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Analytical approach to PWR fuel assembly distortions

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ABSTRACT

More than two years of investigations on the mechanical behaviour of the core have led to clear understanding of incomplete RCCA insertions in PWRs. Since the first event reported in 1994, a large-scale programme based on extensive experience feedback and on a detailed analytical approach has been undertaken. This paper recalls the goals of the analytical approach to in-reactor F.A. bowing, describes the tools developed for this purpose and presents the validation steps and the main results obtained with the preventive measures applied to the products.

1 - INTRODUCTION

Past experience feedback showed that, in Pressurized Water Reactors, fuel assembly bowing could from time to time impede in-reactor handling operations, thus extending core fuelling and defuelling times. More recent events, in various reactors and for a variety of assembly designs, have shown that higher deformation levels could also lead to an increase in the drop time, or even incomplete insertion, of the RCCA into the assembly.

2 - OBSERVED BOWING AND POTENTIAL CAUSES

Numerous measurement campaigns, aiming to control incomplete RCCA insertion problems in particular, have been undertaken. Regarding lateral deformation, assembly bowing is generally measured on the 4 faces at each grid elevation ; most often, the assemblies take a C or S shape. More than 360 assemblies from 15 different reactors were measured, taking care to thoroughly cover all the parameters liable to influence assembly bowing - operating conditions, type of design, burnup, core location for example. In some reactors, the assembly deformation shapes were tracked for several cycles.

The potential causes of bowing are many :

- in manufacturing, the manufacturing tolerances, skeleton assembling and rod loading may lead to deformations, but they generally remain slight (bows on the order of 1 mm).

- during operation, the thermal gradients and the fluence gradients, by generating differential axial growth of the guide thimbles and rods and differential relaxation of the grid springs, lead to F.A. bowing.

- as soon as they are loaded, feed assemblies are also liable to bow through interaction with neighbouring bowed assemblies.

3 - AIMS OF THE ANALYTICAL APPROACH AND METHODOLOGY USED

The analytical approach developed by FRAMATOME with the associated tool DEFI firstly aims for better understanding of the assembly bowing mechanisms in order to identify the key parameters through quantitative evaluations. This approach should then make it possible to predict fuel assembly bowing during the design of new products, particularly when elevated burnups are targeted.

The methodology used to predict the assembly axial behaviour under irradiation and the associated CASI software [1] served as a basis for the program development. The method relies upon :

- a detailed mechanical model of the assembly, consisting of structural elements such as beams, linear and non-linear springs and sliding elements,

- irradiation behaviour models,

- successive mechanical equilibrium calculations carried out by means of non-linear static resolution modules.

4 - TOOLS

Two types of mechanical model were developed : single assembly or set of assemblies.

The detailed single assembly models are used for fine analysis of assembly lateral behaviour in various operating situations. In particular, they are used to evaluate the influence of the various design parameters on the bowing susceptibility of the assemblies.

However, when the interactions between assemblies in the core become large - this is the case when assembly bow becomes substantial compared with the inter-assembly gap - the single assembly model is no longer sufficient ; assembly row and full core models more representative of in-reactor simulation are needed.

For each of the models, the DEFI software is used for sequencing of mechanical equilibrium calculations allowing for the phenomena and loadings specific to the various situations experienced by the assembly during its lifetime and liable to lead to bowing.

4.1 - SINGLE ASSEMBLY MODEL

4.1.1 - Detailed mechanical model

The assembly is modelled in a vertical plane according to the following principle :

- the guide thimble bundle is represented by n vertical beams (n≥2). Each of these beams is discretized into several elements, at least one element per span ; the dashpot and the upper and lower connections generally have specific sections.

- the rod bundle is represented by p vertical beams (p≥2). Each of these beams is discretized into several elements, with at least one element per grid span. The rod-top and bottom nozzle gaps are modelled by gapped springs.

- each of the grids is modelled by a beam linking the guide thimble and fuel rod beams.

- guide thimble restraint in the grid is represented by a linear rotation spring placed between the grid node and the guide thimble node. The rotation restraint characteristics are taken from individual tests on the grid/guide thimble connection.

- fuel rod restraint in a grid cell is modelled by a set of structural elements reflecting the non-linearities and working in the 3 degrees of freedom, i.e.
. a linear translation spring models lateral rod supporting,
. a threshold sliding element models axial supporting,
. linear and gapped rotation springs and a rotational sliding element model the rotational restraint of the fuel rod in the grid cell ; the characteristics of these elements are taken from individual tests on the grid/rod connection.

- the top and bottom nozzles are modelled by a set of horizontal and vertical beams.

- the holddown system is represented by two linear springs at the end of which the holddown forces are applied.

Figure 1 shows for example a detailed assembly model with 2 guide thimble beams, 6 rod beams, one intermediate node per span.

The mechanical model is validated from a lateral tensile test run on a fresh assembly mock-up ; figure 2 shows the good agreement between the model and the test. The development of the model is the result of iterations aiming for a good trade-off between the number of elements and the representativity of the shear effect.

4.1.2 - Phenomena and loadings

On the basis of the detailed assembly model, DEFI simulates various physical phenomena occurring under irradiation :

- thermal expansion of the guide thimbles and fuel rods,
- irradiation growth of guide thimbles and fuel rods,
- relaxation of grid spring forces,

- irradiation creep of guide thimbles and fuel rods,
- fluence gradients and thermal gradients across the assembly.

The irradiation growth of the guide thimbles and fuel rods and the relaxation of the grid spring forces are expressed versus fast fluence (E > 1 MeV). The behaviour laws are drawn from experience feedback in experimental pile and in power reactor.

As for thermal expansion, irradiation-induced elongation is input into the mechanical model by means of preloads in the model beams. Spring force relaxation in the grid cells is reflected in the model in a reduction of the spring deflections and of the thresholds of the sliding elements representing the grids.

Irradiation creep, assumed linear versus time and stress, is defined through the value of the characteristic creep time T_C after which the action of creep leads to a permanent set equal to the elastic strain. The estimation of this characteristic time for various materials is obtained after tests on samples in pile. The creep trend is addressed by elastic analogy (modification of YOUNG's modulus) ; the method used assumes that the elastic deformations are small compared with the creep-induced permanent set, which is confirmed during the irradiation cycle.

The software tool for axial behaviour analysis CASI [1], with an assembly growth database containing more than 500 measurements, enables the modelling of these major in-reactor phenomena to be refined.

These physical phenomena can be combined with specific loadings which are directly input into the mechanical model :

- mismatch of the forces exerted by the holddown system leaves,
- external forces irrespective of their origin (adjacent assemblies for example).

4.1.3 - Analysis of assembly bowing

By means of the detailed model described hereabove, the DEFI software enables assembly bowing to be analyzed at each step in the assembly in-reactor lifetime, i.e. during :

- vessel closure,
- pump startup,
- transfer to hot conditions,
- irradiation,
- return to cold conditions,
- pump shutdown,
- vessel opening.

When several steps are linked, the stresses and strains in the structure calculated at a given step constitute the initial conditions of the following calculation ; the mechanical model is updated so as to consider the phenomena and loadings specific to the new calculation step : characteristics of the elements, boundary conditions, loading. The irradiation phase is discretized into several steps in order to allow for the interaction of the various non-linear phenomena : large deflections, relaxation, creep and growth.

The assembly can :

- be assumed to be initially straight then to develop bowing arising from the imposed loadings (mechanical forces, thermal gradients or fluence gradients) or an assymmetry intrinsic to the assembly (for example heterogeneity of the grid spring forces).
- exhibit initial bowing : the bowing shape and amplitude are then defined by the assembly bows at one or more grids in the model plane.

Each calculation phase supplies the deflections at the model nodes, i.e. the assembly deformation shape.

In addition, DEFI can evaluate at the end of the calculation the tilt taken by the assembly when it is set down or suspended by respectively simulating the assembly set down or suspended as during handling.

Regarding assembly manufacturing, DEFI can simulate the insertion of the fuel rods into the skeleton and thus evaluate any induced bowing.

4.1.4 - Creep behaviour of the assembly under axial loading

In order to closely investigate the creep behaviour of the assembly, a new parameter, called doubling time and noted T_D, was defined. It enables assessment of the capacity of an assembly to bow under axial loading : the doubling time is defined as the time needed for an assembly to double a given initial bow. The detailed model evaluates the doubling time of an assembly according to the materials properties and in response to the axial loadings and operating conditions.

4.2 - ASSEMBLY ROW MODEL

4.2.1 - Mechanical model

The assembly row model is built as follows :

- Each assembly is modelled by a simple beam working in the plane of the row, each of the latter being discretized so that each structural mixing grid is represented by a node. Each assembly beam is restrained at its lower end and semi-restrained at its top end, a linear rotation spring modelling the possibility of nozzle rotation through the holddown system leaves. The characteristics of each assembly beam take into account the specific assembly design and the burnup and are evaluated from the detailed model described hereabove.

- The baffles are represented by fixed nodes on each side of the row.

- The interactions between assemblies and between assembly and baffle are modelled by gapped translation springs whose rigidity corresponds to the external grid stiffness obtained from mechanical tests.

Figure 3 presents a 15-assembly row model.

4.2.2 - Analysis of the behaviour of a row

First of all, the row model enables the in-reactor equilibrium of a row of bowed assemblies to be calculated. The free bows measured at the grids of each of the assemblies are the input data ; the calculation supplies the in-reactor assembly bows, cold or hot, in elastic mechanical equilibrium.

Secondly, based on the equilibrium calculated in hot conditions at beginning of cycle, DEFI evaluates the in-cycle trend in assembly deformation shape under irradiation creep, allowing for the interactions at each of the grids. As for the detailed model, the creep is assumed linear and processed by elastic analogy with consideration for the characteristic creep time.

4.3 - CORE MODEL

4.3.1 - Mechanical modelling of the full core

The full core model is used for modelling all the assemblies in the core and their interactions at a given grid level. The model is built as follows :

- Each assembly is modelled by a spring representing the assembly lateral stiffness at the relevant grid level. This stiffness is adjusted in response to the assembly design and burnup.

- The interactions between assemblies or between assembly and baffle are represented by gapped springs : their rigidity is representative of the grid external stiffness and an average gap between assemblies and between assembly and baffle is generally considered.

Figure 4 presents a full core model for a 900 MW reactor.

4.3.2 - In-core assembly deformation shapes

As for the row study, this model makes it possible to calculate the beginning of cycle in-reactor equilibrium of all the assemblies at this grid level, based on the free bows of the assemblies at a given grid level.

The core variation during the cycle can then be evaluated by allowing for irradiation creep. During the cycle, the initial equilibrium changes under the effect of the holddown forces, the interaction forces and the irradiation creep. For each assembly taken singly, an amplification factor a is applied to the initial deformation shape in reactor :

$a = 2^{T/TD}$

where T represents the cycle length,
and T_D the doubling time evaluated with the detailed assembly model.

By inputting the calculated bows into the mechanical core model, the interactions between assemblies are allowed for and the bows of all the assemblies in the core at end of cycle are calculated.

As it is not practicable to measure all the irradiated assemblies entering the cycle for a new cycle, this model is also used in the extrapolation of the measurements taken at end of cycle to all the assemblies in the core.

5 - RESULTS

5.1 - DETAILED MODEL

The in-reactor experience feedback has shown that lateral stiffness is a first key parameter when the focus is on assembly bowing. Thus, as a first step, the detailed model evaluates and compares the assembly lateral stiffnesses for various existing designs, then analyzes the influence on stiffness of the various assembly mechanical design parameters like guide thimble thickness, dashpot geometry, grid geometry.

Secondly, calculations based on the detailed model were carried out in order to:

- quantify the bowing levels induced by pressure and fluence gradients between the opposite faces of the assembly or due to a mismatch in the holddown spring forces,
- find the mechanisms initiating the S-shape, given that, at identical bow amplitude, an S-shape proves more critical for RCCA drop time than a C-shape.

Figure 5 shows the deformation shape induced by the differential axial growths of the guide thimbles and the fuel rods subjected to a power gradient between the opposite faces of the assembly.

In all the cases, the calculated bow amplitudes remain slight compared with those commonly measured at the end of the cycle : the bows caused by these phenomena are amplified by irradiation creep under axial loading.

This finding led us to closely investigate the creep behaviour of the assembly ; this investigation was conducted by means of the doubling time T_D defined hereabove. The doubling times of various designs existing in a range of reactors were evaluated and mutually compared. As for lateral stiffness, an analysis of sensitivity to the design parameters was conducted.

5.2 - ROW MODEL

The row model serves first of all to estimate the deformation shapes of the assemblies once they are loaded in the core, based on assembly bow measurements or hypotheses on the free bows of each of them. In this way, the calculations provide evidence of the good mechanical behaviour of assembly rows in highly-bowed cores.

Next, this model yields greater insight into the assembly interaction phenomena, either through a complete row model or by fine analysis of the behaviour of two interacting assemblies or one assembly located close to a baffle. In particular, the model calculates the transition from a C-shape to an S-shape by interactions, as observed in reactor.

Further, the row model evaluates the influence of some parameters for which interactions between assemblies are paramount ; these include the length of the irradiation cycles, the fuel loading mode - IN-OUT, OUT-IN and hybrid - and the available gap between assemblies.

The measurement of a complete row of assemblies was performed at end of cycle in a reactor. The comparison of measurements and predictions enabled qualitative and quantitative validation of the row model.

5.3 - CORE MODEL

The core model is used to track the bow trends of all the assemblies in a core. Initialization of the calculations at the start of a given cycle is carried out on the basis of the bows measured or deduced from the location of the assemblies at the previous cycle. Depending on the bow shape, several grid levels can be considered. The calculation supplies the elastic bows and the interaction forces between assemblies. As an illustration, figure 6 represents the deflections at a given grid level of all the assemblies in a 900 MW reactor.

The average bow of all the assemblies in the core at a grid level is a good indicator of the overall core trend in terms of bowing. At each loading, the insertion of feed assemblies and the reshuffling of the core lead to a significant reduction in average bow ; during the cycle, the average bow increases under the effect of irradiation creep. Tracking of this parameter in reactors where the assemblies were heavily bowed enabled the gain yielded by assembly modifications - guide thimble widening and thickening, holddown force decrease - to be analytically quantified ; it was afterwards possible to validate this quantification by experience feedback.

The core calculations also allow the behaviour of the RCCAs during the cycle to be estimated. Based on experience feedback, an indicator representative of the RCCA drop time and calculated from the bows at the grids of the facing assembly is defined. Tracking of this indicator for the rodded assemblies of a given reactor provides evaluation of the risk of slowdown, or even incomplete insertion of RCCAs during the cycle. In particular, the impact of the type of loading pattern on RCCAs behaviour can be studied. Special configurations with 180° inversion of some assemblies in the core can also be allowed for.

6 - CONCLUSION

The analytical approach presented here, developed in three directions - detailed single assembly model, row model and core model - allows F.A. bowing to be investigated both from the standpoint of the initiating mechanisms and from that of propagation of bowing in the reactor.

The calculations provided greater insight into the bow phenomena and made it possible to propose and justify remedies to the problems of incomplete RCCA insertion encountered in some reactors. The tools developed and the results obtained were validated, using the extensive databases on assembly growth and bow coming from in-reactor experience feedback.

These tools are also of great importance for the prevention of F.A. bowing during the design of new products, particularly when the aim is for elevated burnups.

REFERENCE

1. H. SALAÜN, C. CALLENS, S. DE PERTHUIS, J.C. LEROUX. - CASI : Prediction of fuel assembly axial behaviour under irradiation. *SMIRT 12* Stuttgart, 1993.

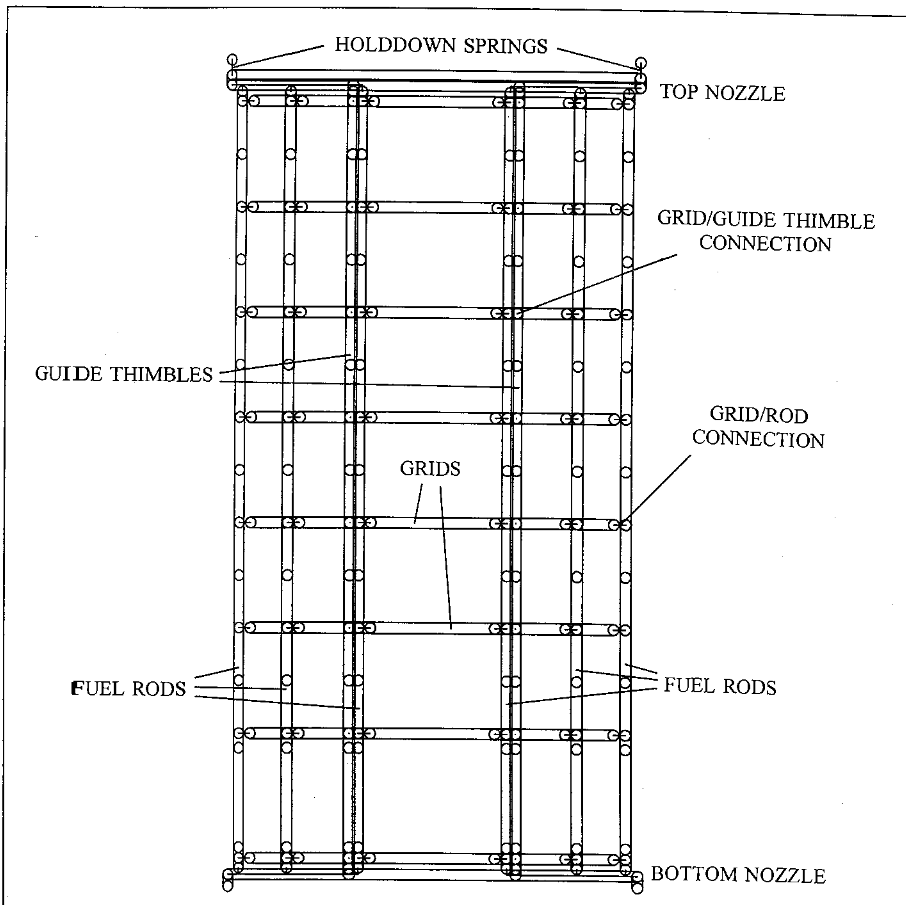

Figure 1 : DETAILED MECHANICAL MODEL OF THE ASSEMBLY

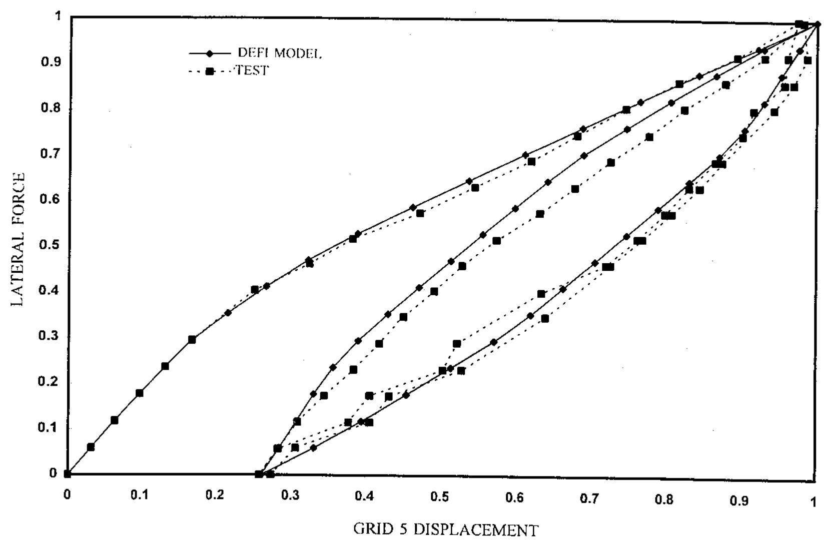

Figure 2 : LATERAL TRACTION OF THE ASSEMBLY - MODEL VALIDATION

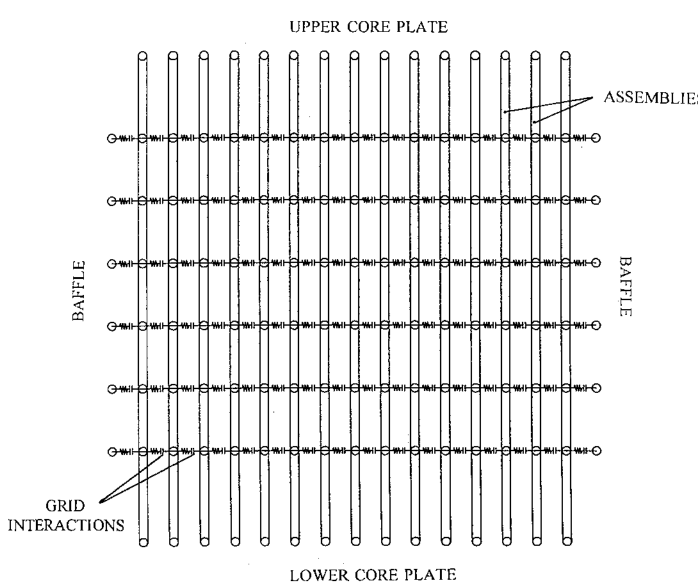

Figure 3 : 15-ASSEMBLY ROW MODEL

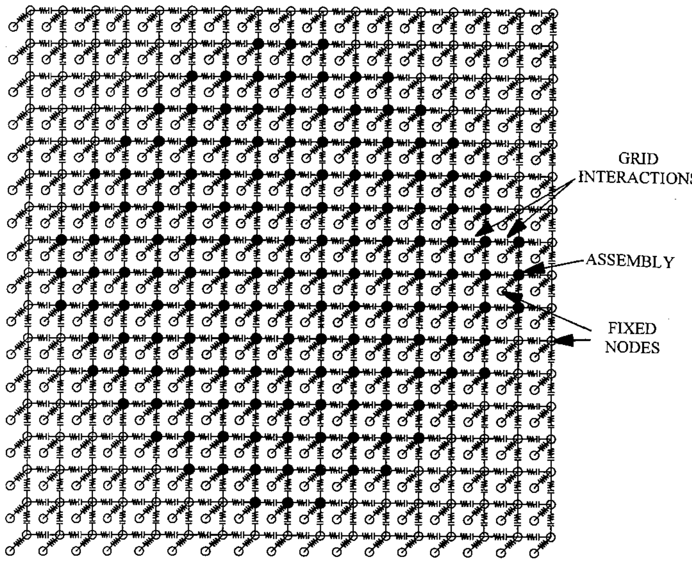

Figure 4 : FULL CORE MODEL - 900 MW REACTOR

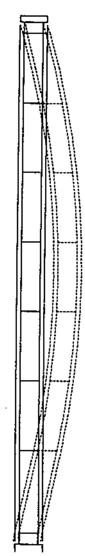

Figure 5 : SINGLE ASSEMBLY DEFORMATION SHAPE UNDER THE EFFECT OF A POWER GRADIENT

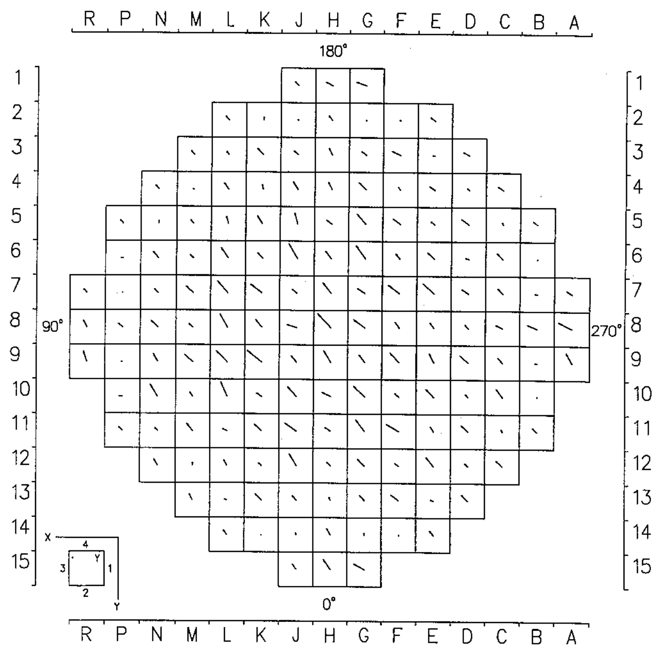

Figure 6 : IN-REACTOR ASSEMBLY BOW - CORE MODEL