GRAPHITE CORE DESIGN IN UK REACTORS

M.W. DAVIES
Nuclear Engineering Division,
NNC Ltd , Knutsford, Cheshire,
United Kingdom

Abstract

The cores in the first power producing Magnox reactors in the UK were designed with only a limited amount of information available regarding the anisotropic dimensional change behaviour of Pile Grade graphite. As more information was gained it was necessary to make modifications to the design, some minor, some major. As the cores being built became larger, and with the switch to the Advanced Gas-cooled Reactor (AGR) with its much higher power density, additional problems had to be overcome such as increased dimensional change and radiolytic oxidation by the carbon dioxide coolant. For the AGRs a more isotropic graphite was required, with a lower initial open pore volume and higher strength. Gilsocarbon graphite was developed and was selected for all the AGRs built in the UK. Methane bearing coolants are used to limit radiolytic oxidation.

1. INTRODUCTION

Up until the construction of the Sizewell B Pressurised Water Reactor, all the power producing reactors in the UK were graphite moderated and gas cooled. As well as functioning as a fast neutron moderator, each graphite core must perform its duty as a structure that will allow unresticted passage of fuel elements and control rods and maintain appropriate cooling flows at all times during the operating life of the station. Over the life of the core, the graphite is subjected to the effects of fast neutron radiation, and radiolytic oxidation by the carbon dioxide coolant. The former gives rise to dimensional change, causing individual components and complete brick channels to distort, thus potentially affecting the safe operation of the reactor. The latter has an affect on dimensional change behaviour, but more importantly causes a reduction in graphite strength which would have a detrimental affect on brick integrity. This paper outlines the ways in which the different graphite core designs in the Magnox reactors and Advanced Gas-cooled Reactors (AGRs) in the UK have evolved to accommodate these degenerative effects to enable them to perform their structural duties.

2. MAGNOX CORE DESIGN

The first commercial stations in the UK were of the Magnox type and were built at Calder Hall and Chapelcross in the late 1950s. Four reactors were built at each site, and used natural Uranium as the fuel, clad in Magnox. Each reactor has around 1700 fuel channels and a design heat output of 180 MW. A further 9 Magnox stations were built, the last being a twin reactor station at Wylfa. The cores in the Wylfa reactors were the largest to be built, each having over 6100 channels and a design heat output of around 1700 MW.

The graphite used for the construction of each core was Pile Grade A (PGA) graphite. The coke used for the production of the graphite was referred to as 'needle' coke because of the needle like appearance of the grains after crushing. The method of forming the basic shape of the graphite blocks involved extrusion. This method had the effect of preferentially aligning the grains and hence crystallite basal planes in a direction parallel to the direction of extrusion. As a result, the properties of the graphite are anisotropic. Production graphite had a density of about 1.6 g.cm^{-3} , was quite porous and had a moderate strength.

1.1 Graphite dimensional change

The dimensional change behaviour of PGA graphite is, as would be expected, very anisotropic. In the direction parallel to the direction of extrusion, the graphite shrinks progressively with increased dose, and at all irradiation temperatures of interest. In the perpendicular direction however, the graphite shrinks at irradiation temperatures greater than around 300°C, but below this it exhibits growth, the lower the temperature the greater the rate of growth.

When the graphite moderator structure for the Calder Hall and Chapelcross reactors was being designed, it was erroneously believed that PGA graphite exhibited growth in the both the perpendicular and parallel directions, and that the ratio of these growth rates was about 6:1. To allow for this apparent behaviour, the core and interfacing structures were designed and constructed as shown in Fig 1.

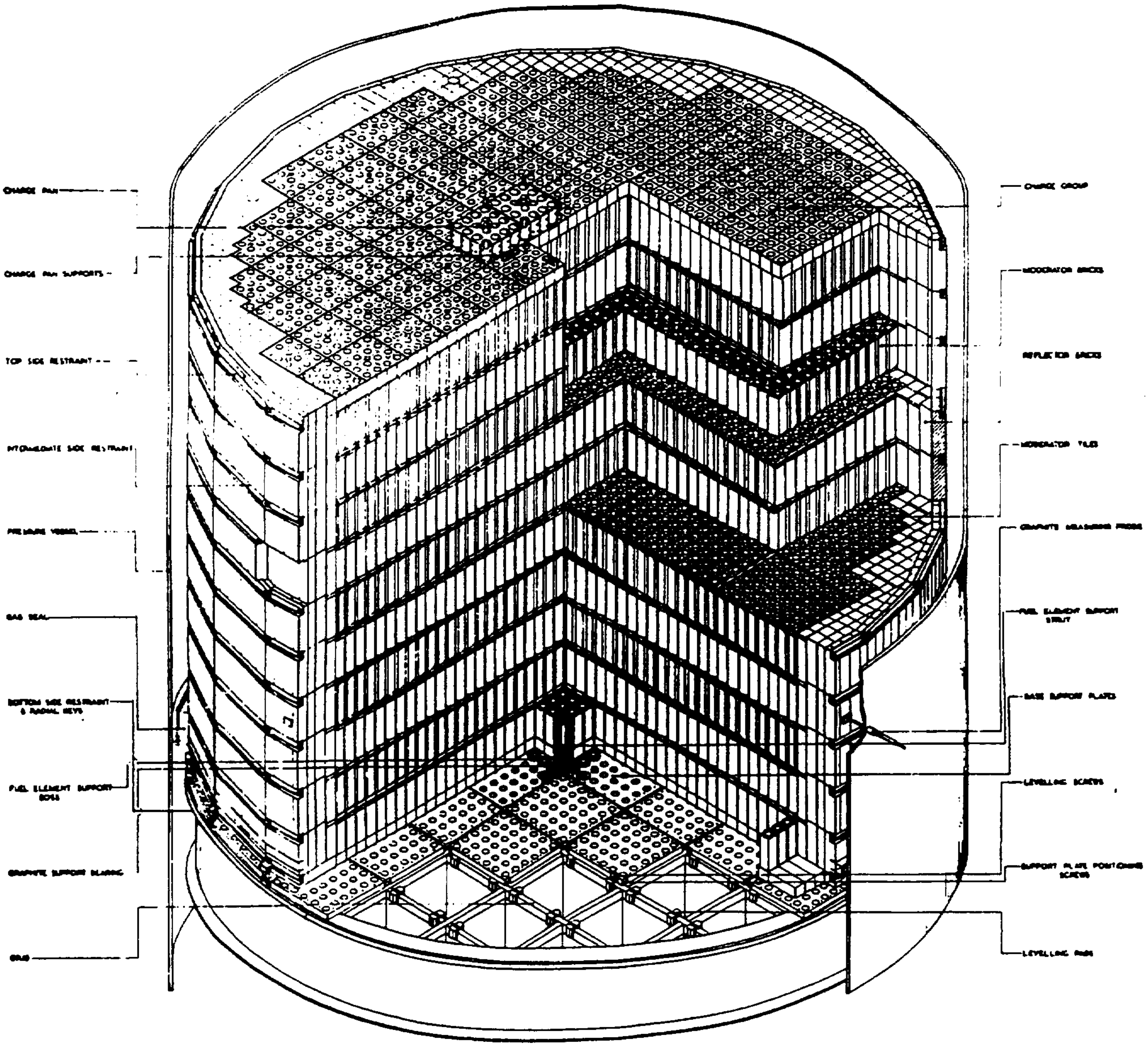

FIG 1 ISOMETRIC VIEW OF CALDER HALL GRAPHITE STRUCTURE

The core is made up of layers of square bricks of side slightly smaller than the lattice pitch of 8 inches (20.3 cm), having their extrusion axes placed vertically. The bricks are interleaved with two layers of rectangular tiles having their extrusion axes placed horizontally and parallel with the long sides. The length of the long sides is equal to that of the lattice pitch. All the tiles in the bottom layer were arranged with their long sides running North-South forming parallel chords across the core face and those in the top layer were arranged with their long sides running East-West.

The reflector region around the core was built with no inter-brick gaps since irradiation effects in this region were considered to be negligible. Garter restraints (in the form of compensating beams) were placed around the periphery at the same height as the tile layers which meant that the tiles were fully constrained and the lattice as a whole would expand as graphite in the long tile direction (in effect radially). The compensating beams were designed to have a coefficient of thermal expansion close to that of the graphite and so always provided the necessary restraining forces at the core boundary. The core does, however, expand at a different rate relative to its support structure and therefore the columns were mounted on ball bearings to cater for the differential movement.

The bricks and tiles in each column are located relative to one another by means of cruciform keys as shown in Fig 2. In this way, the moderator bricks are located in their correct lattice position by the tiles, and because they have sides which are slightly shorter than the lattice pitch, have a gap around their vertical sides to accommodate the predicted lifetime growth of the graphite.

One problem with machining and arranging the tile axes with one direction parallel to the extrusion direction and the other perpendicular, is that the tile bores would become oval during irradiation and so could interfere with fuel handling operations. To obviate this potential problem, each tile bore was made slightly larger than its brick bore, so that at no time during the design life of the reactor should the inner surface of a tile encroach into the fuel channel passage.

It was discovered later that PGA graphite actually shrunk in the direction parallel to the extrusion axis. Shrinkage of the tiles in the parallel direction obviously affects lattice control because the tiles are arranged with this axis in the long (butting) direction. It was realised that gaps will consequently open up between the tiles and so permit lateral movement of individual columns which could affect fuel cooling and control rod insertion. The problem at the time was that the graphite bricks for the Berkeley, Bradwell and Hinkley Point cores were at an advanced stage of machining. A decision was therefore made to incorporate Zirconium pins in deep horizontal holes drilled into the bricks and/or tiles to maintain lateral alignment. Zirconium has a low neutron absorption cross-section and therefore the small penalty of slightly reduced reactivity was considered acceptable. The Trawsfynydd design was less advanced and a single tile at each brick junction utilising radial keys on the 90° and 45° axes was adopted.

After Trawsfynydd, the brick and tile method of maintaining channel lattice alignment was abandoned, in favour of a full brick radial keying arrangement as illustrated in Fig 3. Keyways are machined in the individual blocks and rectangular shaped keys are inserted into the keyways which therefore limit brick to brick movement. A radial keying system has the advantage of allowing the core to freely expand volumetrically and so by surrounding and attaching it to a steel restraint tank, the core can expand (as steel) with the support structure. The important requirement here was to ensure that the initial key/keyway clearances were small enough to limit individual brick to brick and cumulative brick movements, yet large enough to ensure that they did not reduce to zero at any time in life thereby restricting free lattice expansion.

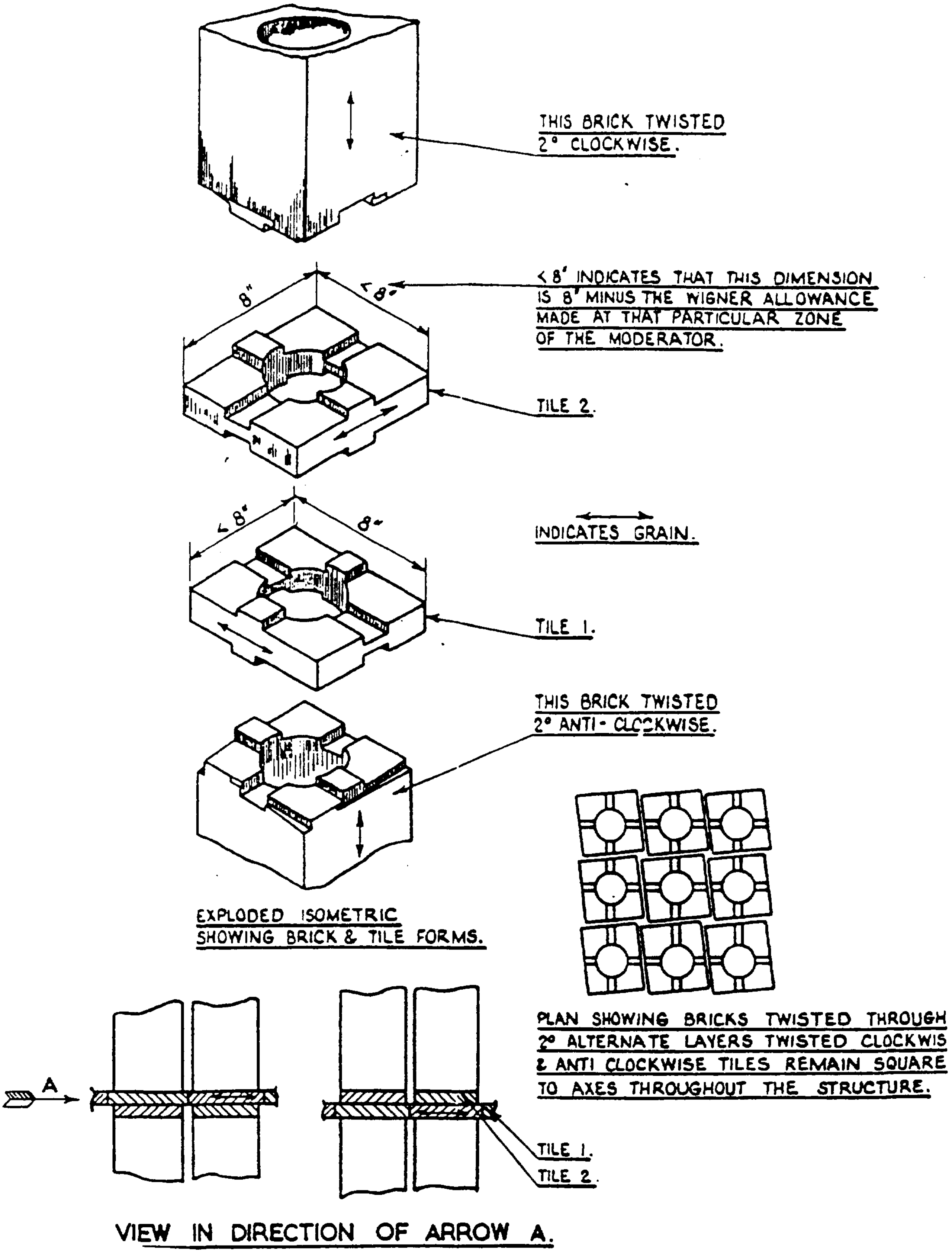

FIG 2 BRICK AND TILE ARRANGEMENT IN EARLY MAGNOX CORE DESIGNS

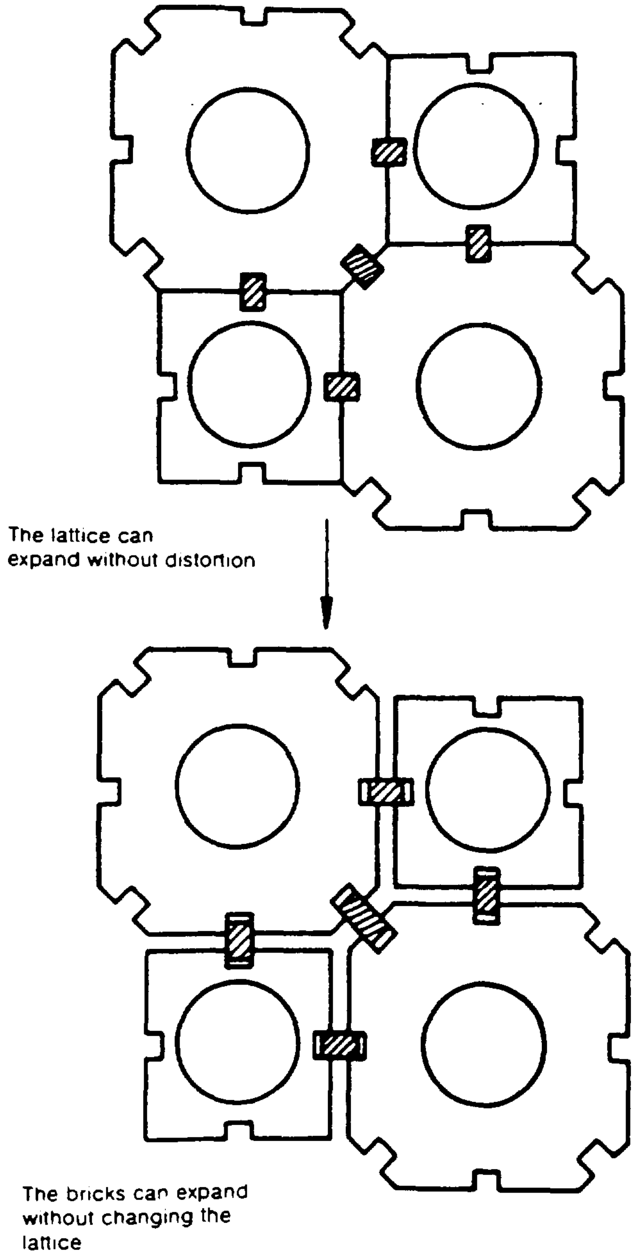

FIG 3 KEYING ARRANGEMENT IN LATER MAGNOX CORE DESIGNS

One further problem identified was caused by the variation in fast neutron flux across a brick section, due for example to the proximity of a control rod channel, which gave rise to differential axial shrinkage. This would result in the individual bricks assuming a curved shape, referred to as brick bowing. Because of the restrictions on lateral movement imposed by the tiles or the keying system, curvature of the overall brick column was limited, and when this limit was reached a hinge would be forced at the contact points. Wedge shaped gaps would then open up as bowing progressed leading to out of channel leakage of the coolant gas. In the later core designs, circular sealing rings were introduced between the bricks in a column to significantly reduce any leakage flow.

2.2 Radiolytic oxidation

Radiloytic oxidation of the graphite reduces its strength and could therefore be a concern. The rate of radiolytic oxidation of graphite by the CO_2 coolant increases with increasing gamma heating rate in the graphite and with coolant gas pressure. In the earlier Magnox cores, which operated at relatively low power density and pressure, radiolytic oxidation of the graphite over the life of the station was not significant. However, as the power output of subsequent Magnox reactors was increased, there was a corresponding increase in the gamma heating rate and coolant pressure and so radiolytic oxidation became more and more significant. There are no features specifically designed into the Magnox cores to limit the rate of oxidation, however, operational procedures are in place to control the rate of oxidation and so limit any reduction in graphite strength.

2.3 Limitations

Magnox cores are 'once through' designs in that the coolant gas enters the bottom of the core via the support system, flows mainly up through the fuel channels and exits the core at the top. The problem with this arrangement was that only moderate power densities were achievable due to limits on channel gas outlet temperatures (to limit the oxidation of mild steel components above the core), and therefore progressively larger cores were required to provide more heat output. In fact most of the Magnox reactors were downrated because of the potential life limiting effects of mild steel oxidation.

Not long after Calder Hall and Chapelcross had started operation, work began on the concept of the Advanced Gas-cooled Reactor, and in the early 1960s a prototype was built at Windscale. By using enriched Uranium dioxide fuel, clad in stainless steel, much higher gas temperatures would be allowable. As a result, significantly higher power densities would be possible in the core but the problem then became one of trying to keep graphite temperatures down in order to limit thermal oxidation. The problem of high graphite (and high steel) temperatures was solved by the major innovation of the AGR core : re-entrant flow. By using a gas baffle and sleeved fuel elements, the cooler gas exiting the circulators could be directed to flow over the reactor steelwork and down through passages in the core before entering the fuel channels.

2. AGR CORE DESIGN

The first Commercial AGR designed in the UK is at Dungeness. Later stations of different designs were built at Hinkley Point and Hunterston, and at Heysham and Hartlepool. The last stations to be built were at Heysham and Torness. A section through the reactor, in this case for Heysham 2/ Torness is shown in Fig 4. In all the AGRs, the graphite core, which is supported on a diagrid and surrounded by a restraint tank, is contained within a gas baffle surmounted by a dome which act as a pressure boundary and are the means by which the cool gas exiting the circulators is kept separate from the hot gas exiting the fuel stringers. Each core is penetrated by a system of steel guide tubes which provide continuity of passage for the fuel stringers and control rods.

The core in an AGR comprises an inner cylinder of moderator graphite (in 9 or10 layers) containing the fuel and control rod channels, surrounded (top, bottom and side) by reflector graphite. The top reflector is covered by graphite blocks and 1 layer of steel blocks collectively known as the Upper Neutron Shield. In the earlier reactors, the bottom reflector sits on and locates to a mat of steel plates which in turn sit on the diagrid which is the support for the whole structure. In Heysham 2 and Torness, a Lower Neutron Shield was included to provide shielding for man-access to the sub-diagrid region. Surrounding the graphite structure is a restraint tank, the function of which is to locate and maintain the core boundary at all times.

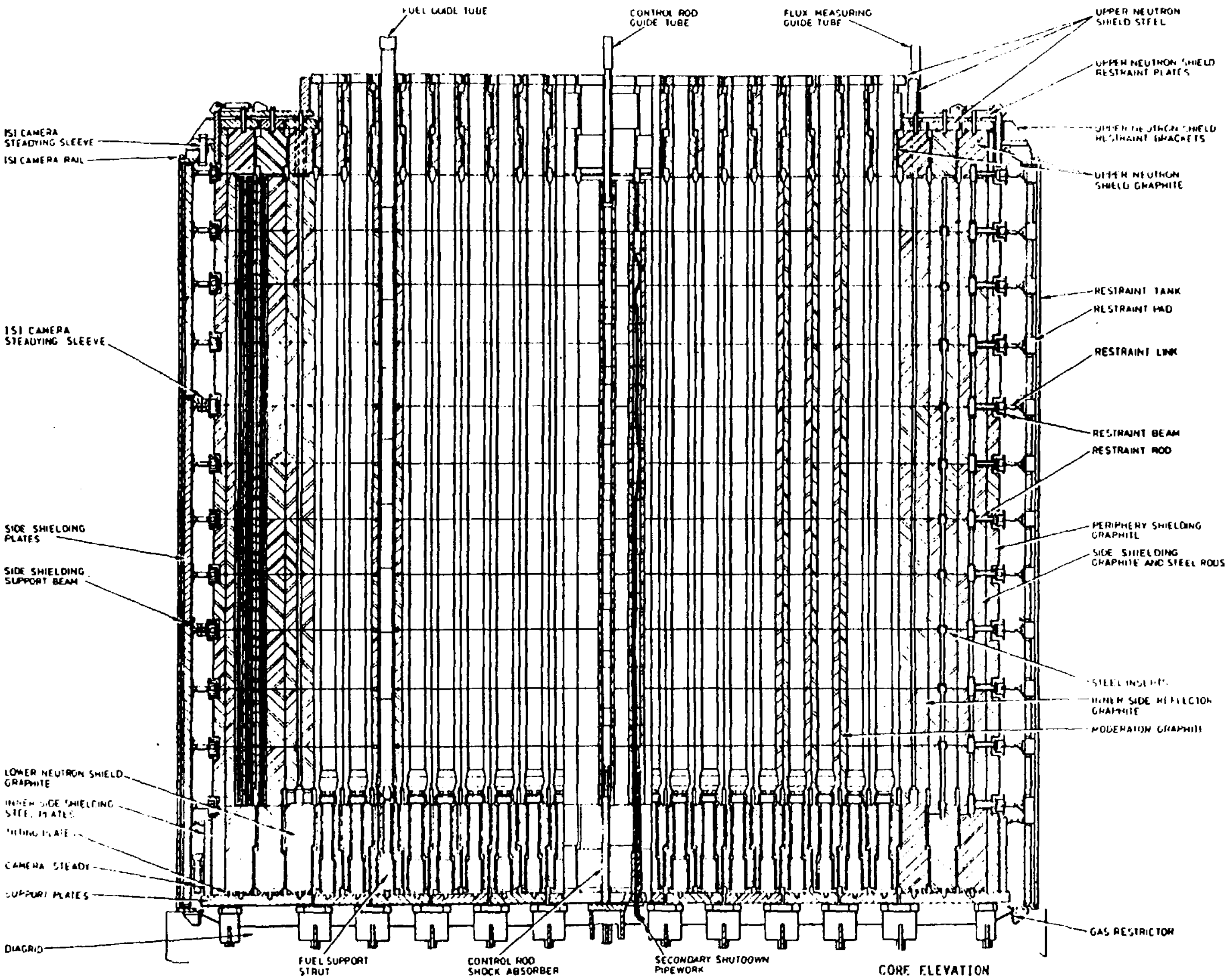

FIG 4 SECTION THROUGH HEYSHAM 2 AND TORNESS REACTOR CORE

2.1 Graphite dimensional change

Although suitable for use in the Windscale AGR, it was soon realised that the dimensional change rates exhibited by PGA graphite were unacceptable for the much higher irradiation doses which would be attained in Commercial AGRs. A dimensionally more stable graphite was thus required. Development and testing of graphites with greater dimensional stability and also with reduced radiolytic reaction rates and higher strength was undertaken. Several materials were produced to specification but the graphite eventually chosen for the first AGR at Dungeness, and all subsequent AGRs, was made using Gilsonite pitch coke. The coke grains are rounder in shape after crushing and by using a moulding process to make the graphite blocks, a near isotropic graphite was produced. The graphite is referred to as Gilsocarbon graphite.

Gilsocarbon graphite shrinks at all temperatures of interest but, after a certain dose, and in the absence of radiolytic oxidation, a peak of shrinkage is reached after which the graphite begins to grow. This is referred to as 'turnaround'. If the graphite experiences high weight loss, however, it continues to shrink up to the peak doses expected. For the predicted levels of weight loss in AGRs, the actual behaviour of the graphite will be somewhere in between.

The brick and key arrangement in Heysham 2 and Torness is shown in Fig 6, which is indicative of the arrangement in the other AGR cores. It is similar in principle to that utilised in the later Magnox cores which was described earlier. Volumetric expansion of the core as steel occurs but there is an added requirement for an AGR in that the fuel stringer passes through the guide tubes in the dome before entering the fuel channels. By arranging that the coolant gas sweeps the underside of the dome, as well as the support and restraint tank, differential movement between the structures during reactor start-up and shut-down is minimised.

Within each core there are two major types of brick. The (larger) bricks which form the fuel channels, and the reflector bricks, are octagonal in shape, whereas the smaller (interstitial) bricks are basically square. Two types of key are used, namely loose and interstitial keys. The loose keys are rectangular in shape and locate in keyways along the 0° and 90° axes, whereas the interstitial keys are integral with particular interstitial bricks and locate in keyways along the 45° axes. The keying system provides the means of maintaining the verticality of a particular column and its position relative to its neighbouring columns. At the free ends of the brick are connecting features which locate the bricks relative to each other in a column. The various designs involve keys and keyways, a spigot and recess, circular I-section rings and hollow cylinders.

The initial key/keyway clearances are set to limiting the possible cumulative brick movements and the possibility of clearances reducing to zero during life. Initial clearances are also required to ensure that differential shrinkage between brick columns does not lead to vertical interactions which could cause bricks to tilt or lift. Guide tube insertion depths into the core must be such that overall column shrinkages, in combination with thermal expansion effects, do not lead to their disengagement.

2.2 Radiolytic oxidation

It was known that at the much higher graphite heating rates and gas pressures in an AGR, radiolytic oxidation of the graphite would be a serious problem. Fortunately it was discovered that methane in relatively small concentrations was a very good inhibitor. The Windscale AGR was used to test the level of inhibition afforded by methane, but it was found that at concentrations of a few hundred parts per million, carbon deposition on the fuel pins and other steelwork in the circuit was occurring. Only a thin coating of carbon would significantly affect the heat transfer between the fuel and the coolant and also the performance of boilers.

The choice of coolant composition for the Dungeness AGR was therefore limited. The trouble was that at the low concentrations thought necessary to prevent carbon deposition, the oxidation rate of the graphite would be unacceptably high, especially as the methane concentration is depleted as it diffuses through a brick. The solution adopted to alleviate the problem was to introduce a number of full length holes of small diameter into the brick to improve the supply of methane to the inner regions of the brick.

These so called 'methane diffusion' holes were also introduced into the bricks in Heysham 1, Hartlepool, Hinkley Point and Hunterston. A more effective method of ensuring a better supply of methane to the inner regions of a brick would be to introduce a pressure drop across the brick from the outside to the inside. The resulting impressed flow would carry methane into the regions remote from a surface, supplemented by diffusion holes. The necessary design changes to bring this about were made for the Heysham 2 and Torness cores. Because of the problem of brick bowing causing hingeing and thereby generating flow leakage paths which would reduce the pressure drop, circular seals were introduced between each brick in a column to limit the effect of the gaps. (These can be seen in Fig 5.)

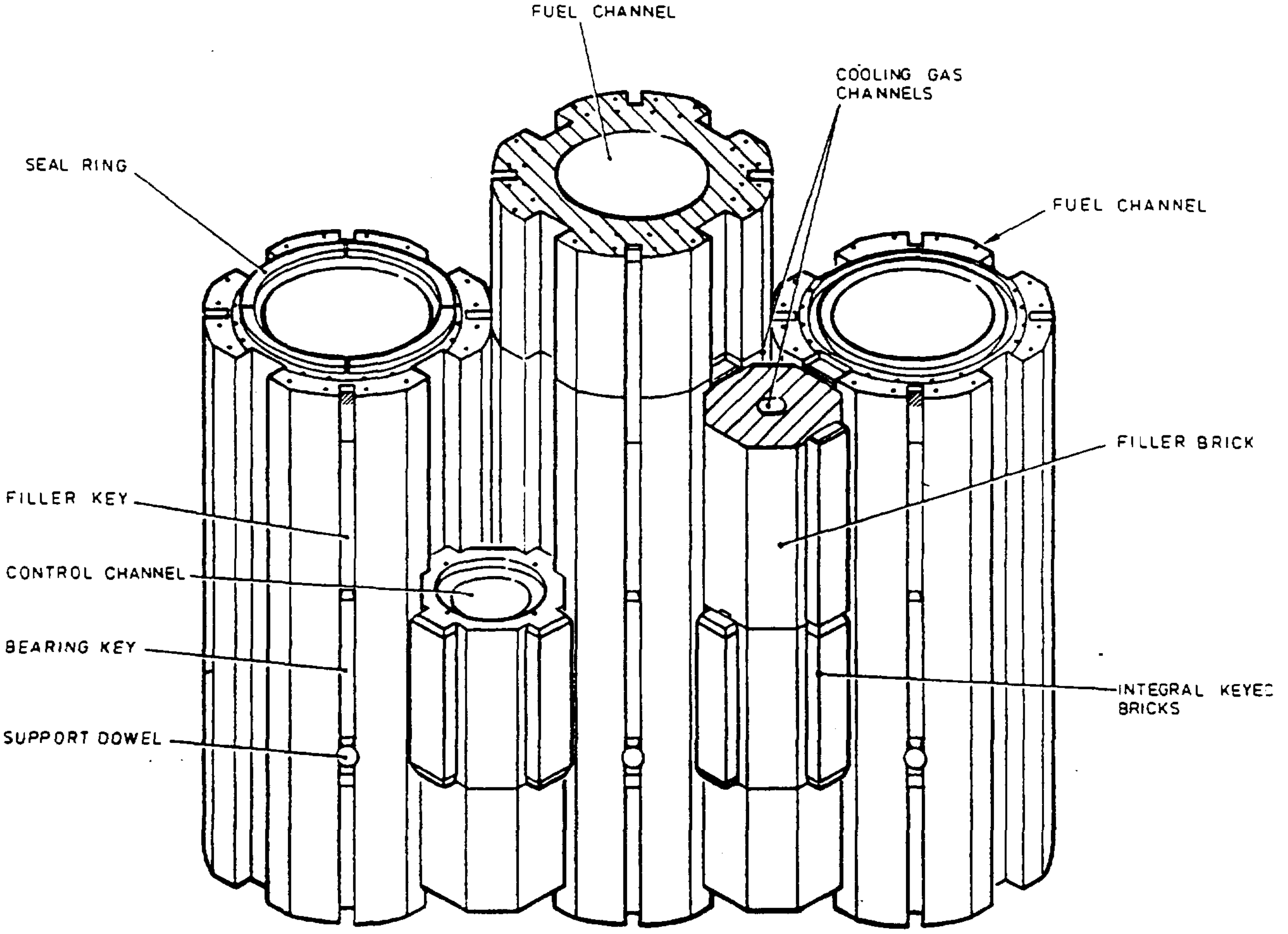

FIG 5 ARRANGEMENT OF GRAPHITE COMPONENTS IN HEYSHAM 2 AND TORNESS AGRs

3. SUMMARY

The cores in the UKs Magnox reactors were all built using PGA graphite which, due to the shape of the coke grains used and method of manufacture, exhibited very anisotropic behaviour when subjected to fast neutron irradiation. To cater for this behaviour, the cores were initially built with a brick and tile arrangement, and constrained in such a way that the core expanded as graphite. Minor alterations were made to the design as more information on dimensional change behaviour was gained, but it was eventually abandoned in favour of a radial keying arrangement which allowed volumetric expansion of the core as steel and was which therefore essentially independent of dimensional change.

The introduction of the AGR concept with its much higher cumulative doses and gamma heating rates necessitated the development of an isotropic graphite, with reduced porosity and higher strength. Gilsocarbon graphite was chosen for all the AGRs built in the UK. A radial keying system similar in principle to that used in the later Magnox cores was retained. The potentially much higher radiolytic oxidation rates in AGR cores have been reduced to acceptable levels by the use of methane bearing coolants, and by the introduction of methane diffusion holes, and more recently, impressed flows.