Mechanical Static and Dynamic Behaviour of an FBR Core

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ABSTRACT

The mechanical static and dynamic behaviour of an LMFBR Core depends on the sub-assembly design and the adopted core restraint concept. It is important to achieve design optimization regarding stress and strain analysis and safety requirements at the very beginning of the project studies.
We present and discuss, in the present paper, some of the preliminary studies performed in the frame of the new project. The presentation will cover two aspects :

- the analysis of the mechanical static behaviour of the core which has led to the definition of certain essential parameters proper to the sub-assemblies, such as axial location of the interaction levels, clearances, core periphery, ...
- the evaluation of the core behaviour under safe shutdown earthquake conditions to confirm the validity of the options proposed for fuel sub-assembly design (shorter sub-assembly with a lighter top structure than the one designed for SUPER-PHENIX,...).

1 - INTRODUCTION

The core layout, the sub-assembly design and the core restraint system concept play a fundamental role in the mechanical, static and dynamic behaviour of an LMFBR core and have a direct impact on the loadings supported by the inner core supporting structures.

The mechanical static behaviour must fulfill the following conditions :

1. Maintain the heads of the fuel, blanket and control sub-assemblies in a position such that they can be handled and removed from the core without excessive demands on the refueling machine ;
2. Provide a reproducible structural response of the core in accordance with reactivity insertions in the case of temperature transients ;
3. Provide acceptable loadings at the interaction levels between sub-assemblies in the lattice. These loadings will be used for stress strain analysis of sub-assembly overall structure. In addition, these loadings must not lead to plastic crushing of the hexagonal sub-assembly duct transverse section at the spacer pad level.

The dynamic behaviour studies are performed on the basis of core behaviour under severe earthquake conditions and have to confirm the validity of the design adopted for the core sub-assemblies and the inner core supporting structures.

It is thus important to achieve design optimization regarding stress and strain analysis and safety requirements at the very beginning of LMFBR project studies.

We present and discuss, in the present paper, some results obtained in the frame-work of a new commercial LMFBR project studies.

2 - BASIC DATA

The core restraint concept adopted in future LMFBR is identical to that adopted in PHENIX and SUPER-PHENIX i.e. the free standing core restraint system /2/. A large number of peripheral stainless steel reflector and shielding assemblies act as a spring round the core, restraining outward bending of the fuel and blanket sub-assemblies due to thermal expansion and void swelling induced-bowing (figure 1).

Because of their remoteness from the core center, the restraint spring sub-assemblies undergo no significant deformation due to irradiation. Void swelling induced-bowing generates reaction loads at the interaction levels in the restraint spring sub-assemblies and consequent restraint stresses in the fuel and blanket assemblies. Those stresses are relieved by irradiation creep which induces a counter bowing.

The core layout adopted at the preliminary stage of the following project, as shown in figure 1, consists in a two fissile zone core surrounded by a blanket sub-assembly ring and three stainless steel reflector and shielding assembly rings.

The lateral neutron shielding is made of two rings of sub-assemblies filled with boron carbide. Only the stainless steel reflector sub-assemblies fulfill the functions required by the core restraint system. Two different types of stainless steel reflector sub-assemblies have been designed : the P70 (figure 1) which consists of a hexagonal wrapper tube filled with solid stainless steel pins. The stainless steel filling ratio of this reflector sub-assembly is about 70%. The second type of stainless steel reflector sub-assembly (RAC in figure 1) is a hollow cylinder with stainless steel filling ratio of about 50%. However, the elastic flexibility of these restraint sub-assemblies, which strongly depends on the stainless steel filling ratio, remains a free parameter in our investigations. The interduct gap, and consequently the core lattice pitch, has been sized in order to accomodate the distance across the flats maximum dilation due to void swelling, irradition creep and thermal expansion.

Measures were taken at the beginning of the new LMFBR project to improve the whole core behaviour under seismic conditions. We have therefore systematically investigated solutions to reduce the sub-assembly masses and lengths and to increase the stiffness.

For this purpose, natural boron carbide has been used instead of stainless steel for lateral and upper neutron shielding purposes.

Figure 2 shows the main differences between the new LMFBR fuel sub-assembly design and the present SUPER-PHENIX fuel sub-assembly design, i.e. :

- a lighter top structure (boron carbide is used for upper neutron shielding purposes instead of stainless steel),
- a reduced nozzle length,
- a shorter hexagonal wrapper tube for an identical fuel stack length.

3 - MECHANICAL STATIC BEHAVIOUR OF LMFBR CORE

The calculation models as well as the associated computer codes used in our evaluation have been fully described elsewhere (see references /1/ to /4/).

3.1. Parametric study

Contacts between the core sub-assemblies are only allowed at the following interaction levels :

- the end of the hexagonal wrapper tube ; the outer distance across the flats and the resulting inter-assembly clearance is not modified at the level ;
- an intermediate level between the diagrid and the previous interaction level, where the spacer pads are located.

Nevertheless, contacts are preferentially made at the spacer pad level, for the following reasons :

- to permit interaction of the natural encircling medium i.e. the restraint reflector and shielding sub-assemblies, even at the beginning of life where the only deformations involded result from thermal expansion ;
- to provide a rigid interlocking array, providing a satisfactory structural response of the core i.e. a negative reactivity feedback effect, in the case of a temperature excursion.

The axial location of the spacer pads, the clearance between ducts at the spacer pad level and the stiffness of the transverse hexagonal section of the duct at the spacer pad level are essential parameters in the mechanical static behaviour evaluation of an LMFBR core.

A parametric study has been carried out to optimize those essential parameters. The different axial spacer pad location we have considered in our study are shown in figure 2.

3.2. Discussion of the results

Figure 3 shows the effect of the axial spacer pad location on the head deflection due to bowing and on the removal force for the most critical sub-assembly located at the core periphery.

The induced-swelling deflection as well as the thermal deflection do not depend on the axial spacer pad location.

Spacer pads located at the top of the fuel stack (level (1) on figure 2) guarantee a minimum removal force and the best core compactness. Nevertheless, the residual deflection due to induced-swelling bowing and creep bowing is maximum. We can also observe an extremum in the removal force evolution. These results can easily be explained : the interaction between the sub-assemblies in the core lattice is preferentially made at the spacer pad level. The elastic flexibility of the sub-assemblies - which is described by the Maxwell coefficient matrix - and the creep matrix are function of the spacer pad location. The stiffness of the restrained sub-assemblies increases as the axial coordinate of the spacer pad level decreases. Inversely, a bending momentum at core line center (maximum neutron fast flux) and bowing deflection increases with the axial coordinate of the spacer pad level. Therefore, counter-bowing due to creep and the resulting interaction force relaxation is expected to be maximum when the spacer pads are located at the wrapper tube end (level(4) in figure 2), which will induce a minimum residual head deflection at EOL and a low removal force. For spacer pads located at the lowest admissible level for neutronic reasons (level (1) in the figure 2), the low interaction forces lead to a minimum removal force.

The clearance between ducts at the spacer pad level has been adapted so that differential thermal expansion of the distance across the flats closes the gap, contact being then ensured despite the thermal bowing when the reactor reaches nominal power at the beginning of life, as shown in figure 4.

However, the significant bowing of the fuel sub-assemblies located at the core periphery and the appaerance of contacts at the sub-assembly heads lead to a release of the contact at the spacer pad level and the core is no longer compact at the end of life (figure 4).

The time at which compactness of the core is no longer guaranteed is maximum for the spacer pads located at the top of the fuel stack (level (1) in the figure 2).

Finally, the stiffness of the hexagonal transverse section at the spacer pad level must be relatively high to reduce the elastic crushing during a temperature transient and therefore to obtain the expected negative reactivity feedback effect.

4 - MECHANICAL DYNAMIC BEHAVIOUR OF LMFBR CORE

The preliminary concept improvment work has given the following results, which are compared hereafter with the SUPER-PHENIX evaluations :

- the total core mass has been reduced by about 500 tonnes (11 10^6 lbs) ;
- the resonant frequency of fissile sub-assemblies has been increased by about 70% ;
- the first modal mass has been reduced by about 26%.

We then planned calculations of mechanical dynamic behaviour of the core under safe shutdown earthquake conditions to confirm the validity of those new concepts.

4.1. Seismic model

The dynamic analysis was performed with the 2D computer code CORALIE developed by the CEA and fully described elsewhere (see references/5/to/7/).It is based on a spectral modal analysis taking the nonlinear effect of shocks into account. It has been benchmarked against experimental data.

The calculations were performed on a central row of the core, assuming it parallel with the main direction of the diagrid acceleration and using 5% damping (assessed from tests).

4.2. Diagrid acceleration response under safe shutdown earthquake conditions

For the building and containment response analysis, the input accelerogram, scaled at 0.15 g, was taken as the horizontal component of an artificial time-history matching the U.S. NRC regulatory guide 1-60 design response spectrum at 5% damping. The resulting acceleration time-history and the response spectrum at 5% damping of the diagrid are given in figures 5 and 6.

4.3. Results

The core layout consists in four different zones which show different dynamic behaviours, depending on the modal characteristics (see figure 2) :

- twelve fissile and blanket sub-assembly rings ;
- two rings of stainless steel reflectors named P70 and previously described ;
- one ring of stainless steel reflectors named RAC ;
- two rings of shielding sub-assemblies filled with boron carbide, named B4C.

The sub-assembly displacements at the core mid-plane and at the top-level (figures 7 and 8) are relatively slight. They vary along the row. The maximum displacement values at the top-level in the different zones range from 3mm to 8mm maximum.

The value observed in the fissile zone has to be compared with the corresponding SUPER-PHENIX value (around 40mm).

The shock force magnitude is maximum at the interfaces of the different core zones. The maximum load due to shocks on spacer pads is about 2000 N and a little bit more on the assembly heads. These values are acceptable with regard to stress and strain analysis (figure 9). All the other loadings, including the relative displacements between the sub-assembly heads and the core cover plug and the loadings on the inner core supporting structures as well as on the sub-assembly structures have been found less than in the SUPER-PHENIX project.

5 - CONCLUSIONS

The preliminary investigations of the mechanical and dynamic behaviour of the new LMFBR core has evinced the fundamental role played by parameters proper to the core sub-assemblies.

A parameter study has demonstrated that a compromise can be reached in the axial spacer pad level and both inter sub-assembly gap and stiffness of the hexagonal transverse section at that level to optimize the mechanical static behaviour of the core with respect to fuel handling and safety requirements.

In further parametrical studies, we intend to investigate the effect of the elastic flexibility of the restraint stainless steel sub-assemblies.

This study has also confirmed the validity of the shorter sub-assembly with a lighter top structure design and a reduced nozzle length, over a long assembly, with a bulky heavy stainless steel top structure.

The core and the sub-assembly mechanical dynamic behaviour has been found satisfactory.

We are thus confident in the results of the next structural analysis step, already planned.

6 - REFERENCES

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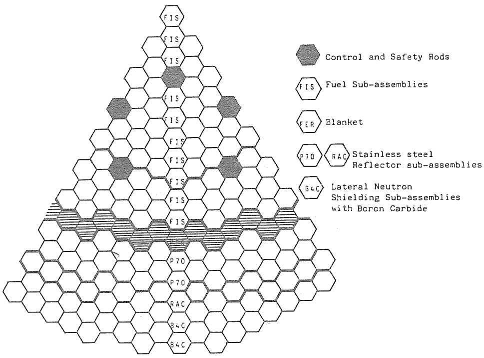

FIGURE 1 - NEW LMFBR PRELIMINARY CORE LAY-OUT

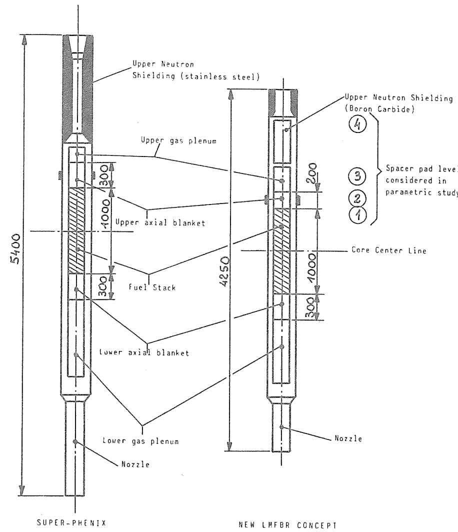

FIGURE 2 - FUEL SUB-ASSEMBLY

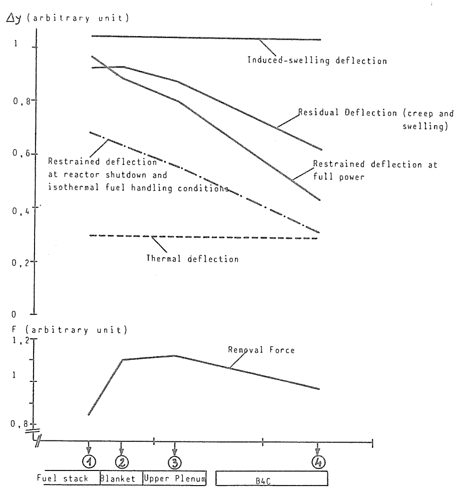

FIGURE 3 - HEAD DEFLECTION AND REMOVAL FORCE AT EOL FOR THE MOST CRITICAL SUB-ASSEMBLY AS A FUNCTION OF THE AXIAL SPACER PAD LOCATION

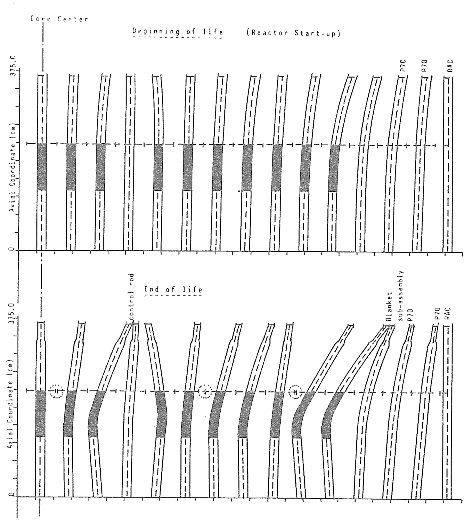

FIGURE 4 - AXIAL SHAPE OF BOWED CORE SUB-ASSEMBLIES AND INTERACTION LEVELS IN A ROW UNDER REACTOR NORMAL OPERATION
Spacer pads located at the top of the fuel stack Lateral Displacement : 10mm

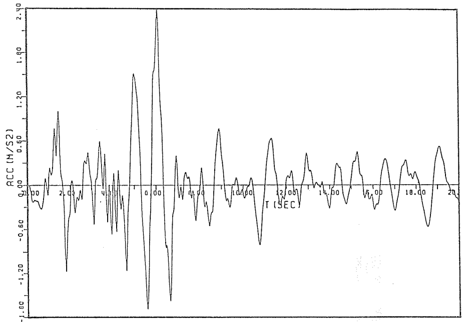

FIGURE 5 - ACCELERATION TIME-HISTORY OF THE DIAGRID UNDER SAFE SHUTDOWN EARTHQUAKE CONDITION

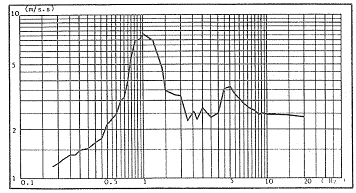

FIGURE 6 - RESPONSE SPECTRUM OF THE DIAGRID (5% DAMPING)

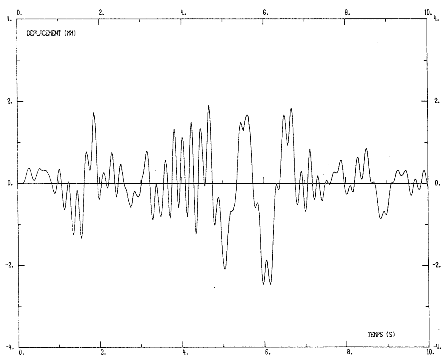

FIGURE 7 - DISPLACEMENT TIME-HISTORY AT MID-CORE OF THE MIDDLE SUB-ASSEMBLY

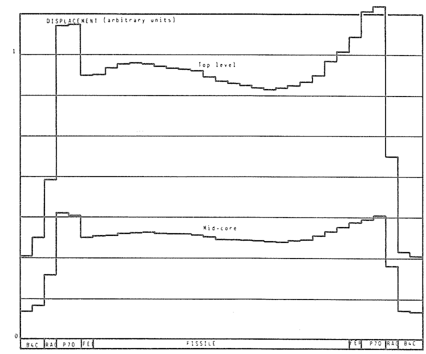

FIGURE 8 - MAXIMUM DISPLACEMENT AT MID-CORE AND TOP LEVELS ALONG THE ROW

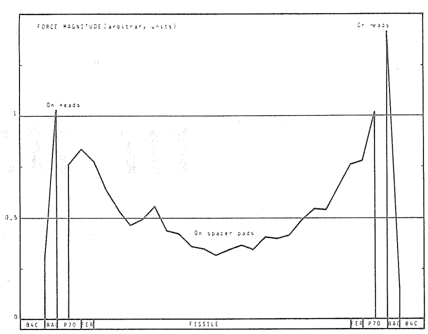

FIGURE 9 - SHOCK LOAD MAGNITUDES ALONG THE ROW