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SIMPLIFIED METHOD OF RESTRAINED DISTORTION ASSESSMENT OF REACTOR CORE COMPONENTS

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SUMMARY

Owing to the appreciable variations in intensity of fissile power and fast neutron damage flux which occur in prismatic components of reactor cores under steady state operating conditions, it is necessary to assess the stresses and deformations arising. These deformations may become unacceptably large in graphite structures in which the temperature and damage flux variation is unsymmetrical with respect to the geometry of the component. Even with the simplifying assumption of an axi-symmetrical core power loading the problem is complicated by the wide variations obtained in both axial and radial directions within any single fuel carrier or reflector structure.

In order to reduce this complex time dependent problem in three dimensions to one that is within the scope of a relatively small computer, a simplified approach was developed starting from the concept of bi-metallic strip theory. The main assumption made in this simplification is that the variations in temperature and irradiation dose (on which hinges the mechanical and thermal property changes) occur only in the direction of a single vertical plane drawn through the centre of the component. By dividing the body into a number of parallel layers normal to this plane and also into a number of separate vertical sections, it is possible to ascribe average temperature and damage flux intensities to each of the laminated lengths thus formed.

A computer code CURVO has been written using a "spring and plate" analogy to evaluate both the free and the restrained distortion behaviour of such components in which variation of temperature and dose dependent structural parameters can be taken into account throughout the residence time of the component in the reactor.

An example of the application of this analysis to a vertical reflector column bounding the core of the Dragon Reactor Experiment is presented in some detail together with comparisons of the predicted and observed distortions.

A derivation of the method has been used in the preparation of a computer subprogramme PISC for use in conjunction with the finite element code STAG to predict post-irradiation distortion of cut sections of fuel element structures.

Brief mention is also made of the application of the method to fuel element bowing problems.

1. Introduction

The variations of fissile power within a reactor core give rise to three-dimensional variations in the temperature and neutron damage flux occurring in the graphite components. The physical properties of the graphite are also changing with time as neutron damage accumulates. A rigorous analysis of stresses and distortion in a member under such complex conditions is expensive and time consuming. In the initial design stages it is desirable to have a less rigorous method, which can look at a number of possible variations of the design parameters. The method described here was developed for the design of replacement reflector blocks for the Dragon reactor.

2. Subdivision of Member

A rough method of assessing the effects of fuel pin bowing was to treat the member as consisting of two parts, spliced about the central axis, and analyse as for a bi-metalic strip [1].

The present method, which is incorporated in computer programme CURVO [2], achieves greater accuracy by dividing the member, at right angles to the plane of bowing, into a convenient number of layers of equal thickness and the axial length into a number of sections with varying lengths as shown in Fig. 1.

As bowing will be mostly in the radial direction, the circumferential temperature and neutron flux gradients are ignored and average values are given to each layer. Axial variations are treated in a step-wise manner, conditions being assumed uniform in each axial section. The axial sections will normally be chosen shorter at locations where the greatest axial variations occur.

3. Spring and Plate Analogy

The effects of gradients of temperature and neutron damage flux cause variations in each layer and section of the following.

3.1 Thermal expansion and expansion coefficient.

3.2 Shrinkage and dimensional change rate.

3.3 Creep and creep rate.

Each effect is taken in turn and the stresses and curvatures found by a 'spring and plate' analogy.

Taking a unit length of each section, the layers are assumed to be springs with a spring rate of Area x Young's Modulus. Both of these properties will vary, the area according to effective width and thickness and the modulus with temperature and accumulated neutron dose.

The 'springs' are first allowed to change their initial lengths according to the effect being considered. When looking at the differential expansion effect, for example, the initial length change will be the temperature rise multiplied by the coefficient of expansion appropriate to the temperature and neutron dose of each layer.

A plate is then assumed to be pressed against all the springs compressing them back to unit length. The plate is analogous to the concept that planes remain plane.

The springs are then assumed to be connected to the plate and the plate is allowed to move axially along the member, without rotating, until it is in equilibrium. The spring forces are then redistributed such that their total is zero. These residual forces will cause a moment to be applied to the plate.

The plate is then allowed to rotate under the influence of this moment and this will have a linear variation effect on the spring movements. The bending moment can then be replaced by a series of forces calculated from the simple bending equation:

$$BF = A \cdot y \cdot E/I \qquad (1)$$

where

BF is the bending force,

A is the area of layer,

y is the distance of its centre from the neutral axis

E
I are the Young's Modulus and the Inertia of the member

The bending forces are then combined with the residual forces to give the final forces in the springs from which the layer stresses can be calculated.

Small correcting moments are generally required to be applied to each layer to give continuity of strain at the layer boundaries. The larger the number of layers taken the smaller is the significance of these moments.

The radius of curvature for each axial section can now be calculated from the bending equation:

$$R = E \cdot I/M \qquad (2)$$

4. Equivalent Inertia

It is assumed in this treatment that the section of the member is uniform throughout its length. The E value, however, will vary in every layer and every section.

In order to apply the bending equations in (1) and (2) it is necessary to have an E value which applies throughout the section. This is achieved by taking the ambient E value with an equivalent I obtained by the method used for beams of composite materials. The breadth of each layer is multiplied by E/EO giving an equivalent breadth and an equivalent inertia I_E is computed using these equivalent breadths.

The bending equations then become:

$$BF = A \cdot y \cdot E/(EO \cdot I_E) \qquad (3)$$

$$R = EO \cdot I_E/M \qquad (4)$$

and each axial section has a different I_E

5. Interaction Effects

When the free bow of a member is greater than the available clearance, an interaction takes place with an adjacent member or surface. This produces a point load reaction at the point of contact sufficient to deflect the member by an amount equal to the difference between the unrestrained bow and the available clearance. It is assumed in this treatment that the free bowing of the member is small (e.g., less than 1 per cent) compared with the length and that multipoint contacting or flattening, as postulated in [1], will not occur.

The CURVO programme proceeds in a series of dose steps (which are specified in full power days) and after each step the unrestrained bow is computed and compared with the available clearance. Where interaction takes place the reaction, which is necessary to restrain the bow to the allowable clearance, is calculated, assuming it is applied at the point of maximum free bow. The deflections caused by this point load reaction at each axial section are then calculated and subtracted from the unrestrained displacements to give a resultant shape. Except for the case of a central reaction, it will be found, at this stage, that the final shape is such that the maximum sagitta is not at the place where the reaction load has been applied. An iteration procedure is necessary to arrive at the situation where the maximum sagitta occurs at the same axial position as that taken for the reaction load application.

Having found the amount and position of the restricting reaction the bending stresses are calculated and combined with those obtained from the effects of differential expansion, shrinkage and creep.

For the Dragon inner live reflector block, inwards bowing (the radially inside face becoming convex) meets with a theoretically rigid restraint because of the equal and opposite bow of an identical block on the opposite side of the core. Outwards bowing, however, is resisted by the outer live reflector blocks, which are of similar proportions. In this case the relative stiffness of the pairs of blocks is taken into account when computing the interaction forces, deflection and stresses.

6. Creep Effects

Creep is also treated by an interaction process. At each dose step the stresses due to thermal, shrinkage and bending effects are combined and the resultant stresses used, in conjunction with the final stresses from the previous dose step, to give an average stress level in each layer.

This stress level and the accumulated dose are used to obtain the creep strain occurring at the temperature concerned. Creep stresses are then computed by the method described in Section 3 and combined with the initial stress summation. The first assumed average stress level is now modified, giving a different creep strain, which in turn modifies the creep stresses and again changes the average stress level. This process is repeated until the change in average stress level is less than five per cent.

It will be appreciated that the creep and the restraint effects overlap due to the bending component of stress effecting the stress level which in turn effects the creep coefficient. This results in an iteration within an iteration and a lengthy process can ensue if acceptance limits are set too tight.

7. Overall Shape

The differential expansion, shrinkage and creep effects are assumed to cause a radial curvature in each axial section. These curvatures are connected tangentially and the free bowing sagitta at each section is computed. The deflections at the same positions due to the point load reaction are calculated by simple bending theory and subtracted from the free deflections to give a final set of sagittae which define the overall shape.

A check is made, where interaction occurs, to ensure that the point load reaction does not cause a 'dent' or 'valley' in the overall shape. When this occurs it indicates that flattening has taken place and the CURVO programme is not, at present, applicable.

8. Application to Reflector Blocks

This method has been used to assess the bowing of the inner row of reflector blocks surrounding the Dragon core. These blocks are about 240 cm long and of varying shape to suit the core outline but generally similar to that shown in Fig. 1. Each inner block is connected by a small tie bar, at the top, to an outer block of similar proportions and both blocks have a hinge type of base support. The outer block is relieved over most of its inner face length to give a clearance of 0.38 cm into which the inner block can deflect before interaction takes place. The blocks are made from Pile grade A graphite for which the mechanical characteristics are fairly well established.

It was originally intended to change the inner blocks before the interaction forces were of any significance but for economical reasons the change was postponed until the bowing of the blocks began to effect the loading and unloading of fuel elements. Using the above method, with certain modifications to suit the particular circumstances, it was possible to predict that the interaction force was sufficient to cause creep rupture failure of the top tie bars after about 900 full power days. It also showed that after a similar period, the interaction force during operation would begin to exceed the shutdown force due to changes in the coefficient of thermal expansion (Fig. 2). It was therefore decided to shutdown the reactor and change the inner reflector blocks one core loading earlier than planned. This has now been successfully completed and measurements of some blocks have taken place.

The CURVO programme was used to predict the bowing of the replacement inner reflector blocks using two different graphite materials, one similar to the original PGA and the other a gilsocarbon graphite. The gilsocarbon material showed a much less bowing effect with time, due to its smaller radiation shrinkage properties but gave a larger initial inwards bow due to its higher coefficient of thermal expansion (Fig. 3). The eventual choice of material was dictated by availability and the PGA type of graphite was used for about one third of the blocks, the remainder being gilsocarbon.

The basis of the replacement block design was to eliminate the interaction effect and a design incorporating two axial joints was considered. This had the disadvantage of having to introduce metal joining components at points of high neutron flux and it was therefore decided to make a repeat of the original block design but to machine additional clearances on the inner and outer faces based on the CURVO prediction such that interaction would not take place for approximately 900 full power days. Additional thermocouples have been introduced into the new blocks to give a better idea of the thermal distribution and sets of contacts have been incorporated to give an indication when interaction occurs between the inner and outer blocks.

9. Results

The results from CURVO are obviously effected by the accuracy of the input information and in two respects this could be improved. The thermal distribution being used is based on calculations by C. Zanantoni [3] in 1963 and these are at present being updated. Creep data available indicates a considerable spread of results but the values taken are from a plot which is specifically for gilsocarbon [4] graphite and gives average creep rates. Two curves are plotted in Fig. 4 to show the predicted shape assuming tie bar rupture at 900 days and no outer block distortion against the measured values for a block type 003 [5].

10. Application to Strip Cutting Technique

The method has been used in conjunction with the more sophisticated finite element predictions of residual stresses in teledial fuel pins. A 5 mm wide strip is cut longitudinally from the fuel pin and when freed from the adjacent body of material it assumes a bow which corresponds to the amount and nature of the residual stresses.

The cross section of the strip is drawn on the finite element diagram and divided into a convenient number of layers. The predicted residual stresses across each layer are averaged and used to calculate the initial 'spring movements' for the analogy. The curvature is thus obtained together with a new set of residual stresses and the calculated sagitta compared with measurements of the sample strip. This procedure can then be repeated by making a further longitudinal cut down the strip producing two half strips with different radii of curvature which can again be checked against measurements. This procedure has been written into a small programme PISC which will be used and further developed for post-irradiation inspection. By measuring the forces necessary to flatten the strips, the absolute values of residual stress can be deduced to a reasonable accuracy.

11. Comments

This method embodies a simple mechnical concept and is intended mainly to give an approximate picture of the order of bowing distortion in one plane during the in-core life of a prismatic graphite member. The order of magnitude of a possible interaction force can also be assessed. These two parameters are required at the design stage and the programme allows easy variation of such characteristics as material properties, clearances, length of core life, etc., which can be investigated at the design stage.

The results obtained so far, for the Dragon reflector blocks compare quite well with the measurements taken and give a sufficient degree of confidence to use the CURVO predictions for the design of replacement members.

12. Acknowledgments

The authors wish to acknowledge the advice and help of Mr. E. Smith in the development of this method. Thanks are also due to Mr. D. Kinsey for advice on computer store problems and to Mr. D. Collins, AEE, Winfrith for his independant check and assessment of the CURVO code.

13. References

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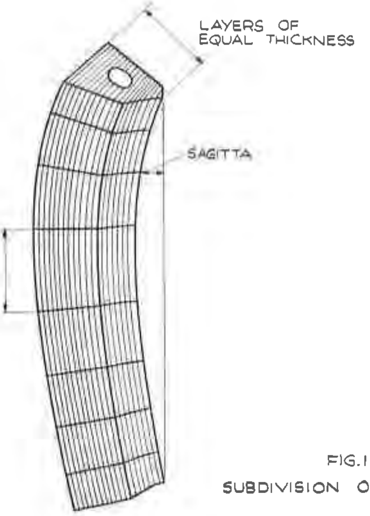
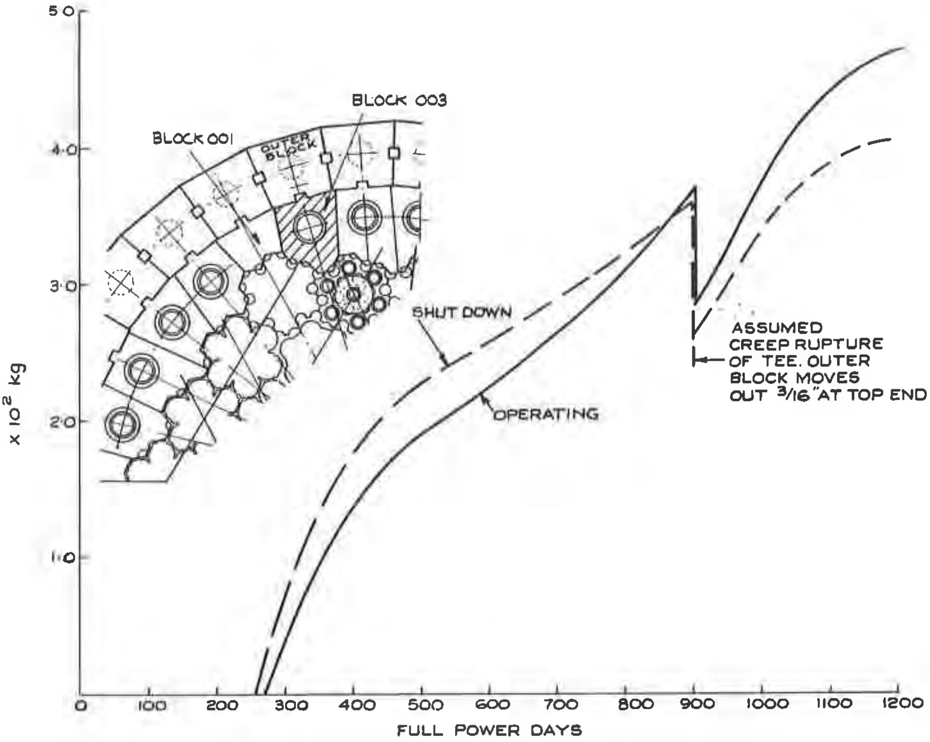


FIG. 1
SUBDIVISION OF MEMBER



'CURVO' RUN 6·11·72

FIG. 2. BLOCK 003 TOP REACTION

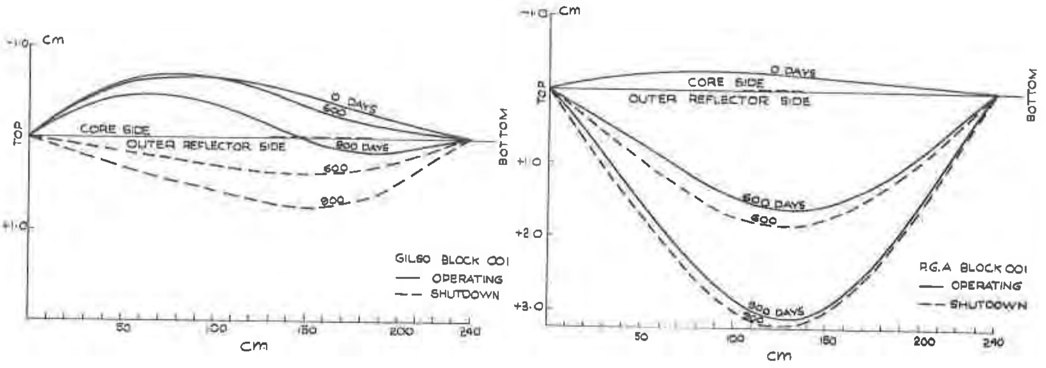


FIG. 3
COMPARISON OF DISTORTIONS WITH TWO DIFFERENT TYPES OF GRAPHITE.

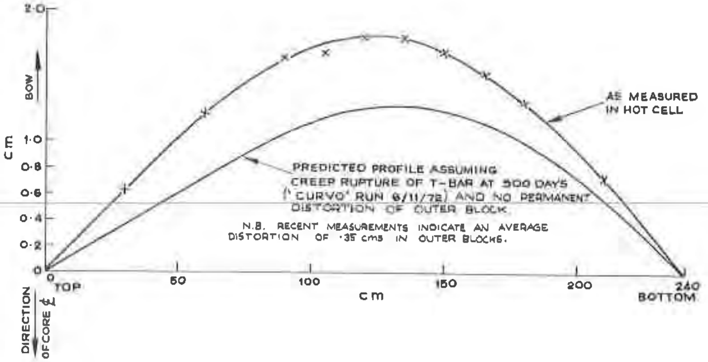


FIG 4 BOW OF INNER REFLECTOR BLOCK No.27 TYPE 003
MATERIAL P.G A