SATIN: A Computer Model for the Analysis and Prediction of Thermoelastic Vibrations in FBR Gridded Subassemblies

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ABSTRACT

Deep wearing marks on fuel claddings at the level of the grid dimples, repeatedly appeared on some LMFBR subassemblies irradiated in the KNK-II reactor.

Similar observations have been encountered with almost identical subassemblies, irradiated in PHENIX, in view of testing the gridded design of the second core of the SNR-300. Theoretical and experimental evidences indicate that those damages are likely due to thermoelastic vibrations. This paper presents the SATIN simulation code, which integrates the major physical first principles that induce or influence such instabilities. It also reports on the agreement of SATIN with available experimental observations.

INTRODUCTION

The subassembly design of the first SNR core has been successfully tested since many years and none of the irradiated pins showed wearing marks, if one excludes those irradiated in the KNK-II reactor.

A new design was proposed for the second SNR core, featuring an increase of the 6 mm pin diameter up to 7.6 mm and a reduction of the pitch-to-diameter ratio from 1.32 to 1.16. Standard subassemblies of this type in the KNK-II reactor indicated clad failures initiated by a wearing process at the level of the grid dimples. Similar subassemblies irradiated in PHENIX showed similar damages on the claddings at the level of the grid dimples. An intensive experimental research activity, especially at INTERATOM and KfK, has been devoted to the study of heat induced vibrations, both by examining again previous experiments and by performing new out-of-pile tests. The SATIN program presented here, is part of the theoretical effort made by BELGONUCLEAIRE to identify that thermoelastic wearing process and, ultimately, to check the stability of subassembly designs.

DESCRIPTION OF THE HEAT INDUCED VIBRATIONS

The oscillation mechanism, as reproduced by SATIN and also identified in [1], can be considered as a sequence of elementary steps :

1. Due to any reason, a very small deformation of a pin appears.
2. The flow around it becomes asymmetrical.
3. The heating of the surrounding liquid therefore becomes asymmetrical too and produces a horizontal temperature gradient.
4. That temperature gradient induces a bending of the pin.
5. The process depicted by steps 2 to 4 repeats and usually amplifies the initial small deformation.

6. The shape of the pin is finally restrained by the grid supports, as their dimples only allow a small clearance for easy dismantling after swelling. A "Loch Ness Monster" shape tends to develop to best use the limited freedom left to pin contortion (Fig. 2). At that time, the plot of the horizontal gradient and of the pin deflection versus elevation are similarly shaped and a pseudo-stable position is reached.
7. The upward coolant flow then shifts the temperature profile toward the top. The gradient is thus blown upward and so is the deformation profile.

The bottom line is that a deformation wave is continuously generated and blown upward, inducing a remarkable oscillation process.

Some designs do NOT amplify the initial deformation (step 5). They are inherently stable as disturbances tend to vanish. Advanced designs are usually unstable, as one tends to decrease the space between the pins, making the effectiveness of the cooling more sensitive to pin deflection.

According to that scheme, the occurrence of oscillations increases with the average linear power within the core, the thermal expansion coefficient of the steel and the diametral clearance at the level of the grid (i.e. the maximum pin diameter that the dimples could accommodate minus the actual pin diameter).

It decreases with the coolant velocity and the pitch between the pins.

The flexion modulus of the cladding section does not favor instability but, it has a direct effect on the severity of the damages as the generated forces are proportional to it.

The span between grids is a very sensitive parameter. If its size is comparable or larger than the wave length of the oscillations, the pin deflections may become significantly larger than the grid clearances and allow pin to pin contacts.

THE MODELS INCLUDED IN SATIN

SATIN integrates consistently several submodels to simulate the vibrations of one reference fuel pin among six neighbours.

1. Variation of the section of the liquid cells surrounding the pin

The fluid around the pin is modelled by n elements, each subdivided into six liquid cells (see Fig. 1). The cross-section of those cells depends on the deformation of the pin. To account for the other pins, one notices that when a cell is, e.g. abnormally hot, the contiguous pins tend to bend toward each other. Actually, any section change due to the deflection of the reference pin could be multiplied by a factor 2 to account for the symmetrical motion of the neighbour pins. For most calculations performed up to now, that factor 2 has been lowered down to 1.5, as in reality, the pins of the subassembly are not likely to all move perfectly symmetrically.

2. Transient axial flow in the liquid cells

Assuming that pressure is uniform at any given level of the subassembly, hydraulic friction theories provide an estimate of the axial flow in the cells. The total axial flow being a constant, the mass conservation law enables to calculate the azimuthal flow between the cells, provided one rejects solutions that allow fluid rotation around the pin (rotation momentum conservation).

3. Transient axial heat convection in the liquid cells

The evaluation of the axial flow is made using a simplified equation for transient convection in a heated pipe, neglecting axial conduction in the coolant allowing for the large axial velocity.

4. Azimuthal heat transfer between the liquid cells

Azimuthal conduction in sodium imposes a correction that tends to equalize temperature at any given level.

Turbulent flow tends to apparently increase conduction transfers. Evaluations made using steady thermohydraulical codes show that eddies can "improve" azimuthal heat transfer by up to a factor 9. To account for that effect, one multiplies adequately the conductivity of the coolant by some kind of Nusselt number.

Azimuthal convection, produced by deformation changes versus elevation, is modelled assuming that the temperature is uniform within the cells. The liquid received by a cell is mixed with its own liquid content. Temperature in the cells that only export liquid to the others remains unchanged.

5. Transient temperature evolution inside the fuel pellets

It is calculated at each of the n levels, using a finite-difference form of the Laplace equation for 2D transient conduction in a cylinder. Axial conduction is thus neglected. The boundary conditions derive either from symmetry conditions or from the heat flow toward the liquid cells.

6. The shape of the pin

It is derived from the thermal gradient which tends to bend it. A trial and error method is necessary as the points where the pin touches the grid supports are not known a priori. It is based on the iterative displacement of Fictitious Grid Supports (FGS). Actual support is usually provided by three dimples at every levels. The dimples are designed to leave a clearance, so that the centreline of the pin is free to move inside a virtual triangular clearance (Fig.1).

A FGS is a perfect hinge, located inside that clearance. A first guess of the position of the FGS is made and the reaction forces on them are derived together with the shape of the pin, using the three-moment equation for a beam submitted to a thermal gradient and supported by n unequally spaced hinges.

The fictitious supports are then moved by very small steps inside their triangle of freedom, until they all satisfy one of the following conditions :

a) if the pin does not touch the grid dimples, the position of the FGS must be such that the reaction force equals zero ;
b) if the pin touches a dimple and can glide (neglecting friction), the position of the FGS must be such that the tangential reaction force equals zero ;
c) if the pin goes into a corner formed by two dimples, the reaction force on the FGS must be inward oriented.

COMPARISON OF TWO SUBASSEMBLY DESIGNS

1. Subassembly from the first SNR reactor core (6 mm pins)

The standard output of SATIN displays up to eight animated graphs on a standard PC [2]. Those shown here have been obtained after a 2.5 second time history.

Fig. 2 presents the deflection of the pin and the corresponding horizontal temperature gradients versus elevation. One can see that those curves are very similar.

Fig. 4 shows the track of the displacement of the pin centreline within the allowed space of freedom at every grid levels (limited to the last 300 ms).

Fig. 6 is a display of the reaction force and of the friction power at the grids. The very small forces acting on the grids are not likely to allow any damaging process, as proven by the irradiation experiments done to qualify those subassemblies. It is worth noting that all those results show little sensitivity to the initial small disturbance.

2. Subassembly from the second SNR reactor core (7.6 mm pins, with grids)

The major difference with the previous design comes from the pin diameter change, the resulting increase of the flexion modulus (+ 166 %) and the decrease of the space left between pins, i.e. the pitch minus the pin diameter (- 37 %).

Fig. 3 is very similar to Fig. 2, but it features a slightly longer wave length.

Fig. 5 shows that, in this case, the pin motion is more erratic than in the previous one. The friction energy and the reaction forces on the grids have soared by an order of magnitude (compare Fig. 6 with Fig. 7), thus explaining why large damages occurred during the irradiations of these subassemblies.

Although, we have no physical law to relate friction and/or forces to damages, we may plot them on the same graph, taking their peak value as unit of damage and the height of the fissile column to scale the pin length representation. Fig. 9 shows that both subassemblies irradiated in KNK-II and in PHENIX presented damage profiles comparable to the SATIN curves, i.e. peaking above the midcore. The calculated force profile seems to better agree with the damage measurements than the friction profile. That might suggest that below a given force threshold, no damages develop. Both calculated curves, showing force and friction, peak about one grid span below the distribution curves of the measured damages. If one could relate forces to damages by a physical law - the still "missing link" - one would probably observe a better matching with the experimental results as the higher temperature in the upper part of the core favors the damages by weakening the steel strength [3].

Fig. 8 is a Fourier analysis of the calculated outlet temperature of both subassemblies, showing for instance a marked peak for the 6 mm design at 5 Hertz, while the 7.6 mm design oscillates at 10.5 Hertz. Those graphs could possibly be compared with records from in-reactor thermocouples.

3. Improvements to fuel design

If one cannot significantly improve a design by acting on its major parameters, one may possibly prestress the pins so that they initially press on the grids, creating reaction forces larger than those induced by the instabilities. Doing so, the pins remain blocked in the same position. Misalignment of the grids or bending of the pins could possibly provide such solutions. However, it must be examined how creep relaxes the initial stresses and how swelling changes the geometrical begin-of-life conditions.

As manufacturing and irradiation conditions are seldom perfectly symmetrical, one may think that marginally unstable designs are usually protected by "unintended" prestresses that prevent pin oscillations in most situations.

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CONCLUSIONS

The SATIN model reflects the existence of thermoelastic vibrations in gridded subassemblies. Up to now, some comparisons with experiments confirm at least qualitatively the validity of the model.

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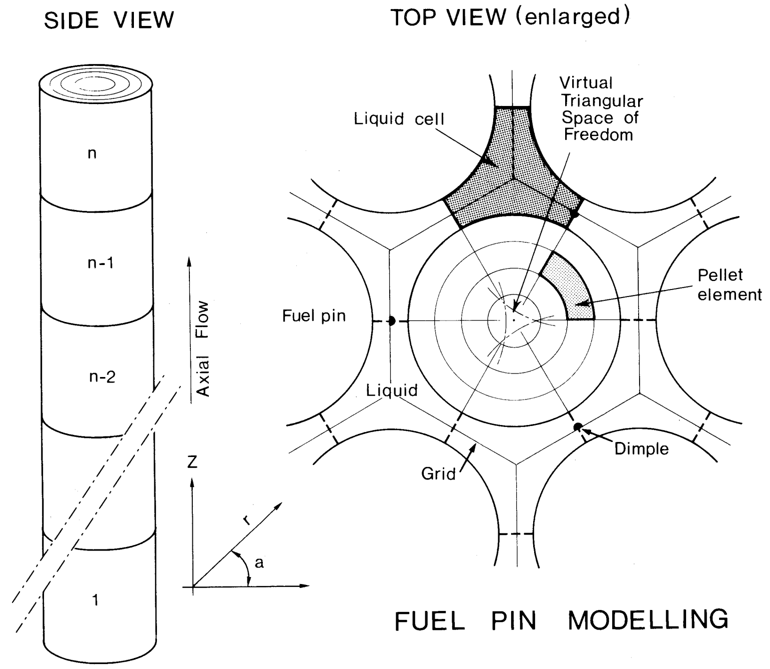

FUEL PIN MODELLING Fig. 1

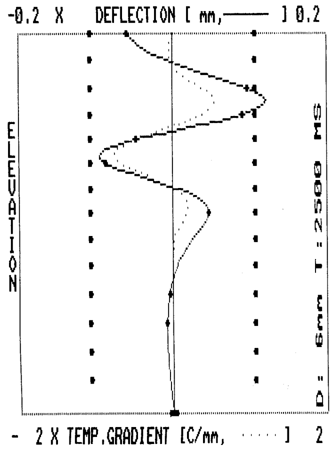

Fig. 2

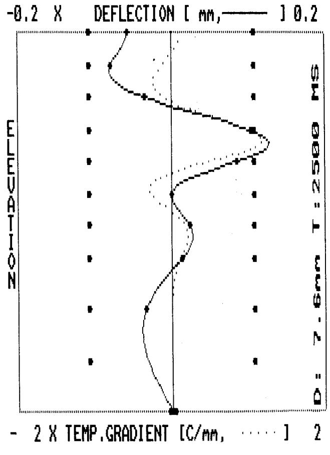

Fig. 3

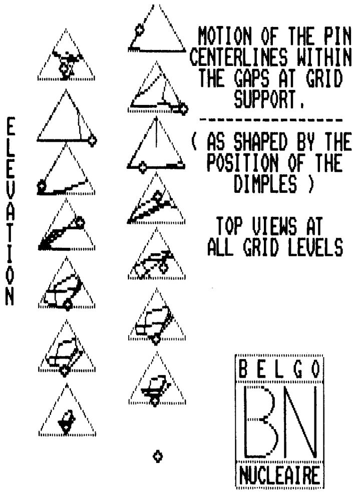

Fig. 4

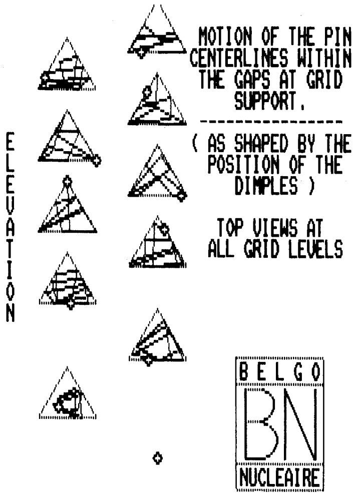

Fig. 5

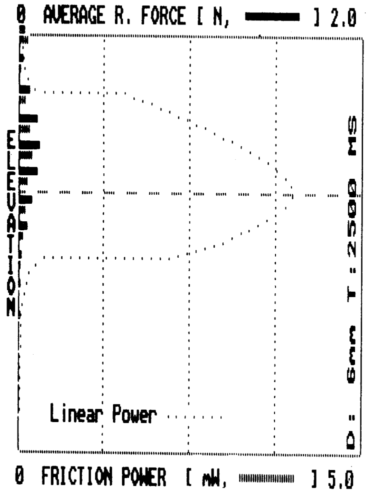

Fig. 6

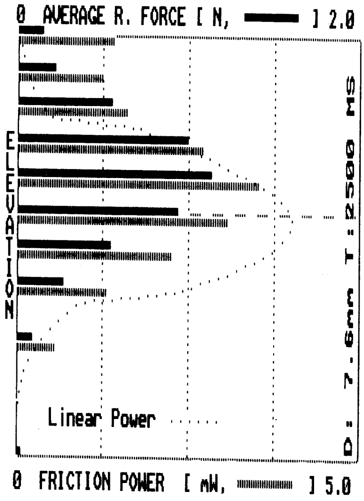

Fig. 7

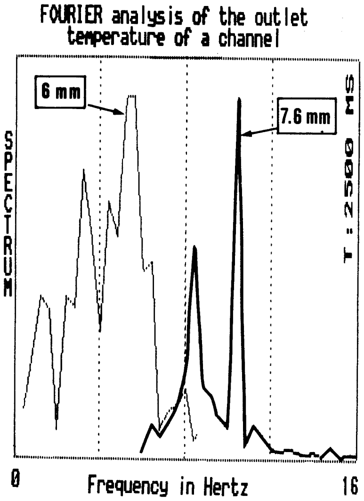

Fig. 8

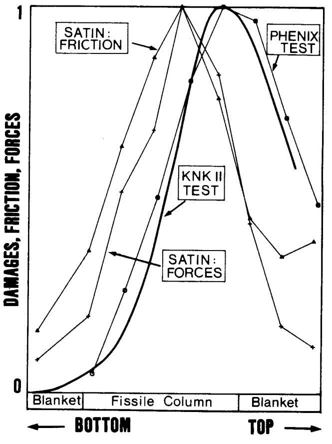

Fig. 9