to FA and confirm hypotheses used in safety-criticality studies.

2. EXPERIENCE FROM TESTS

At that time, TNI already had some knowledge concerning the mechanical behaviour of fresh FA during 9-m drops, as dummy PWR and BWR FA were used during qualification drop tests of FS-type packaging (see Figure 1 (a) and (b)). The adjective ‘dummy’ used here refers only to the fissile material as enriched UO2 pellets were substituted with depleted UO2 pellets with similar mechanical properties. These tests have brought some precious preliminary information related to fuel pins deformation modes, grids and nozzles yielding, array deformation (expansion or contraction) and sliding (uniform and heterogeneous). In complement, some elementary tests (lateral bending, axial compression…) were also carried out on fresh PWR fuel rod samples to determine maximum loads supported by un-irradiated claddings (see Figure 1 (c)).

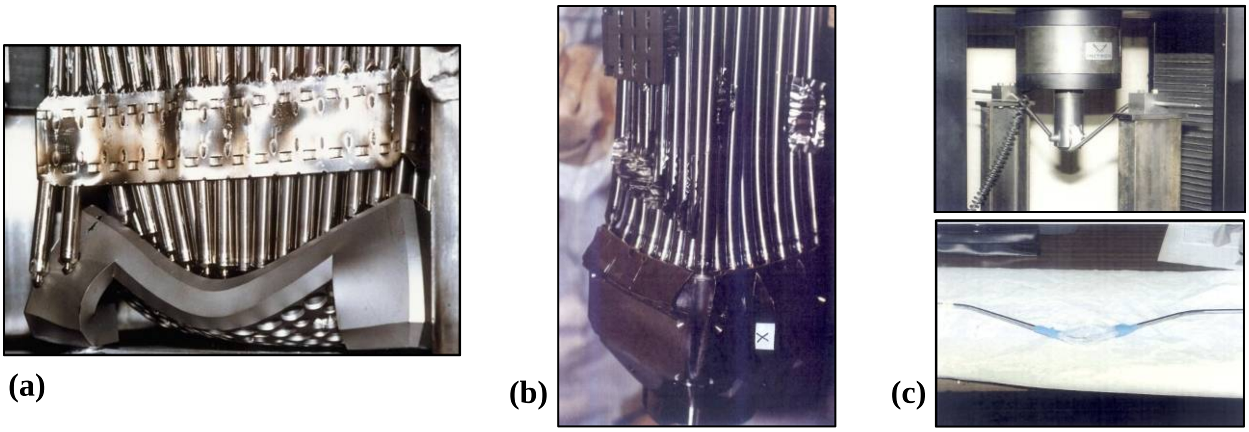


Figure 1: Views of dummy fuel assemblies and rods used in TNI qualification tests: (a) Fresh PWR FA after 9-m drops, (b) Fresh BWR FA after 9-m drops, (c) Bending test of fresh PWR fuel rod sample

Typical damage to fresh FA were then well observed; but not much data concerning irradiation effects on FA in drop conditions was available to deduce used FA behaviour from fresh FA drop tests results. In consequence, TNI and INS decided in the early stages of the project to carry out an extensive testing programme with both fresh and used fuel rods in order firstly to obtain information on used fuel rods properties, and secondly to determine uncertainties relative to some specific loading configuration of fuel rods in FA. Details concerning the objectives and test devices of the twelve tests of this programme have been presented in [1] and some of them are illustrated on Figure 2.

On the basis of a preliminary analysis of potential damage to FA, these tests were focused on elementary phenomena with simple experimental set-ups to study bending or buckling of rods sample, or even the 9-m drop of single fuel rod. Fresh fuel rods samples were generally made of actual Zircaloy claddings with natural or depleted UO2 pellets. Used fuel rods samples were cut from actual fuel rods that were irradiated up to 40 or 50 GW.d/tU. Results of some already available INS tests on used fuel rod samples were also included in the results of this testing programme.

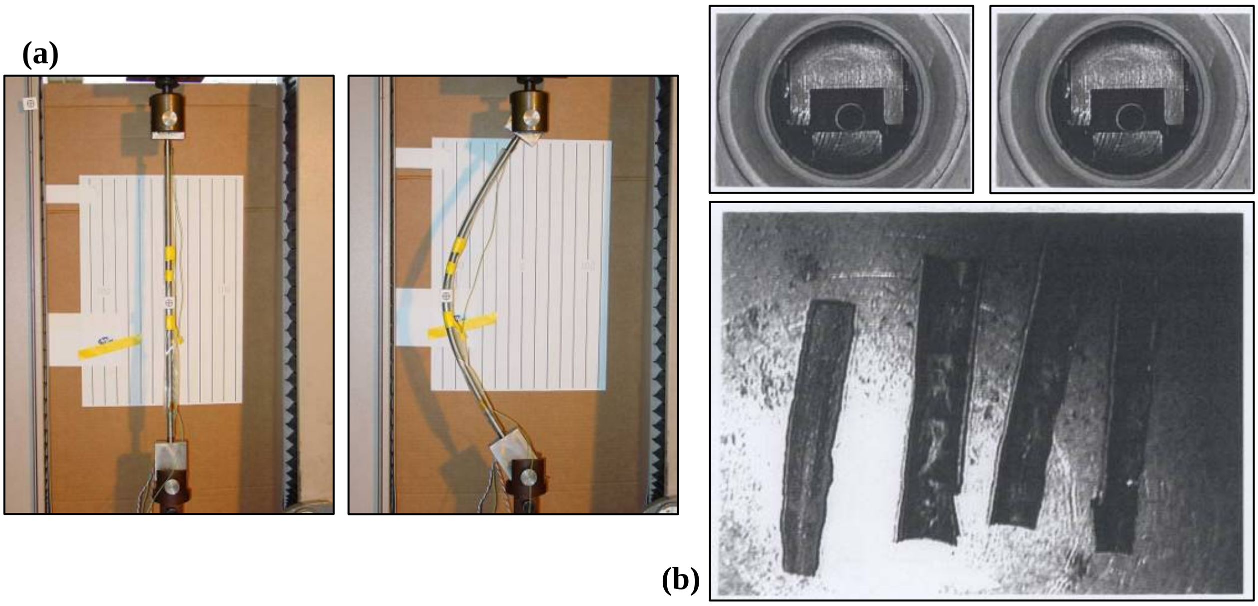


Figure 2: Views of elementary tests on fuel rods samples: (a) Tests 1 to 3: Buckling of fresh LWR fuel rods samples, (b) Test 8: Crushing of empty claddings from used BWR fuel rods

3. BUILDING THE FIP METHODOLOGY

From the data collection arising from the testing programme described above and the preliminary damage analysis, most of the phenomena that could potentially lead to fuel rods and FA damage (i.e. mainly axial sliding, plastic deformations, and the resulting potential ruptures and fuel release) have been observed and studied in order to determine, either directly (by tests results analysis) or indirectly (by finite elements analysis), maximum allowable loads (i.e. maximum loads before or at rupture) sustained by fuel rods in configurations associated to accident conditions of transport.

Considering FA typical structure and the sequence of events during FA deformation, these tests results have helped building up an extensive damage analysis that describes each type of damage specific to the drop direction (i.e. axial or lateral), and sometimes depending on the type of assemblies (i.e. PWR or BWR FA). Main phenomena leading to fuel rods damage and deformations are:

- In lateral drop:
    - Bending in intergrid region and transversal shearing at grids level;
    - Longitudinal compression and shearing on cladding generatrix by rod-to-rod or rod-to-wall contacts;
    - Transversal shearing at rods ends in BWR FA when the nozzle is not supported by lodgement walls.
- In axial drop:
    - Buckling in the bottom intergrid region, mainly in PWR FA;
    - Pure axial compression and impacts of fuel rod ends on the nozzle;
    - Concurrent bending of rods ends and nozzle plate in BWR FA.

Additionally, one of the many information coming from all tests is that fuel rods and structural elements from fresh and used FA are submitted (depending on the FA type) to the same mechanical loadings (in relation to the drop direction) with similar boundary conditions. In consequence:

- Fuel rods maximum loadings occur in the same locations leading to preferential rupture sites;
- Only the extent of fuel rods deformation before rupture is modified by irradiation effects because of the evolution (hardening) of claddings material properties with irradiation.

As a result, similar analytical approaches are used to quantify fuel rods deformation extent under such loadings, provided that claddings material properties are corrected to take into account the hardening effect of irradiation (mechanical strength increase and ductility decrease).

Therefore, analytical approaches proposed in FIP methodology are of two types:

- In the elastic domain of claddings, direct analytical calculations are possible.
- In the plastic domain of claddings, similarity calculations with a reference test (either drop tests results of fresh FA, or elementary tests on fresh or used fuel rods) using elastic formulas are made. If results of tests on used fuel rods are available, comparisons of these results are used preferentially when studying a used fuel case.

FIP methodology application domain is essentially focused on standard designs of LWR FA in typical configurations of lateral and axial drops. But the frame remains open: it does not preclude differences in assemblies' design, partial or adapted application of proposed approaches or FEA-based analyses provided that evaluations are performed in the same spirit.

4. STRUCTURE OF THE METHODOLOGY

FIP methodology structure is based on flow charts of methods that give step-by-step guidelines to analyse fuel rods mechanical behaviour in all possible loading configurations arising from accident conditions of transport.

As the mechanical behaviour of FA during drops depends simultaneously on the drop direction (2 cases: lateral or axial), the FA type (2 cases: PWR or BWR) and the irradiation state (2 cases: fresh or used), it is necessary to distinguish the resulting 8 (= 2 x 2 x 2) typical drop configurations, which is done through 11 flow charts (some drop configurations can be studied using two different flow charts in relation to the available data and the necessary safety margin).

Each flow chart has a similar structure from top to bottom. On the top part, the considered case ("case definition") is defined with the following data: drop direction, associated g-load, FA type, burn-up, and claddings temperature. Then, the central part is a series of mechanical calculations (firstly, "elastic approach"; then, "uncontrollable rupture risks"; and finally, "limited rupture risks") that permit to estimate rupture risks. Finally, in the bottom part, a synthesis ("criticality hypotheses") on potential fissile material release, array deformation and sliding is presented. The main steps of the analysis of a typical flow chart are presented on Figure 3.

Also, flow charts have a similar organisation from left to right: the severity of the case and thus the severity of the conclusions increase towards the right. Therefore, the left side is dedicated to cases of low severity (only low or insignificant deformations and no rupture risk). In the right side, extreme cases are excluded as they lead to uncontrollable rupture risks (which are not further deepened) and unacceptable hypotheses for the safety-criticality study. Finally, in the central part, cases leading to limited rupture risks are evaluated and the associated conclusions (i.e. entry data for criticality study) are presented.

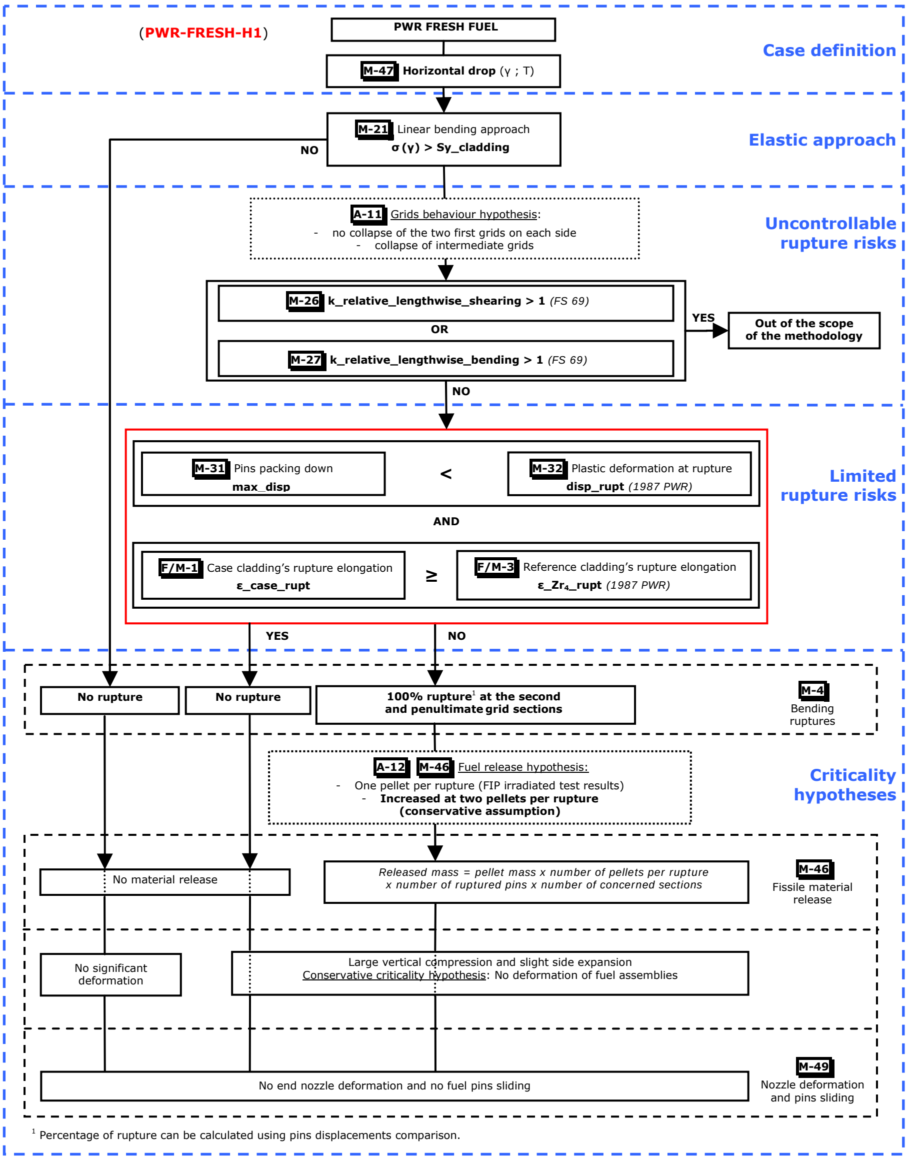


Figure 3: Typical flow chart of FIP methodology

5. STEP-BY-STEP DESCRIPTION

The primary data to define a given case are the drop direction, associated g-load, claddings temperature, FA type and burn-up; knowing these leads to the selection of one drop configuration among eight, and further considerations of the necessary safety margin or available data lead to the selection of a single flow chart.

The elastic approach consists in determining the appearance of yielding by direct calculations of fuel rods intergrid bending in lateral drop, and of fuel rods buckling and nozzle plate bending in axial drop. If there is no yielding (case with low g-loads), there is absence of fuel material release, array deformation and sliding, and nozzle deformation.

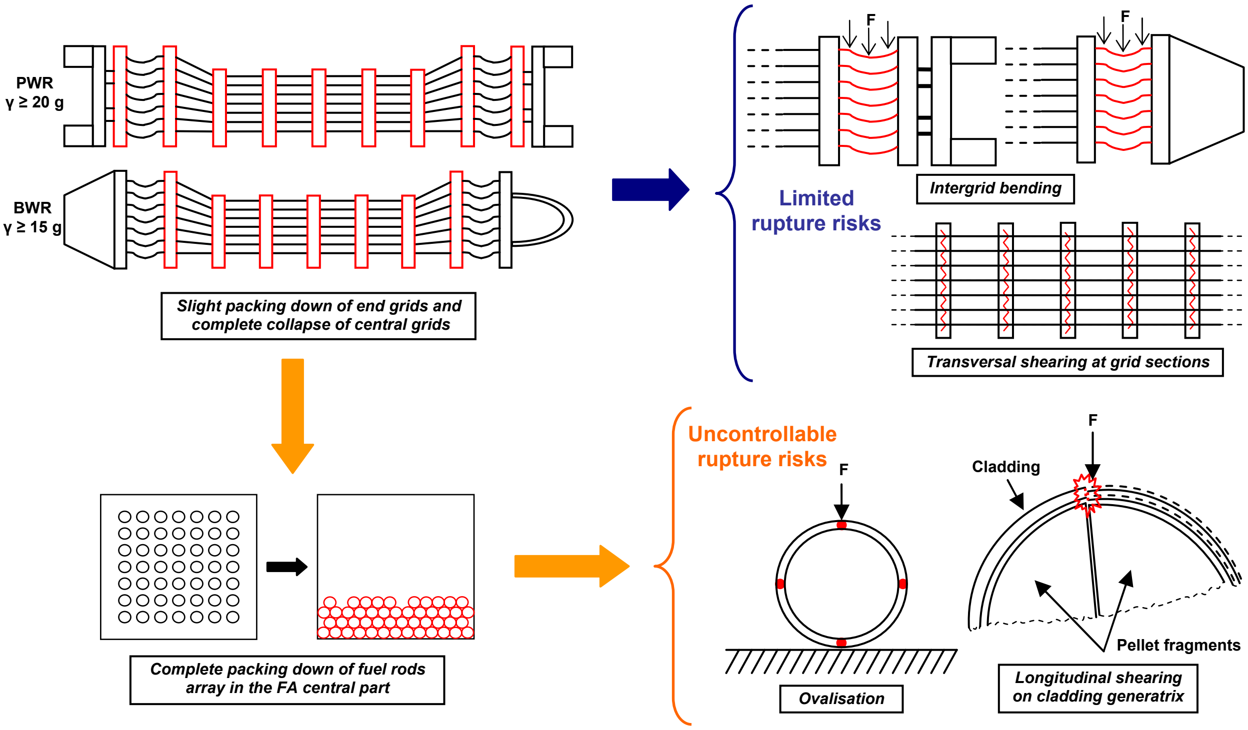


Figure 4: Claddings rupture risks evaluation in lateral drop

In lateral drop, in case of yielding, rupture risks evaluation (see Figure 4) leads to consider in a standard way grids collapse in the central part of FA: end grids remain with their initial section, while the central ones are collapsed. This collapse pattern was established on the basis of the results of drop tests with fresh FA and on the consideration of the stiffness provided by end nozzles. This results in a similar collapse pattern of the array that leads to two types of loading on LWR fuel rods:

- A longitudinal loading due to fuel rods stacking up in FA central part that induces rupture risks by ovalisation and shearing in presence of pellets fragments. In case of ruptures, longitudinal crack extent cannot be predicted. Therefore, these two rupture configurations are classified as uncontrollable rupture risks.
- A transversal loading in FA end parts that induces rupture risks by intergrid bending and shearing at grid sections. In these conditions, potential ruptures appear in two cladding transversal sections leading to limited fuel material release. Therefore, these two rupture configurations are classified as limited rupture risks.

In axial drop, in case of fuel rods yielding, rupture risks evaluation (see Figure 5) concerns:

- Limited rupture risks in fuel rods bottom end transversal section:
  - LWR (mainly PWR) fuel rods' buckling that preferentially appears in the bottom intergrid region (in relation to the drop direction).
  - BWR FA nozzle plate bending, which induces the concurrent bending of fuel rods bottom ends, rigidly connected to it.
  - BWR nozzle plate shearing that could lead potentially, in case of plate rupture, to extreme bending and rupture of all fuel rods ends.
- Uncontrollable rupture risks induced by :
  - Claddings axial compression that potentially leads to local plastic buckling mainly ahead of each inter-pellets zone.

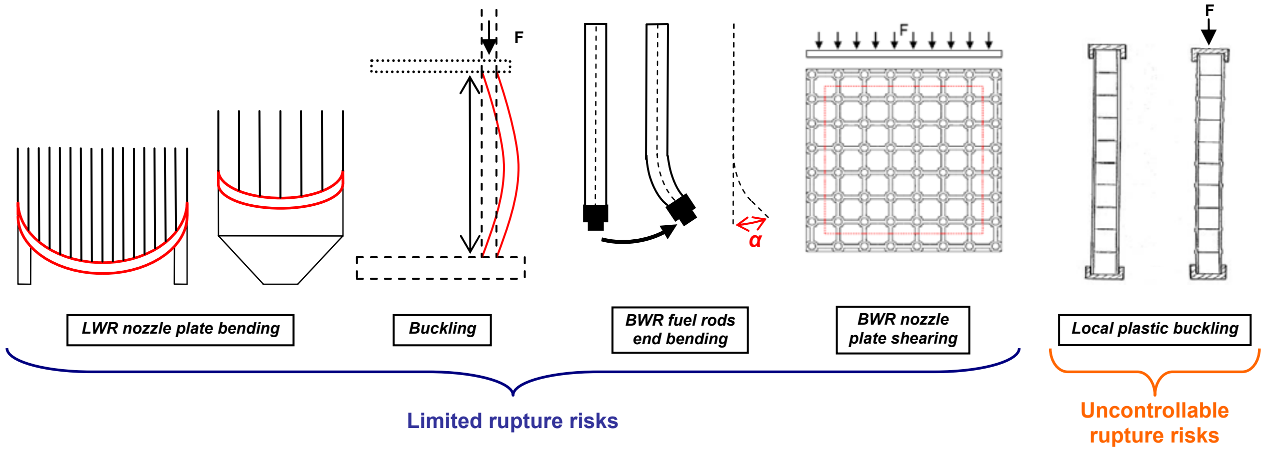


Figure 5: Claddings rupture risks evaluation in axial drop

Then, considering the type of fuel rods loading, their most loaded zone and the grids collapse pattern, the position and number of ruptures in a FA section (this latter can be conservatively increased to 100 % fuel rods ruptures in the concerned section in relation to the necessary safety margin), and the number of concerned FA sections (i.e. 2 sections in lateral drop and 1 section in axial drop) are defined according to FA type and drop direction. In lateral drop, potential ruptures occur in the section of the two penultimate grids in PWR FA and in the two end intergrid zones in BWR FA. In axial drop, potential ruptures occur in the mid-span section of the bottom intergrid region of PWR FA and at the bottom ends of fuel rods in BWR FA.

From this number of ruptures, the total amount of released fuel is estimated considering results of FIP tests 11 and 12, which analysis provides standardized amount of fuel released per open section of fuel rod in relation to FA type and irradiation state. Indeed, a statistical analysis of the fuel mass released from each broken sample of tests 11 and 12, and the consideration of additional margins have led to build conservative hypotheses of fuel mass release per broken fuel rod section. These hypotheses, expressed in terms of integer number of pellets (1 or 2 pellets, depending on the drop case), bound the effects of any uncertainties in tests results analysis, rupture location and local burn-up.

Array deformation in lateral drop (see Figure 6) is connected to grids collapse pattern. As grids are collapsed in the central part of FA, there is a reduction of the fissile section of LWR FA that are generally under-moderated. The conservative hypothesis consists in retaining the initial fissile section as entry data for the criticality study.

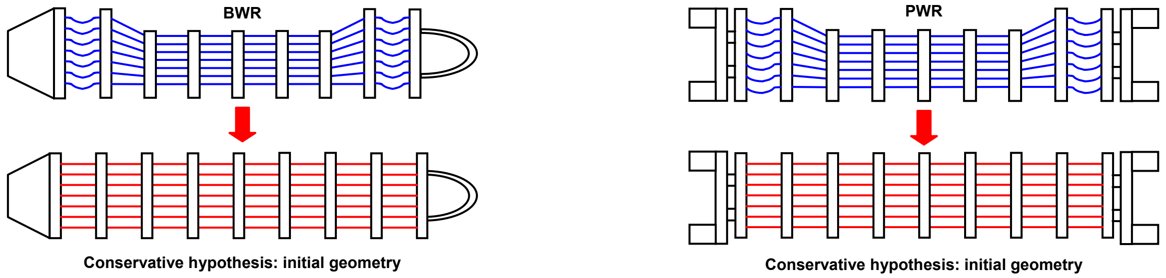
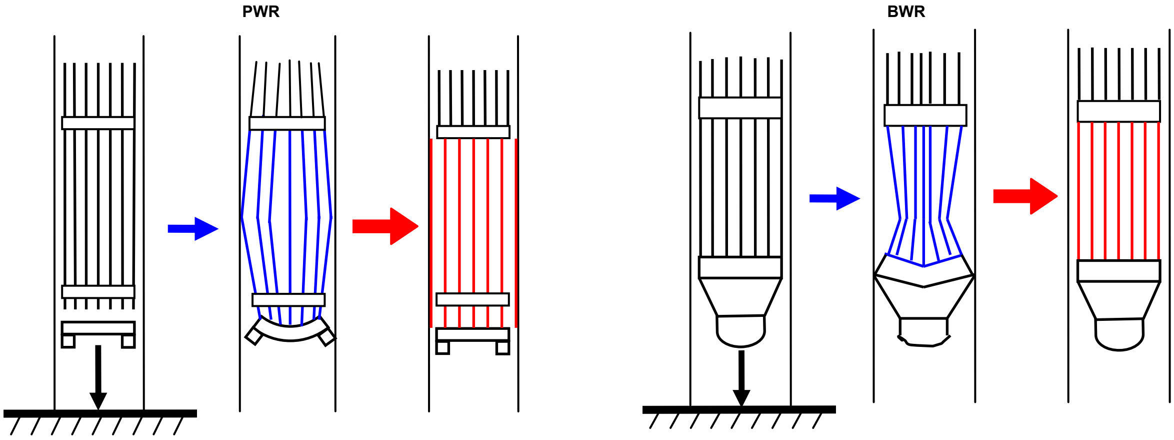


Figure 6: Hypothesis for array deformation in lateral drop

Array deformation in axial drop (see Figure 7) is connected to fuel rods deformation mode: PWR fuel rods buckling and BWR fuel rods ends bending, leading respectively to an expansion of the PWR array and a contraction of the BWR array in the bottom (in relation to the drop direction) intergrid region. For BWR FA, similarly to the lateral drop, the conservative hypothesis is the initial non-deformed geometry in the bottom intergrid, while an expansion could be introduced in the next intergrid by continuity of deformation. For PWR FA, as buckling extent cannot be easily determined, the pessimistic hypothesis is to consider a uniform expansion of the array in the deformed bottom intergrid. Complements on these hypotheses for LWR FA are discussed in [2].



Conservative hypothesis: uniform expansion up to lodgement walls in the bottom intergrid region

Conservative hypothesis: initial geometry (Possible expansion in the second intergrid region)

Figure 7: Hypothesis for array deformation in axial drop

Finally, array displacements, which main contributions are uniform and differential sliding of fuel rods induced by nozzle deformations, are presented in relation to the drop direction. In lateral drop, there is no load to induce either fuel rods sliding through grids, nor nozzle deformation; in consequence, no array displacement is considered so that the active zone of fuel rods remains in its initial position. In axial drop, even for low g-loads, PWR fuel rods are uniformly moving as they close the initial gap between their ends and the nozzle plate. There is no such gap in BWR FA as BWR fuel rods are connected to nozzles. Then, depending on the design of the nozzle for both type of FA, LWR fuel rods displacement consists of: uniform sliding in case where the nozzle has easily crushed parts (shell, tripods, etc.) and differential sliding induced by nozzle plate bending resulting from the loading of FA top part (including fuel rods and upper nozzle) in axial drop. As a result of array displacement, the final position of the active zone is deduced.

Therefore, combining the amount of fuel potentially released, the hypotheses of array deformation and sliding that are the results of FIP methodology application, realistic and conservative hypotheses are used as entry data for the safety-criticality evaluation of a package design.

6. CONCLUSION: PRESENT SITUATION

In response to safety requirements and to British and French CA questions related to fuel behaviour in transport conditions, a joint effort from INS and TNI has permitted a better understanding of potential FA damage and interactions between FA components during impacts, and helped building a methodology to assess conservatively LWR FA behaviour in accident drops.

All knowledge acquired in the course of FIP development is synthesized in the so-called Technical Guide, which is the final deliverable of the project. It extensively presents the methodology (described above) and builds up all background experimental data (tests specifications, results and analyses).

FIP methodology and Technical Guide have been submitted to CA in late 2008 and are under review since then. Further studies and developments to integrate claddings embrittlement effects will lead to a comprehensive knowledge of FA behaviour in accident conditions of transport.

REFERENCE

[1] Testing of LWR fuel rods to support criticality safety analysis of transport accident conditions, Peter Purcell & Maurice Dallongeville, 14th International Symposium on the Packaging and Transportation of Radioactive Materials (Patram 2004), Berlin, Germany, September 20-24, 2004, Paper 134

[2] Method to evaluate limits of lattice expansion in light water reactor fuel from an axial impact accident during transport, Peter Purcell, 14th International Symposium on the Packaging and Transportation of Radioactive Materials (Patram 2007) Miami, Florida, USA, October 21-26, 2007, Paper 310