

CORE MECHANICS OF LARGE FAST BREEDER REACTORS - SENSITIVITY OF REACTIVITY FEEDBACK

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ABSTRACT

A core-bowing analysis code called ATLAS has been developed to calculate core reactivity feedback behavior. Based on the neutron physics of a reactor, the code also incorporates thermo-hydraulic and structural mechanics calculations. Using this new system code, the core barrel restraint system of a typical large fast breeder reactor was investigated in detail and the core-bowing reactivity coefficient determined.

1. INTRODUCTION

In recent FBR core design studies (such as PRISM), it has been seen that core bowing may, in view of its magnitude and quick response, act as one of the most important sources of negative reactivity feedback. Thus it may be a major passive safety feature in regard to surviving an anticipated transient without scram (ATWS).

An analysis of core bowing requires a number of calculations covering neutron physics, thermo-hydraulics, core mechanics and so on. These calculations should preferably be performed by an integrated system to ensure consistency in the handling of data among these different coding regimes. This is the purpose of our new computer code, ATLAS. This code is able to calculate reactor core reactivity feedback coefficients from basic neutronic, making use of thermo-hydraulics and structural mechanics calculations to do so. It comprises four calculation codes: a power and neutron flux distribution code (CITATION), an inter-subassembly thermo-hydraulic code (ATHENA), a core-bowing structural analysis code (ARKAS), and a core reactivity calculation code (VEGA).

The ATLAS system code has been used to investigate the core barrel restraint system of a typical large fast breeder reactor. Besides the loading and deflection of subassemblies (S/As), the core-bowing reactivity coefficient -- which describes the reactivity change in the core due to S/A displacements -- was investigated in detail. Sensitivity studies have been carried out on the negative reactivity feedback resulting from core bowing, and the results of these were used to assess its potential effectiveness as an FBR passive safety feature as regards surviving an ATWS. An analysis has also been carried out to obtain the best geometrical conditions for a core restraint system for several power to flow ratios (P/F) up to 2.0.

2. ATLAS SYSTEM

Figure 1 shows the configuration of the ATLAS code. The code comprises four parts.

- (1) Calculation of power and neutron flux distributions using the 3-D diffusion reactor physics code CITATION;

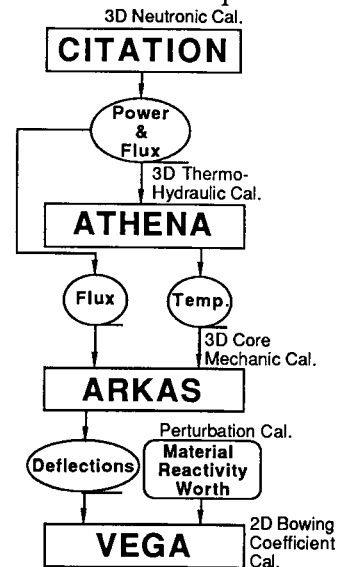


Fig.1 Core bowing calculation system ATLAS

- (2) Calculation of wrapper tube temperature distribution using the 3-D inter-subassembly thermo-hydraulic code ATHENA;
- (3) A core-bowing calculation using the 3-D FEM core static mechanical code ARKAS; and
- (4) A core reactivity calculation using the 2-D worth map code VEGA.

Although CITATION is in common use, the other three codes are special-purpose codes developed by one of the present authors. For this reason, we describe these three codes in some detail.

2.1 ATHENA

ATHENA is a three-dimensional finite-difference code for predicting the thermo-hydraulic behavior of the core in a fast reactor. It is capable of treating a large number of S/As in a cluster with flexible boundary conditions, including mirror and rotational symmetry, as well as a whole core.

The porous body model proposed by Khan E.U⁽¹⁾ is adopted to describe the thermo-hydraulic behavior of each fuel S/A. The model can handle the effects of spiral flow caused by the spiral wires in a wire-wrapped fuel bundle. The spiral flow velocity is assumed to be formulated with the geometrical data and axial flow velocity. And the axial flow velocity is assumed to be uniform within a bundle. Therefore, if flow rates are given for all S/As as input data, it is unnecessary to solve the conservative law of momentum, a calculation which usually requires a lot of computing time.

Figure 2 shows a cross-sectional view of the discretization model for a part of an S/A cluster. The model is axially divided into a number of zones according to a user-specified input. Each S/A is separated into many control volumes, as the figure shows, and these are linked to gap control volumes specified between wrapper tubes. The finite-difference method is used to obtain a linear matrix equation by discretizing the basic equations obtained from the energy conservation law. To solve this linear, and usually very large, matrix equation, the conjugate residual method is adopted. This successfully saves computation time and drastically reduces the memory requirements.

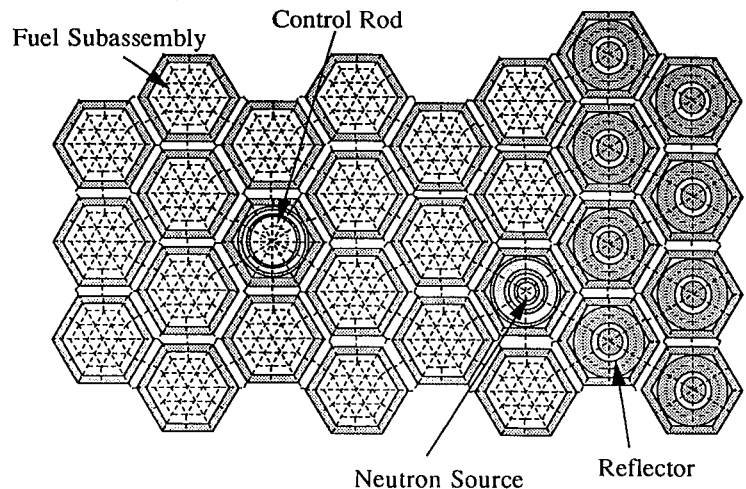


Fig. 2 Cross-sectional view of analysis model in ATHENA code

2.2 ARKAS

ARKAS⁽²⁾ is a three-dimensional finite element code for predicting core distortion and mechanical behavior in fast reactors. It is capable of handling a large number of S/As in a cluster with flexible boundary conditions, including mirror and rotational symmetry, as well as a whole core.

In this code, one of two models can be selected to describe each hexagonal S/A. One is the beam model, and the other the shell model. Figure 3 depicts these models. To represent the non-linear stiffness arising due to the contact between neighboring surfaces, a fictitious element called a joint element is placed on each contact surface. This element also has the ability to represent frictional effects and to describe the state of partial, or angled, contact.

To solve the non-linear equations, the Newton-Raphson method is adopted. This method requires that the linear, and usually very large, matrix equation be repeatedly solved until convergence is obtained. A new technique⁽²⁾ employing a substructure method has been developed to implement this calculation, reducing the size of the matrix to be solved. This reduced matrix is constructed only for freedoms at kept nodes included in the joint elements

(see "Kept Nodes" in Fig.3). This new technique successfully saves computation time and drastically reduces the memory requirements.

This code has been made assessed in a study with IAEA benchmark problems⁽³⁾ ⁽⁴⁾.

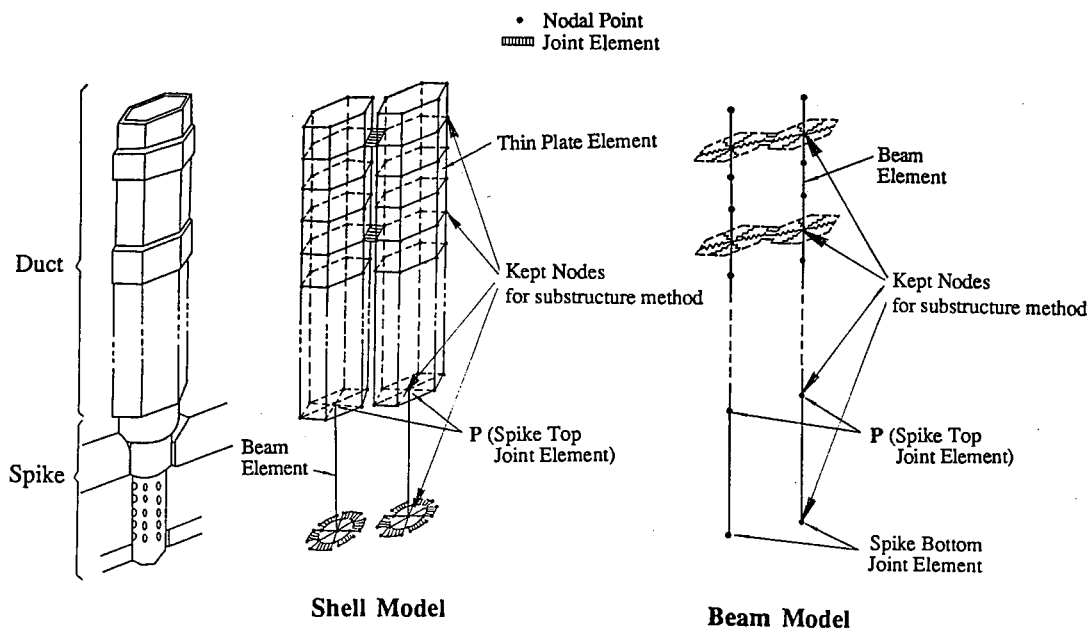


Fig. 3 Configuration of LMFBR fuel subassembly and analysis model in ARKAS code

2.3. VEGA

Vega is a two-dimensional worth map code, which integrates the inner product of displacement and material reactivity worth gradient with respect to volume over the whole core.

3. APPLICATION TO A LARGE FAST BREEDER REACTOR

3.1. ANALYTICAL CONDITIONS

(1) CORE DESCRIPTION

The reactor core investigated in this study is a 1,000 MWe mixed-oxide fueled core comprising 367 driver fuel subassemblies, 150 radial blankets, and 24 control rods. Figure 4 shows the core configuration. Figure 5 shows the lateral layout of the core restraint system, which is assumed to be of the barrel restraint type. There are four restraint planes, corresponding to the top restraint pads (TLP), the above-core restraint pads (ACLCP), the nozzle base and the nozzle tip. The active core length is 1,000 mm and the upper and lower axial blankets are each 350 mm long. The total length of a subassembly is 4,300 mm, including the 350 mm entrance-nozzle. The duct and the core support materials are assumed to be SUS.

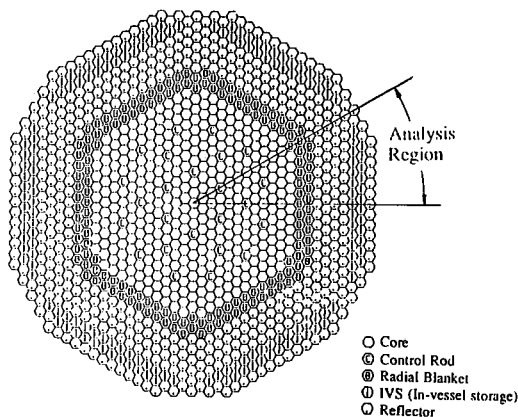


Fig. 4 Core configuration and analysis region

(2) ANALYTICAL MODEL FOR CORE BOWING AND INDUCED REACTIVITY CHANGE CALCULATIONS

For convenience, all calculations were carried out for an array of 30 degree symmetry, as indicated in Fig.4.

Core-bowing performance was calculated using the beam model; the duct bottom was fixed and a bending stiffness was used to model the restraining effect caused by bending deflection of the entrance-nozzle.

The material reactivity worth distribution used in the reactivity calculations for core bowing was obtained with a two-dimensional RZ model, based on the first-order perturbation theory, using the JFS-3-J2 group constant library.

3.2. STANDARD CASE

Figure 6 shows the radial deflections in a radial section from the central S/A toward the two o'clock direction in the core layout shown in Fig.4. Deflections for P/F values of 0.0, 1.0, and 2.0 are shown. The active core region expands radially as P/F increases from 1.0 to 2.0. This expansion is caused by both ACLP radial expansion and increased core bowing. The overall ACLP radial expansion mainly results from a combination of ACLP thermal expansion and ACLP compression due to inter-subassembly loading. Figure 7 represents the displacement vectors for all S/As on the core central plane at P/F=2.0. This figure verifies that outward movements (core expansion) are observed for nearly all S/As in the core region and that the magnitude of the expansion is especially large for S/As on the periphery of the core zone, where the negative gradient of material reactivity worth is large.

Core expansions in LMFBR cores are generally expected to cause negative reactivity feedback due to the decrease in material reactivity worth toward the core edge.

Figure 8 shows the reactivity change as a function of P/F ratio. From this figure, it can be shown that a negative reactivity feedback of about 40% is obtained as P/F increases from 1.0 to 2.0.

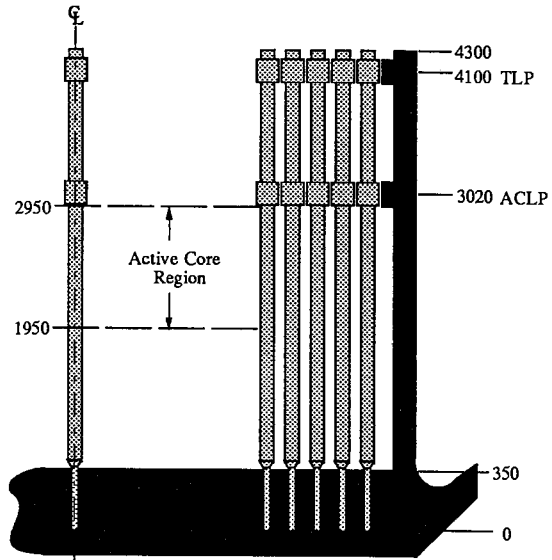


Fig. 5 Lateral configuration of core restraint system

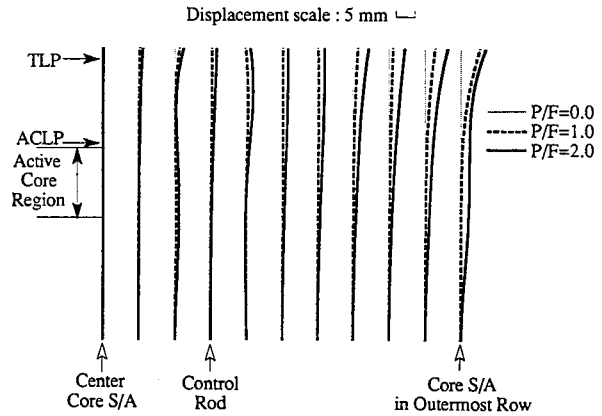


Fig. 6 Typical subassembly displacements during ATWS (radial section)

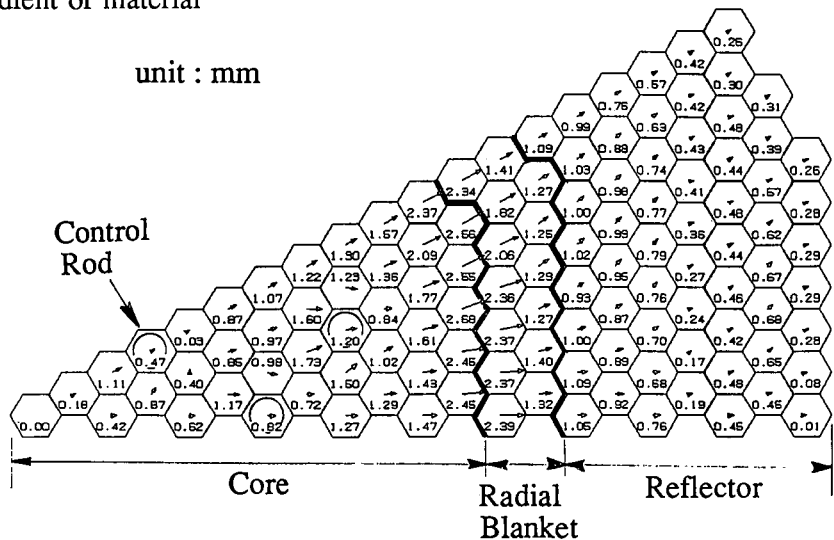


Fig. 7 Displacements on core mid-plane at P/F=2.0

3.3. SENSITIVITY STUDIES

(1) EFFECTS OF CONTACT STIFFNESS AT ACLP

ACLP compression, which depends on the contact stiffness when compression forces are acting, is one of the important characteristics determining the magnitude of negative reactivity feedback as P/F increases.

Under compression, the contact stiffness of pads on a hexagonal shaped duct is thought to take on a characteristic value corresponding to the pad design: dimple, plate welded, or massive ring format. It is also said to vary according to the number of contact faces⁽⁵⁾.

To test sensitivity of the negative reactivity feedback during P/F increase to contact stiffness at the ACLP, three cases were selected: 1,00 kg/mm, 1,000 kg/mm, and 10,000 kg/mm (the figure was 100,000 kg/mm in the standard case). Figure 9 shows the reactivity changes for these four cases as a function of P/F ratio. Note that the reactivity feedback due to bowing as P/F increases from 1.0 to 2.0 could be positive, if the contact stiffness is too small.

This analysis demonstrates that the pad stiffness at the ACLP needs to be sufficiently high to ensure negative reactivity feedback.

(2) GAP CLEARANCE AT ACLP

To ensure the thermal radial expansion at the ACLP during P/F increase, almost all gaps at the ACLP need to be closed in the core region. For this reason, the initial clearance at the ACLP would appear to be one of the important factors affecting the magnitude of negative reactivity feedback during P/F increase.

In the standard case, the clearance at the ACLP was set at 0.2 mm (at room temperature). In our sensitivity analysis, the ACLP clearance was varied from 0.2 mm to 0.5 mm.

The result are shown in Fig.10. The peak of reactivity should occur in the regime where P/F is smaller than 1.0 (the left half of Fig.10) in order to ensure negative reactivity feedback and protect against ATWS (because, at ATWS, P/F becomes greater than 1.0). Figure 10 suggests that negative feedback at ATWS can be achieved by limiting the clearance to below an upper limit. In the core studied here, this upper limit is around 0.2mm.

(3) AXIAL HEIGHT OF ACLP

The axial height of the ACLP seems to influence the core bowing performance. To test this effect, sensitivity analysis was carried out for seven cases, varying the axial height of the ACLP from 1,840 mm to 3,530 mm above the S/A bottom.

Figure 11 shows the reactivity change during a P/F increase from 1.0 to 2.0 for various axial

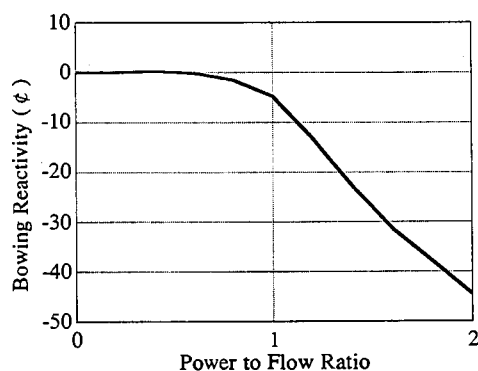


Fig. 8 Reactivity change due to thermal bowing for standard case

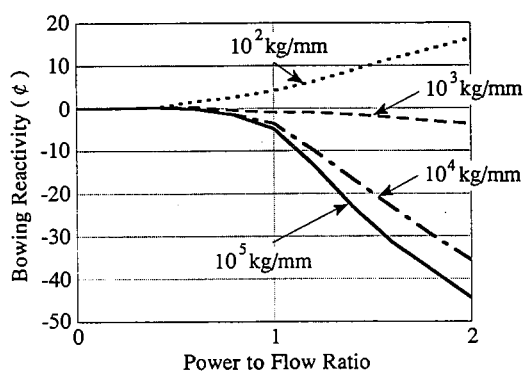


Fig. 9 Effect of contact stiffness at ACLP

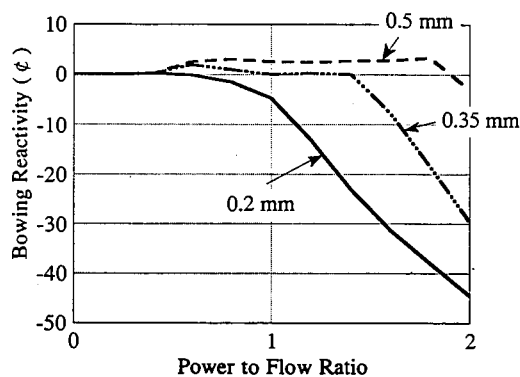


Fig. 10 Effect of initial clearance at ACLP

heights. This gives confirmation that the best axial level for the ACLP is just above the active core region.

(4) BURN-UP EFFECT

In all the above calculations, all S/As in the core array were assumed to be fresh when the P/F is 0.0, implying zero deflection. However, in an operational plant, S/As at P/F=0 have generally been deflected by creep and swelling strains due to burn-up.

In a sensitivity analysis, the reactivity feedback at ATWS was calculated for deflected S/As at the end of the 1st, 2nd, and 3rd operation cycles. The shapes of the deflected S/As were obtained by a core bowing computation continued from the first cycle with fresh S/As to the third cycle. Each cycle length was 365 days. The Gilbert-Bates Equation⁽⁶⁾ was used to give irradiation creep. As for the swelling equation, assuming the use of a low swelling material, the Hanford Engineering Development Laboratory MARK 6 Equation⁽⁷⁾ multiplied by 0.3 was tentatively applied.

The results are shown in Fig.12 in comparison with the standard case with no deflected S/As. Figure 12 shows that all four cases have a similar level of reactivity feedback as P/F increases from 1.0 to 2.0, although a reactivity increase as P/F grows from 0.0 to 1.0 is observed in the burnt cores due to core compression; this is because the total ACLP clearance increases in the core region as core burn-up progresses.

4. CONCLUSION

Using sample calculations, we have confirmed that the new ATLAS system is capable of reasonable analysis of reactivity response due to core bowing.

Sensitivity analyses on several design parameters related to barrel restraint system have shown that the stiffness at the ACLP needs to be sufficient if negative reactivity feedback during an ATWS is to be ensured. It has also been shown that there is an upper limit to the clearance between ducts at the ACLP and that the best axial height for the ACLP is just above the active core region.

A comparison between a virgin core and various burnt cores indicates that there is no difference in the magnitude of the reactivity feedback as P/F increases from 1.0 to 2.0, although a burnt core exhibits a reactivity increase up to P/F=1.0 due to core compression.

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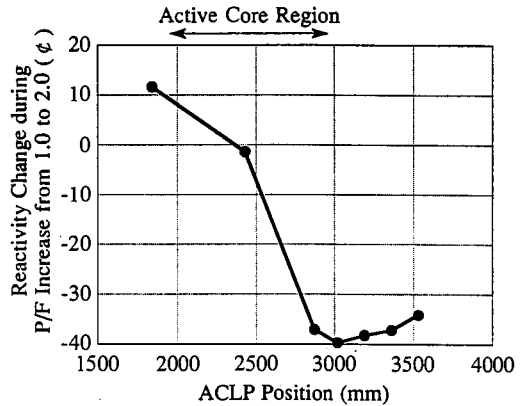


Fig. 11 Effect of axial height of ACLP

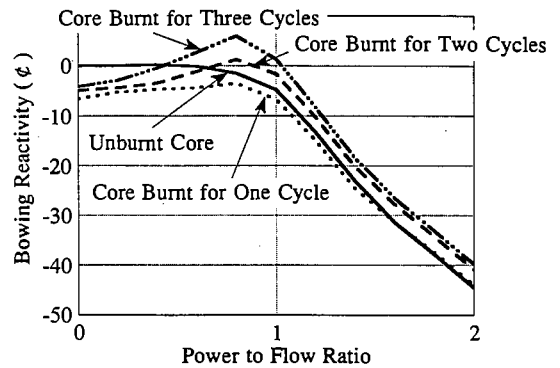


Fig. 12 Effect of burn-up