Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

C03/6

Structural analysis of the graphite moderator cores within advanced gas cooled reactors

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ABSTRACT

The structure of the graphite blocks comprising the moderator core of AGR reactors is subject to change over a period of time due to irradiation and weight loss of the graphite itself. The prediction of the equilibrium configuration of the ensemble of graphite blocks is important with regard to calculating fuel and control channel clearances and underwriting the continuing functionality of the moderator core. This paper describes the modelling of the core by linear programming methods where the structure of the graphite blocks has been modelled as a series of discrete blocks which interact via constraints which correspond to key/keyway interactions between the blocks as well as the basic requirement of no block overlap. The interactions with the surrounding steelwork are also modelled as additional constraints which enable the differential thermal expansion at start-up and shut-down to be incorporated as a mechanism for producing changes in the moderator core state. The resultant series of equations are solved to produce an equilibrium configuration for the moderator core for a given irradiation and weight loss.

INTRODUCTION

Analysis of graphite core structures in nuclear reactors is carried out to underwrite the continuing functionality of the cores currently in service. The graphite moderator cores of Advanced Gas Cooled Reactors (AGR) used by Nuclear Electric Ltd. are designed to the same basic pattern. The principal components of the design are an array of cylindrical graphite blocks, of approximately 0.9m height and 0.45m diameter arranged in layers within a cylindrical steel restraint vessel resting on some form of steel support structure known as the diagrid. The voids between these primary blocks are filled by smaller interstitial graphite blocks. The whole is constrained by a system of graphite keys between adjacent blocks which are designed to prevent distortion of the core as a whole which would compromise the fuel and control rod channels running vertically through the core. These keys can either be integral to the graphite blocks or can be in the form of loose rectangular rods. The keys then fit into slots, known as keyways, in the blocks. All AGR graphite core structures are based on a system of primary octagonal blocks with the gaps being filled by smaller square interstitial blocks.

The primary blocks are arranged horizontally on a square array which is structured to fit within the circular restraint vessel. There are approximately 330 fuel blocks and approximately 220 reflector blocks as well as 830 interstitial blocks per layer within the core. Vertically the moderator core is arranged in layers corresponding to the heights of the primary blocks. Sequentially from the bottom of the core, a typical vertical arrangement of the primary blocks is one lower neutron shielding block layer, eleven fuel or reflector block layers and one upper neutron shielding layer. The height of such a block column is approximately 13m with a mass of 2500Kg. The vertical arrangement of interstitial blocks (keyed and filler) within a primary block layer can vary between reactors. The reactor type studied here has one keyed and two filler blocks for each fuel block. On average there is a 1.0mm clearance between blocks of all types and a clearance of 0.25mm between keys and keyways. The clearance between blocks is increased with the expansion of the core to match the surrounding steelwork (power on) as the coefficient of thermal expansion of the steel is approximately four times that of graphite. The block clearances may be significantly reduced by leaning of the primary block columns due to diagrid sag thus there will be a distribution of block and keyway gaps and some will inevitably be touching. Primary/ primary or primary/interstitial block touching as well as key/keyway touching must provide a constraint on the relative displacement of neighbouring blocks and thus on the global deformation of the moderator core.

The material properties of the graphite changes with irradiation. The most significant of these, in terms of the structure of the graphite core as a whole, is dimensional change (shrinkage) of graphite causing small changes to the linear dimensions of the blocks, leading to distorted blocks. Radiolytic oxidation of the graphite is also a cause of the degradation of the graphite core as it results in a net decrease in the weight of a given block. Both dimensional change and weight loss are a function of the position of a block within the core. The slight distortion of the blocks takes the form of block bowing and to a lesser extent block barrelling as well as dishing of the end faces. The keyways within a block can also become pinched leading to reduced clearances of the keys within the keyways.

The forces acting on a block come from several sources. The primary loading on the structure comes from the self weight of blocks and weight of core structure above the block in question.Thermal loads arise from the difference in coefficients of thermal expansion between the graphite blocks and the surrounding steelwork, that is the restraint vessel and the support structure. As the reactor undergoes heating or cooling transients, this differential expansion or contraction gives rise to a series of forces imposed on the outside of the graphite core. Other forces arise from coolant gas pressure and frictional forces between graphite blocks within the core. A special case of this is key/keyway pinching in which keys can become frictionally locked at a set position within a keyway.

The modes of functional impairment of the graphite core consist of the loss of required clearance within any fuel rod or control rod vertical channel and the restriction or blockage of coolant channels caused by misalignment of blocks. The theoretical determination of these quantities from the analysis of the graphite core structure is therefore required for the assessment of the continuing functionality of the reactor.

The requirements of a mathematical model of the graphite core are that the model should be able to calculate the configuration of the graphite blocks as the reactor cycles between hot and cold states. The model must also be able to incorporate the effects of irradiation i.e. weight loss, dimensional changes and consequent distortion of the graphite blocks and associated keys.

Linear programming methods of analysis are based on the linearization of the principal features of the problem under study. Other features which are non-linear must either be linearized in a piecewise fashion or be shown to be sufficiently small to be neglected. The procedure is then to divide the problem into an objective function which must either be maximized or minimized subject to a system of constraint equations which define the limits on the variables and how they are dependent on each other. This method was used by Soanes [1] to determine the maximum movements of the graphite core blocks within a single horizontal layer of the core of an AGR reactor. Linear programming methods have also been used by McLachlan [2] to model vertical sections through the graphite core and thus attempt to determine the geometry of the graphite columns. This approach corresponds to a minimization of the total energy of the graphite core (i.e. the self weight of the structure). The secondary load from the surrounding steelwork is then treated as prescribed displacements on the boundary of the core.

GRAPHITE CORE MODEL

The present method consists of a full 3-dimensional model of the core, with detailed modelling of the interactions of individual blocks. The displacements are calculated by linear programming methods from the minimization of the total energy of the graphite core within a system of constraint equations which define the allowed configurational space of the blocks (i.e. the limits to the motion of the blocks). The total energy for the system, which can be defined as the graphite blocks together with the surrounding steelwork, is composed of a number of terms. However only those terms which can be shown to vary during the loading cycles of the reactor need to be taken into account. Thus the total energy can be written as

$$U = U_{PE} + U_{TI} + U_{GP} + U_F \tag{1}$$

where U_{PE} is the potential energy term and U_{TI}, U_{GP} and U_F are the kinetic terms. U_{TI} is the thermally induced contribution to the energy, U_{GP} the strain energy arising from the differential gas pressure and U_F is the frictional contribution to the energy from both pinched key/keyway interactions and sliding of blocks at vertical block interfaces. The variables to be calculated are the coordinates of the graphite blocks, that is the position of their centres (x_i, y_i, z_i), their angles of inclination (θ_i, ϕ_i) to the vertical axis and their angles rotation (ψ_i) about their vertical axis, together with the variables characterizing the thermal expansion of the steelwork. The coordinates can be expressed in terms of the deviation from their positions in the ideal core lattice. The variables describing the steelwork can be separated in a similar manner. It should be noted that the angles of inclination of the blocks to the vertical (θ_i, ϕ_i) operate in the same fashion as a joystick in that these angles refer to inclination in the *xz* and *yz*-planes respectively, relative to the orientation of the given block as determined by the orientation of the rocking feature at its base. Throughout this analysis, as the limits on the movements of the blocks are relatively very small, the small angle approximation has been used widely within the construction of the core model.

The gravitational potential energy of the graphite blocks can be written as

$$U_{PE} = g\sum_i m_i(z_i - z_0) \tag{2}$$

where i denotes block numbers, m_i being the mass of the i^{th} block. z_0 is the datum height of the ideal lattice. The height of the centre of the i^{th} block z_i may be described as the sum of the heights of the blocks in the given block column up to the i^{th} block from below, starting from the height of the diagrid z_d above the baseline. This vertical height is increased by changes in the corresponding angles of inclination at the vertical interfaces between blocks (γ_i, β_i). By modelling the rocking feature at the base of a block as a rectangle with sides $2r_\gamma$ and $2r_\beta$, and the top of the adjacent block as a plane surface, it can be shown that the change in energy caused by hinges at the vertical interfaces between pairs of blocks in the block columns is given by

$$\Delta U_{PE} = g\sum_i m_i \sum_{l=0}^{L(i)-1} \{r_{\gamma(kl)}|\gamma_{kl}| + r_{\beta(kl)}|\beta_{kl}|\} \tag{3}$$

where $L(i)$ denotes the layer number of the *i*th block within the *k*th block column and *l* is the number of the vertical interfaces between blocks in the column going up from the column base on the supporting steelwork. The angle of orientation of the rocking features has been neglected for simplicity. The contribution of the self-weight of the graphite blocks to the total energy will vary throughout the life of the reactor due to irradiation causing a degree of weight loss of the graphite blocks. For some reactor types a further contribution to the potential energy of the core comes from the weight of the upper neutron steel shielding blocks found at the top of each graphite block column and the weight of the upper neutron steel restraint plates on the top of the peripheral region of the graphite core. These contributions are treated in a similar manner to potential energy of the graphite blocks.

The suppression of the thermal expansion or contraction of the steelwork surrounding the graphite core, gives rise to a strain energy contribution to the total energy of the system and therefore the linear programming objective function. This arises from three distinct parts of the steelwork, namely the diagrid, the restraint vessel and associated restraint links and the upper neutron shield (UNS) restraint plates, each of which is described by its own variable(s).

$$U_{TI} = U_D + U_V + U_L + U_U \tag{4}$$

The temperature distribution within the core and the surrounding steelwork is approximately uniform for AGR reactors. As the coefficient of thermal expansion (α) of the graphite is typically a quarter of that of steel, the differential expansion coefficient $\alpha_d = (\alpha_s - \alpha_g)$ may be used to describe the suppressed thermal strain energy associated with the steelwork. The variables describing the thermal expansion/contraction of the diagrid, restraint vessel, restraint links and UNS restraint plates are all strictly independent from the variables associated with the positions of the graphite core blocks. However any thermally induced displacement of the steelwork will be transmitted to the graphite blocks via the constraint conditions requiring either no slip or limited slip of the graphite blocks at their interfaces with the steelwork, which are in the form of support struts, restraint rods and/or dowels.

For the calculation of the thermal strain energy associated with the diagrid U_D, it is assumed that the diagrid is modelled as a thin circular disc under plane stress conditions such that $U_D = U_D^0(1-\psi)$ where ψ is the fractional thermal expansion, such that ψ=0 for complete suppression of the expansion of the diagrid to ψ=1 for free thermal expansion. This free expansion corresponds to a radial displacement of $u = \alpha_d \Delta T r$ where r is the radial distance of the point from the centre of the diagrid disc and ΔT is the temperature change within the core. The magnitude of the stored strain energy when the expansion of the diagrid is fully suppressed U_D^0 is given by

$$U_D^0 = \pi R_D^2 h_D \left(\frac{E_s(\alpha_d \Delta T)^2}{(1-\nu)} \right) \tag{5}$$

where R_D and h_D are the radius and the effective thickness of the diagrid circular disc respectively. The fractional displacement of the circumference of the diagrid disc is given by $\psi = \Delta R_D / (\alpha_d \Delta T R_D)$.

The procedure for the restraint vessel closely follows that used for the diagrid. In this case the restraint vessel is modelled as a thin cylinder. For simplicity it is assumed that there is free vertical thermal expansion of the thin cylinder, thus the stored strain energy is associated with the suppressed radial and circumferential expansion of the restraint vessel which is given by

$$U_V = U_V^0 \left\{ \frac{2}{3(1+\nu)} (1-\psi) \right\} \qquad \text{where} \qquad U_V^0 = 3\pi R_V h_V L_V \left(\frac{E_s(\alpha_d \Delta T)^2}{(1-2\nu)} \right) \tag{6}$$

where R_V, h_V and L_V are the radius, thickness and length or the restraint cylinder respectively. The thermal strain energy associated with the restraint links and the upper neutron restraint plates are found in a similar manner.

The strain energy terms arising from the differential gas pressure gradient throughout the graphite core and those arising from frictional sources are neglected as these can be shown to be at least an order of magnitude smaller than the above contributions. In the case of the differential gas pressure it is difficult to estimate the magnitude and direction of these forces which come from gas flowing in the passages between the outside of blocks throughout the core. For the estimation of the frictional contribution an additional calculation of the forces between the graphite blocks within the core is also required.

SYSTEM OF CONSTRAINT EQUATIONS

The constraint equations for the graphite core determine the allowed configurational space for the blocks by setting limits on their relative motion. For simplicity the effects of block rotation about their vertical axes has been neglected. It should be noted that in the absence of vertical hinges between blocks, large forces are required at the block interfaces to overcome the frictional stick limit and thus allow block rotation to occur.

The side of a block in 3-dimensions can be represented as a plane. The block overlap constraint on the motion of a block is that a point feature on an adjacent block, such as the corner of a key or block, must not cross the plane defining the physical side of the block or keyway. At the vertical interfaces between blocks within a block column there is a requirement that no horizontal slip between blocks at their vertical interfaces takes place, i.e. the x and y coordinates of the centres of the upper and lower faces of the block pair in contact must be equal. There must also be no change in the angle of block twist at the interface.

The calculation of the integral and loose key constraints follows the method used for the block overlap constraints. That is the plane defining the sides of the key must not be penetrated by the points defining the outside corners of the keyway. This is the most important constraint as it will become increasingly dominant as keyway pinching occurs within the core. If there is no mutual rotation of adjacent blocks then the sides of the key effectively remain parallel to the keyway sides, and this constraint is all that is required to describe the allowed motion of the key in the keyway. However if mutual rotation of adjacent blocks is allowed, then an additional constraint must be provided such that the plane defining the sides of the keyway must not be penetrated by the points defining the corners of the integral key. The basic procedure is the same for both integral and loose keys, however in the case of loose keys there is an additional term in the constraint equation which is a function of the distance between the graphite blocks. This models the increased amount of movement allowed by the loose keys when the distance between the graphite block pair is increased. It is within the block overlap and keying constraints that the effects of diagrid sag are incorporated into the structure.

The remaining constraints require that the positions of the graphite blocks which are in direct contact with the steelwork by dowels, rods or struts remain linked to that position on the steelwork during the process of expansion or contraction of the core.

RESULTS

The solution of the linear programming model of the core has been obtained using the CPLEX package [3] which specializes in large sparse problems. A typical configuration of graphite blocks in a vertical section through a core in the hot 'power on' state is shown in Fig.1 where the deformations have been scaled by a factor of 100 to make the core behaviour visible. In fact the diagrid sag seen in this figure is approximately 0.01m. From this figure it can be seen that the effect of diagrid sag is to allow the tops of the block columns in the central section of the core to touch. At the periphery the columns are held upright by their interactions with the restraint vessel and associated links. Between these regions the block columns are seen to fan out as a result of the keying interactions between individual blocks in adjacent columns. These deformations are consistent with the known deformation of the core in the 'as built' state. In a sequence of solutions going from a two-dimensional vertical slice model to a three-dimensional slice across the core incorporating nine full-width lines of blocks and then to the full core solution, the block columns are seen to become increasingly upright as the degree of constraint within the core model increases.

This behaviour of the core can also be seen in the plan view in Fig.2 where only the blocks in layers 2 and 12 are displayed. It can be seen that the central interstitial column and the peripheral primary columns remain strictly upright. This particular example is for a reduced core of 4000 blocks which is approximately a quarter of the size of a full core.

CONCLUSION

From the calculation of the equilibrium configuration of cores in the hot or cold states, it is concluded that the present method is a valid and very accurate method of modelling the displacements of the graphite blocks within an AGR core.

ACKNOWLEDGEMENTS

This paper is published by kind permission of Nuclear Electric Ltd. The author is gratefully acknowledges the contribution of N. McLachlan with many useful and informative discussions and the assistance of H. Whittaker in carrying out this work.

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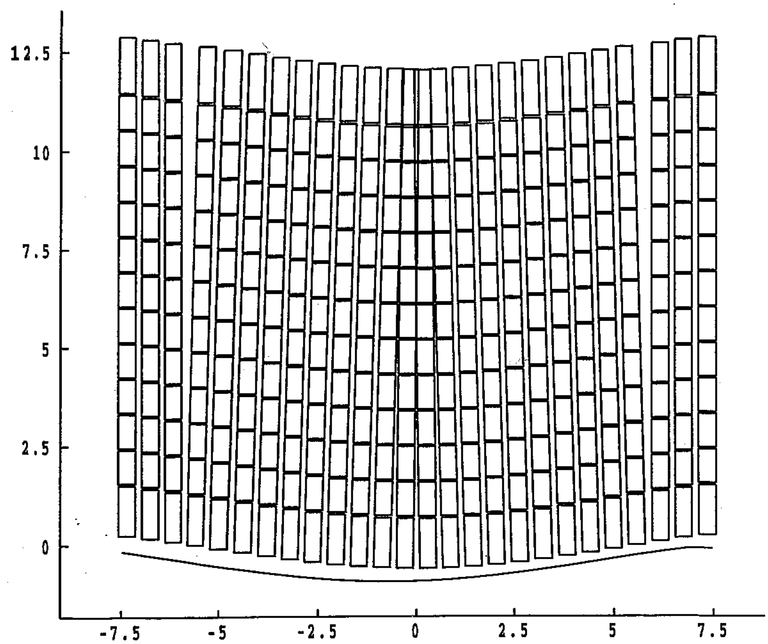

Figure 1 - Vertical section through the graphite core showing the deformation of a line of primary block columns and the diagrid contour

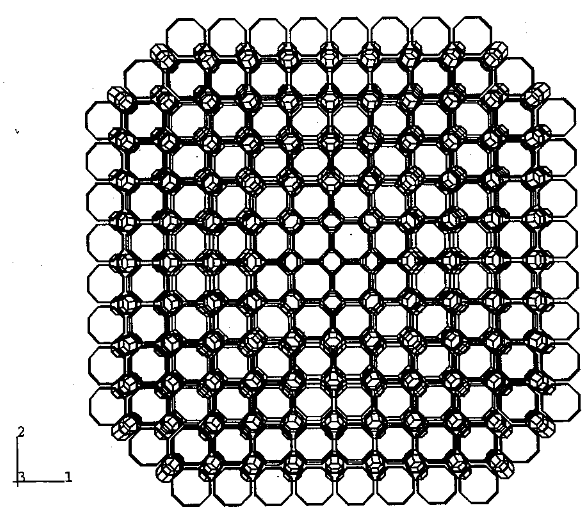

Figure 2 Plan view of the graphite core showing layers 2 and 12 only