ANALYSIS OF BOWED REACTOR CORES USING THE FIAT-PROGRAM

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SUMMARY

The core elements of a LFMBR are bowed due to neutron flux and temperature gradients. The movement of the elements due to free bowing is restricted by neighbouring elements or constraint rings. Consequently forces are induced in the core. To calculate the forces and bowed shapes of the fuel elements at different power and burn-up situations the program FIAT was developed.

FIAT is based on the NUBØW code of ANL. FIAT calculates the force equilibrium configuration of elements in a spoke, treating the ducts as beam members. The iteration technique, which is taken from NUBØW, is used in FIAT to calculate the gap distribution between the pads of the elements in the considered spoke. Knowing the gap distribution a direct solution of the unknown mechanical displacements and forces in the load planes can be given. As the gap distribution hardly changes during the burn-up history, the use of the iteration part is not required very often.

The computer running times of the combined method are about 10 times less than the strict iteration technique as used in NUBØW. The computer running time reduction is improving with increasing numbers of load planes between the elements. Other improvements of FIAT over NUBØW are bowing of elements due to neutron induced swelling and creep effects, and the growth of duct width due to pressure drop and creep (bulging). In small time steps ($\sim 4d$) the additional amounts of swell bowing, creep bowing and growth of duct width are calculated. The equilibrium configuration is calculated after every time step to minimize the error produced by calculating at discrete time points.

The calculation of the bowing reactivity of a burned core can be performed for any desired time in reactor history. The shut-down situation (low temperature level, no temperature gradients but bowed elements due to neutron fluence) can also be calculated at any time. At these time points a management of fuel elements can be prescribed, e.g. insertion of fresh elements or reshuffling of burned elements. With FIAT, the mechanical configuration of a reactor core can be calculated for the whole reactor history in a two-dimensional way.

Comparison with the NUBØW code shows nearly the same results for a fresh core. Due to the more realistic treatment, FIAT results do deviate considerably from NUBØW results for burned core states. A spoke of the core of the SNR-300 is calculated with FIAT for a time of 441 days. The reference case shows a safe margin with respect to technological limits like maximum force or bowing reactivity. Even with pessimistic swell and creep formulas the technological limits are not reached.

1. Introduction

To calculate the bowing behavior of core elements of a LMFBR the program FIAT /1/ was developed. FIAT calculates a spoke through a reactor core (fig.1) at different time steps and different power levels during the core life time. The purpose of the program is to calculate

- the forces acting between the elements
- the deflections of the elements due to swelling and creep and temperature gradients
- the growth of ducts due to swelling and bulging
- bowed shapes of the elements in many different situations for reactivity calculations.

The code has been used extensively for the core design of the German KNK reactor, a small fast test reactor and the German-Belgian-Dutch SNR 300 reactor, a prototype fast reactor of 300 MWe.

2. Calculation method

FIAT is based on NUBOW /2/, a two-dimensional code developed by ANL. This two-dimensional analysis assumes that the core can be represented by a planar series of equivalent elastic beams of variable cross sections, which have thermal and inelastic bowed shapes, with clearances at the supports and between adjacent beams, and local flexibility at the various contacts. Fig. 2 shows a plane series of beams with changes in sectional properties, one support plane and three loadpad planes. Clearance may occur at each contact and support, and it is not assumed that any given point is fixed /2/.

2.1 Deflections of elements

The deflections of elements (beams) are separated into two parts: first an unrestrained bowed shape due to thermal loads, swelling and creep, and second a mechanical deflection due to forces that develop at the contact points. The unrestrained bowed shapes are calculated using conventional beam theory /2/.

2.1.1 Thermal deflections

The beams are bowed due to the thermal moments $M_T(x)$, acting along the beams. $M_T(x)$ is given as

$$M_T(x) = E(T) * \alpha(T) * \int_A T(x,y)ydA \qquad (1)$$

where E(T) is the temperature dependent modulus of elasticity, $\alpha(T)$ the temperature dependent coeffincient of thermal expansion, and T(x,y) is the temperature variation across the beam section at axial position x. The integration across the beam can be expressed as a function of the transverse temperature difference.

$$M_T(x) = \frac{\alpha(T) * E(T) * I(x) * \Delta T(x)}{D(x)} \qquad (2)$$

ΔT is the transverse temperature difference, D(x) is the local width, and I(x) is the local moment of inertia of the beam /2/. Now using the conventional-beam-theory bending equation

$$\frac{d^2V_T}{dx^2} = \frac{M_T(x)}{E(T)I(x)} = \frac{\alpha(T) * \Delta T(x)}{D(x)} \qquad (3)$$

the unrestrained thermal bowed centreline of the beam is calculated.

2.1.2 Swelling deflections

To calculate the deflections of the elements due to neutron induced swelling, eq.(3) is slightly changed into

$$\frac{d^2V_S}{dx^2} = \frac{M_{SW}(x)}{E(T)*I(x)} = \frac{\Delta SW(x)}{D(x)} \qquad (4)$$

where $M_{SW}(x)$ is the swelling moment and $\Delta SW(x)$ the swelling difference of the opposite beam sides. At the present, the following reference swelling formula is used

$$\frac{\Delta V}{V} = (-7.027+4.268 * 10^{-3}*T-7.175*10^{-6}*T^2+3.703*10^{-9}*T^3) * \bar{E}\phi t^{2.181} \qquad (5)$$

where $\frac{\Delta V}{V}$ is the growth of volume in per cent , T is the temperature [K] , $\bar{E}$ is the mean neutron energy [MeV] and ϕt is the total neutron dose [10^{22} n/cm^2] /3/. It is assumed that the swell phenomenon is isotropic and that the assumption

$$\frac{\Delta L}{L} = \frac{1}{3}\frac{\Delta V}{V} \qquad (6)$$

is valid.

Other swelling formulas like the BOLTAX-equation /4/ are incorporated in the FIAT program and can be chosen by input data.

Due to the power law in the swelling equations, one has to divide the reactor time into small time steps. In the calculations presented later, the time steps are about 5 days.

2.1.3 Creep deflections

The creep deflections of the elements are calculated in the same way as the swelling deflections.

$$\frac{d^2V_{CR}}{dx^2} = \frac{M_{CR}(x)}{E(T)*I(x)} = \frac{\Delta CR(x)}{D(x)} \qquad (7)$$

$M_{CR}(x)$ is the creep moment and $\Delta CR(x)$ the creep difference of the opposite

beam sides.
The reference creep formula used for the calculation of the SNR 300 core is

$$\frac{\varepsilon_v}{\sigma_v} = 1{,}48 * 10^{-3} * \bar{E}\phi\, t \qquad \text{for } \bar{E}\phi\, t \leq 3{,}636 \tag{8a}$$

$$\frac{\varepsilon_v}{\sigma_v} = 4{,}83 * 10^{-3} * \bar{E}\phi\, t - 0{,}01218 \text{ for } \bar{E}\phi\, t > 3{,}636 \tag{8b}$$

with ε_v = equivalent strain [%]
σ_v = equivalent stress [N/m^2]

The equivalent stress is calculated for each node and both sides of the ducts, using

$$\sigma_v = \pm \frac{M(x)}{W} \tag{9}$$

where M(x) is the bending moment at axial location x and W is the moment of resistance. This calculation is done every time step, when swelling deflections are calculated.

2.2 Growth of element widths

Due to swell and creep effects, the beam diameter of the elements is growing during reactor history. In case of swell effects, it is assumed, that the hexagonal geometry of the elements is not changed. The growth of the duct diameters is calculated using eq.(5) and (6) at every axial node. It is assumed that the diameter is growing uniformly with the mean value of the volume swelling of all six sides of the element.

The effect of creep growing (bulging), caused by irradiation creep effect and pressure difference across the element wall, is calculated in FIAT with a simplified model /5/ (fig.3). A hexagonal ring is cut out of the duct and due to the symmetry of the hexagon one side of the duct, which is assumed to be cantilevered at both ends, has to be calculated. The bulging in the middle of the duct wall is calculated using

$$f = \frac{3}{128} * \frac{p * l^4}{h^3} * \frac{\varepsilon_v}{\sigma_v} \tag{10}$$

with f = max. deflection of the duct wall [m]
p = pressure difference across duct wall [N/m^2]
l = length of duct wall [m]
h = thickness of duct wall [m]

$\frac{\varepsilon_v}{\sigma_v}$ = creep value, see eq.(8)

A comparison with more sophisticated models shows a deviation of less than 10 per cent.

2.3 Equilibrium force calculation

The free deflections are leading to contact forces between the elements, as the gaps between the elements are closing. The calculation of these forces using the Direct Stiffness Method of matrix structural analysis is described in /2/. The same method is used in FIAT. To obtain an equilibrium force configuration, an iteration technique is used in NUBOW. The same iteration technique is used in FIAT to establish the first equilibrium core configuration. Now the gap distribution is known and one can evaluate the forces with a direct solution /6/. During irradiation, the gap distribution doesn't change often; therefore the direct solution can be used saving computer time. After the calculation of the forces, there is a check, if the residual forces are less than the convergence value (normally 1 N). If not, the direct solution was not able to achieve the equilibrium configuration and the iteration technique is used to calculate the equilibrium forces.

2.4 Management of core elements

A management of core elements can be done in the calculation of a LMFBR with FIAT. Several management operations are available:

1. insertion of fresh elements,
2. rotation of burned elements,
3. shifting of burned elements, and
4. reshuffling of burned elements of previous cycles.

These operations can be done at any time during the calculation with any element in any combination. The equilibrium core configuration is being calculated at the shut-down temperature of the reactor before and after the element management. The forces evaluated at shut-down situation have to be known in view of the withdrawl force limits of the fuel handling machine.

3. Reactivity calculations

There are no reactivity calculations within FIAT itself. The equilibrium centrelines of the core elements are input data for the special program BIER /7/. BIER calculates the reactivity of a bowed reactor core, using first order pertubation theory in r-z geometry. Each element in the FIAT calculation represents a ring of elements in the reactor. BIER assumes, that all ring elements behave the same way, so that the bowed centreline of the element coming out of the FIAT calculation is representative for the whole ring elements. Bowing reactivity values can be given for any core situation at any step in the FIAT calculation. The data transport of the bowed centreline from FIAT to BIER is automatically achieved.

4. Analysis of the SNR 300 Mark 1a core

The figures 4 up to 7 show the bowed centrelines of the elements of a spoke through the Mark 1a core of the SNR 300 at different times during reactor history. The centreelement is numbered 1, the outermost element is numbered 12. The shown duct width and the deflections are out of scale. The scale factor for duct bulging and duct deflections is given in the left corner of the figures. The shown element length reaches from the gridplate up to the top of the elements. There are two restraint rings at the outermost elements at the level of the two load planes below and above the core region. The forces between two elements are given at the load pads and in the foot of the elements. The main data of the elements are given in tab.I.
Fig. 4 shows the fresh core of the SNR 300 at zero power. There are no forces between the elements because there is no temperature bowing. The elements are standing slightly non vertical, because of the small differences in the temperature expansion coefficient of the load pads and the grid plate.
Fig. 5 shows the fresh core at full power operation. The elements are bowed differently due to different temperature gradients and therefore forces are induced. The outermost element is leaning against the lower restraint ring with a force of 319 N. The load pad forces are rising up to 320 N in the middle of the core. The maximum free deflection at the top of a element is 11 mm.
The burned core after 441 full power days is shown in fig.6 at full power. The elements in the centre of the core are in contact with each other, a little bit below core mid plane. The contact force is 651 N. The theoretical overlapping of ducts is 0.63 mm and the first contact has occured after 420 days. The dashed lines show the ducts without bulging and swelling. The maximum free top deflection due to swelling and creep effects is 12 mm, the maximum force 2920 N.
The shut down situation after 441 days shows fig.7. The temperature bowing is zero and therefore the forces are much smaller (max.force 852 N). The maximum deflection of the element heads is 9.2 mm.
This calculation of the SNR 300 Mark 1a core needed 200 sec. computer running time on an CD Cyber 172 computer.

5. Conclusion

The mechanical behavior of a spoke of elements in a core can be calculated with FIAT for all time steps in a sufficient way. All major effects during the life time of an element in the reactor can be handled.

The main developments from NUBOW to FIAT are:

1. calculation of swelling and creep effects
2. capability of management operations
3. calculation of duct growing due to swelling and bulging

4. direct solution method of the equilibrium force configuration.

References

/1/ URBAN, K. : "FIAT: A Program to calculate the Bowing Behaviour of Reactor Cores."
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/2/ McLENNAN, G.A. : "NUBOW: A Fortran-IV Program for the Static Structural Analysis of Bowed Reactor Cores."
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/3/ Bergmann, H.-J. : personal communication

/4/ Claudson, T.T. : Proceedings of ANS meeting in Karlsruhe, 1970

/5/ Dr.Meyer zur Capellen : personal communication

/6/ Menssen, R. : DDT, a 3-Dimensional Program for the Analysis of Bowed Reactor Cores.
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/7/ W.Gebhardt, E.Schmitt : BIER: A two-Dimensional Program for the Calculation of Reactivity Coefficients of Bowed Reactor Cores
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Table I. Main data of SNR 300 elements

length of element (support-top)	3.4	m
duct width	0.11025	m
pitch	0.115	m
wall thickness	0.0026	m
gap between elements	0.00475	m
core height	0.95	m
blanket height	0.4	m
clearence between outermost element and restraint rings, lower load plane	0.0021	m
upper load plane	0.006	m
load pad stiffness	2.5×10^7	$\frac{N}{m^2}$
material of ducts	1.4981	
material of restraint rings	1.6770	
material of grid plate	1.4948	

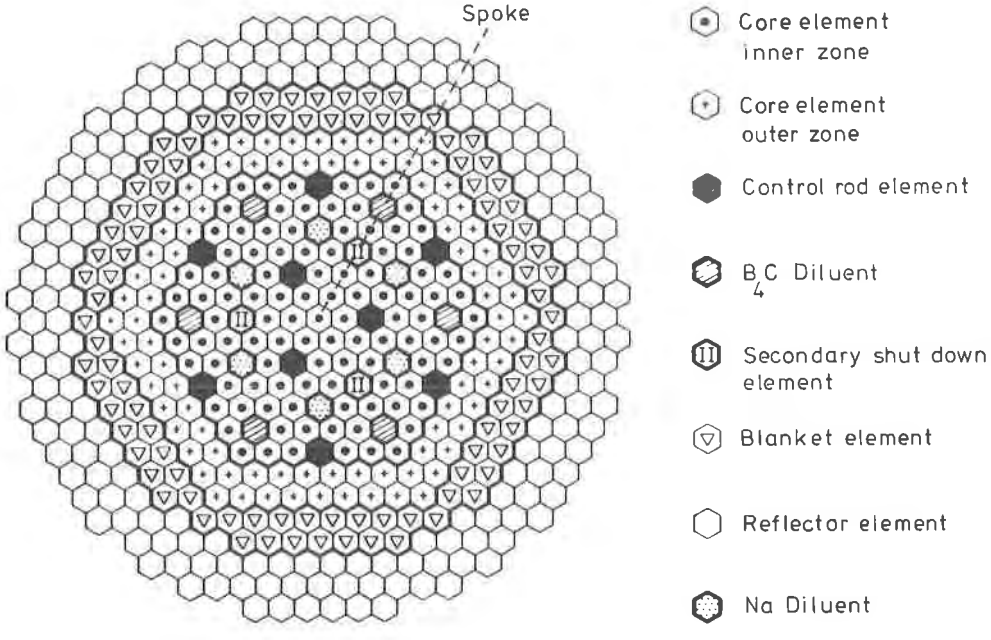

Fig. 1 Core of SNR 300 Mark 1a

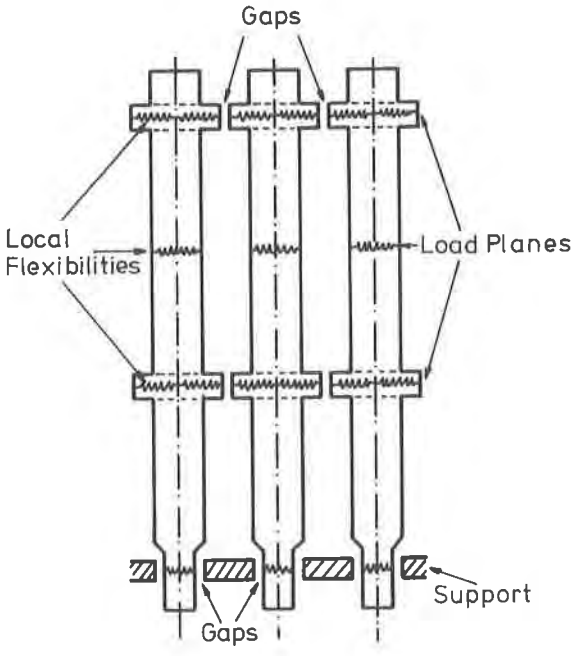

Fig. 2 Schematic representation of elements considered to be elastic beams with local Flexibilities and clearances

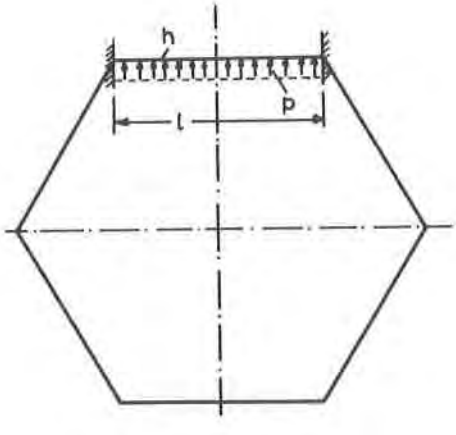

Fig. 3 Model for calculation the bulging of ducts

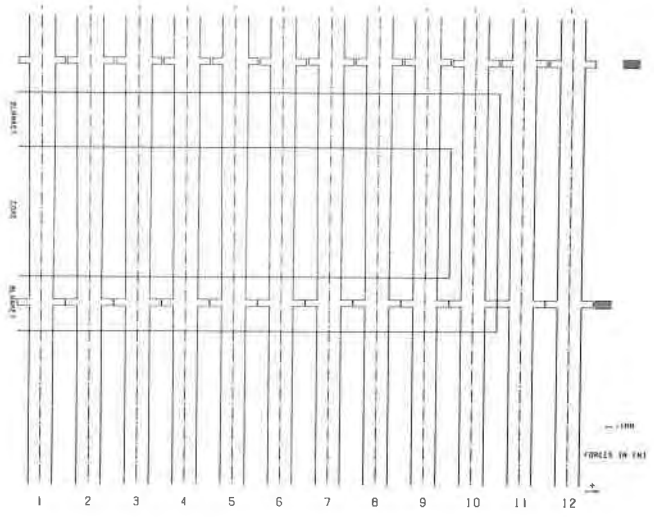

Fig. 4 Deflections and forces of SNR 300 Mark 1a, begin of life, zero power

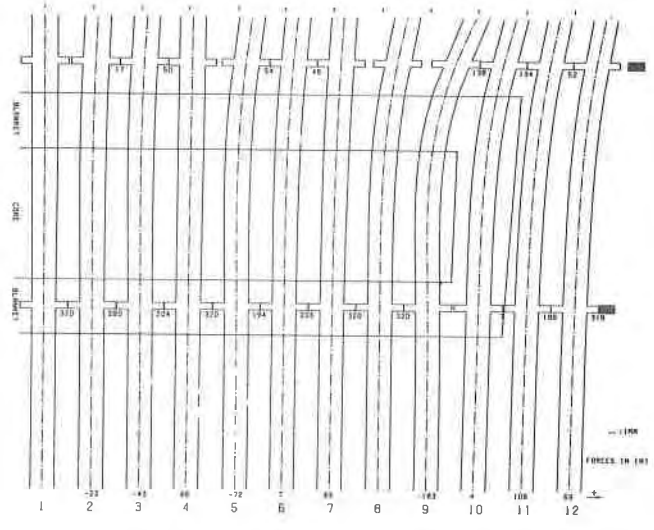

Fig. 5 Deflections and forces of SNR 300 Mark 1a begin of life, full power

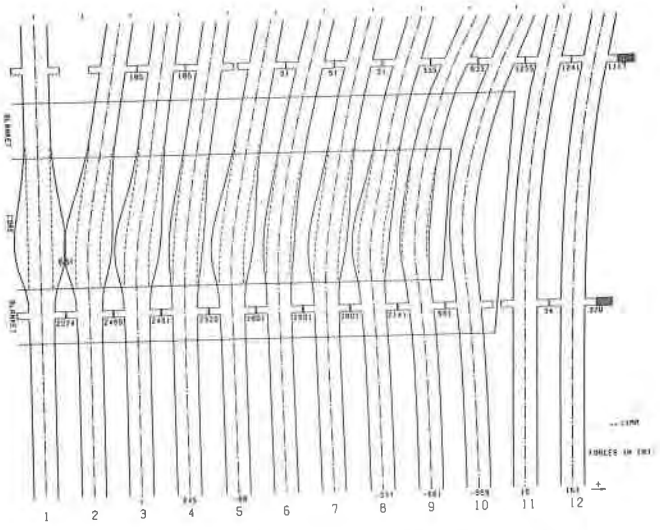

Fig. 6 Deflections and forces of SNR 300 Mark 1a end of life, full power

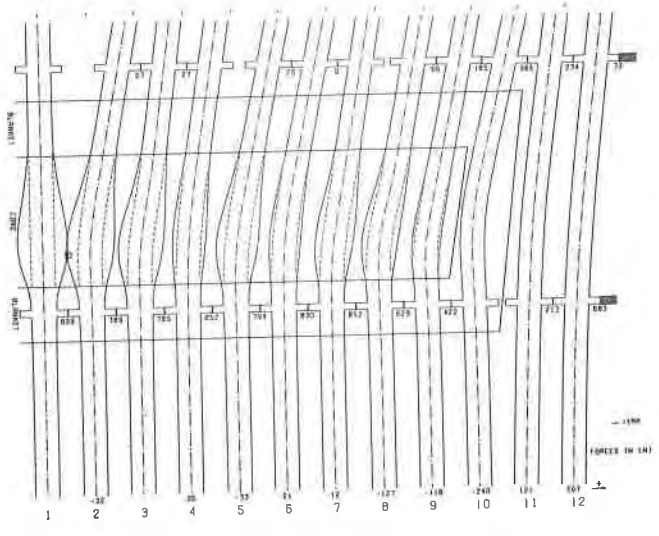

Fig. 7 Deflections and forces of SNR 300 Mark 1a end of life, shut down