Experience on AVR Graphite Structures

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Abstract

The Experimental High-Temperature Reactor AVR with spherical fuel elements has been designed and constructed about 40 years ago. At that time, the experience with manufacturing of nuclear graphite and the knowledge about the influence of fast neutron irradiation upon its physical properties were rather poor compared to what we know today. In 21 years of operation, the AVR graphite experienced a fast neutron fluence of max. $5*10^{25}$ / m^2 (EDN) being much lower than possible life time fluences. After inspecting the graphite structures at several occasions, it became clear that – despite of some mechanical damage of the bottom reflector - the conservative design in combination with excellent properties of graphite in general have made the AVR a successful demonstration of a promising technology.

Introduction

The order for the construction of the 15 MWel Experimental High-Temperature Pebble Bed Reactor AVR in Juelich was placed in February 1959. Construction was basically completed in 1966. The reactor achieved first criticality in August1966 and was synchronized with the grid in December 1967. It was first operated at 850°C. In February 1974, the coolant gas outlet temperature has been raised to 950°C. As was recognized later, the direct pebble bed exit temperature of the coolant in part even reached 1100-1300°C without significant fission product release of the coated-particle fuel. The plant was shut down end of 1988 in expectation of a further operation of the 300MWel Thorium High-Temperature Reactor (THTR-300) in Hamm Uentrop. In 21 years of operation it generated 1.67 billion kWh in 123,381 hours of electrical power operation /1/. Thus, it is leading in operational experience of High-Temperature Reactors (HTR) and represents the main technical basis for the actual Pebble Bed Modular HTR (PBMR) design in South Africa.

During the basic design of the AVR in 1956-58, special attention was already put on the graphite technology taking into account the know-how in the UK and the US. This experience was however not sufficient due to different requirements of the pebble bed core with regard to larger dimensions of the blocks, higher temperature and higher fast neutron fluence in the non-exchangeable reflector /2/. The arrangement of the graphite core structure in the AVR is shown in Figure 1.

The pebble bed core is surrounded by the graphite reflector with a thickness of 50 cm, a top reflector consisting of 24 segments and a conical bottom reflector with slits for the coolant gas. The absorber rods are inserted into 'graphite noses' as seen in Figure 2 showing the upper part of the core cavity before loading the pebbles. The graphite reflector is surrounded by blocks made of baked carbon for radiation shielding and thermal insulation.

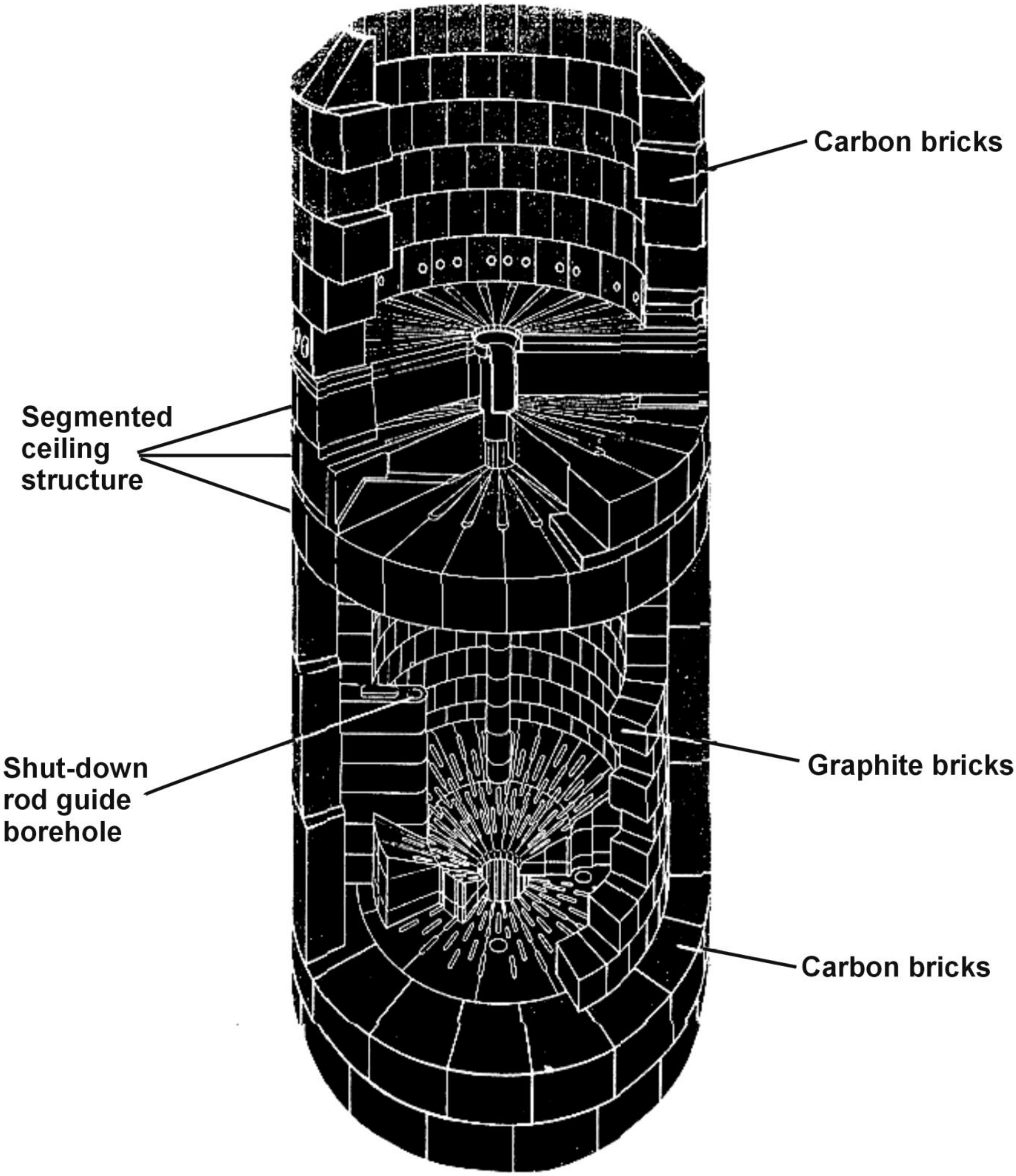


Figure 1: Structure of AVR Ceramic Internals

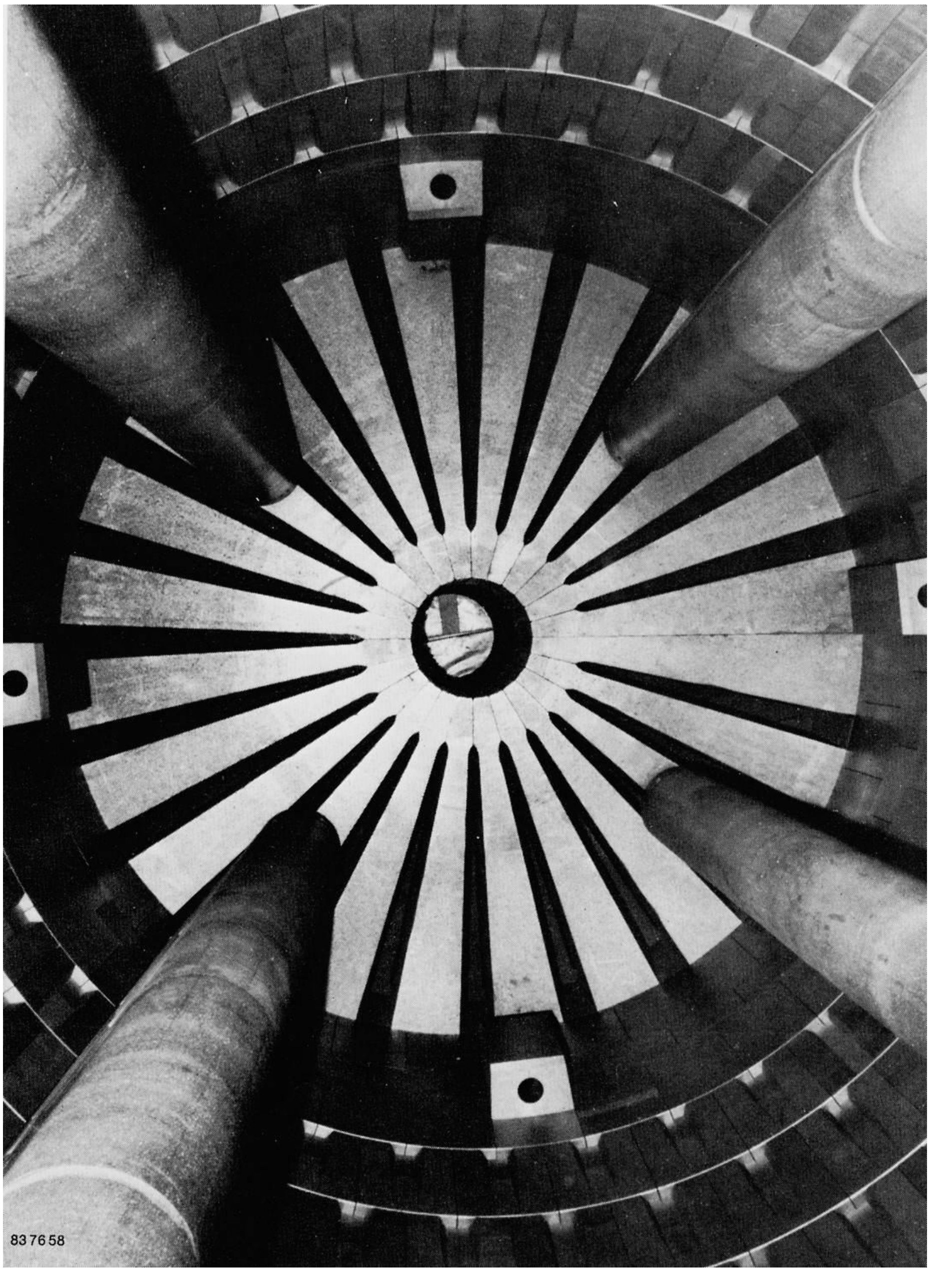


Figure 2: AVR Core Cavity before Start of Operation (upward view)

Graphite Development

In 1958, a working group for the development of suitable graphite grades was established consisting of KFA Department for Reactor Materials, SIGRI Company, Graphitwerke Kropfmuehl, Ringsdorffwerke and NUKEM company. Irradiations were mainly carried out in the General Electric Test Reactor (GETR), in the EL 3 in Saclay and in the Research Reactor Munich (FRM). A lot of parameter studies were undertaken by variation of cokes, binders, pressing methods, heat treatments and impregnations to achieve a material with a high degree of graphitization, good crystallinity, and high density and strength. The ARS graphite finally used for the AVR was based on petroleum needle coke as a filler and coal tar pitch as a binder. The maximum filler particle sizes varied between 1 mm for the smaller and 4 mm for the larger blocks. Forming was done by stamping and extrusion.

A similar graphite called ‘Pile Grade A (PGA)’ has been used in the first British Magnox Reactors, too. At the 1978 International Carbon Conference in London, O’Connor, Brocklehurst & Kelly stated: ‘The development and qualification of nuclear graphites for Gas-Cooled Reactors (GCR) in the UK and HTRs in the Federal Republic of Germany have progressed along similar lines since the early 1960’s. The irradiation behaviour of petroleum needle coke graphite used in both the British MK I GCR (MAGNOX) and the German AVR has been well documented’. Thus, the UK results can also approximately be used for the interpretation of the AVR graphite characteristics.

Petroleum needle coke is a well graphitizing raw material yielding large crystallites. However, it leads to a rather high anisotropy and accordingly to different material properties and irradiation behaviour parallel and perpendicular to the preferred particle orientation.

The further development of reactor graphite for THTR, AGR and other HTR projects took a different direction towards much smaller anisotopy with improved stability under fast neutron irradiation.

Behaviour in Irradiation Tests

As already mentioned, there are many irradiation test data for the early needle coke graphites available, mainly from the British tests of PGA graphite. The ARS graphite for the AVR plant had to be tested at higher irradiation temperatures only, since at lower temperatures credit could be taken from the results on PGA graphite.

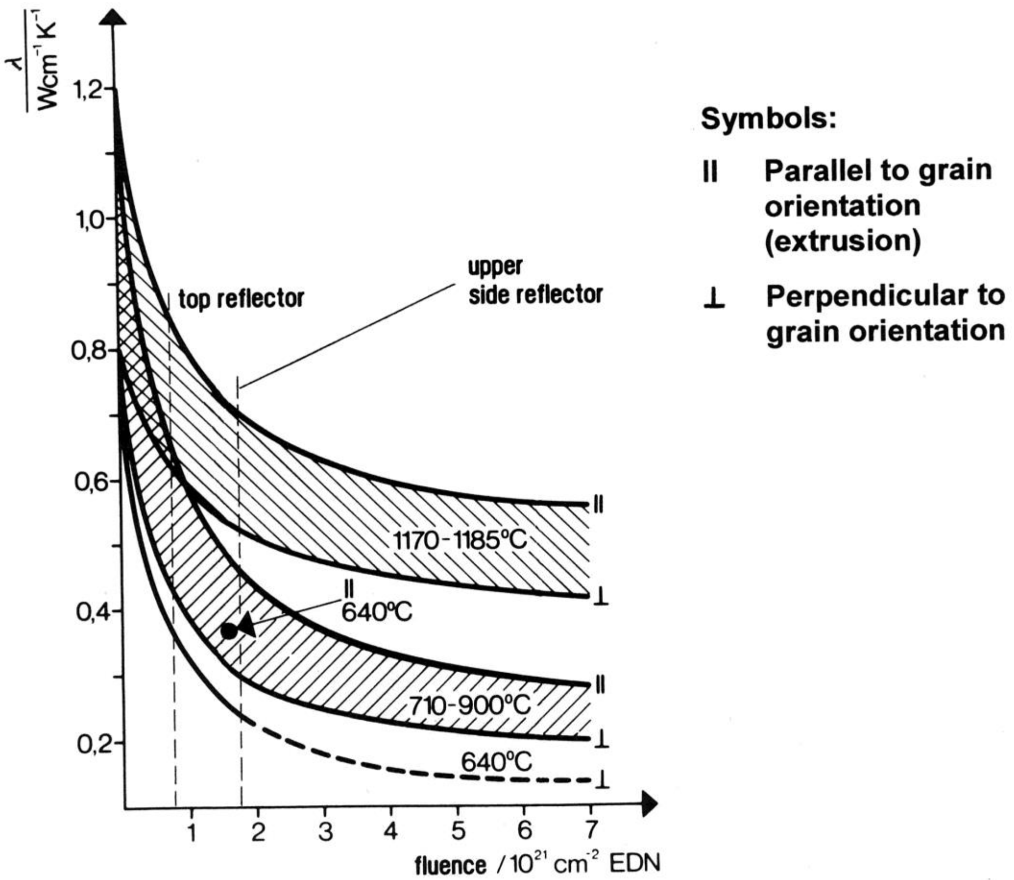


Figure 3: Irradiation-induced changes of thermal conductivity of ARS (AVR) /2/

Figures 3, 4 and 5 taken from /2/, /3/ summarize the irradiation test results for some significant material properties like thermal conductivity, fractional dimensional changes as well as changes of Young’s modulus. The influence of different irradiation temperature and the effect of anisotropy are clearly visible.

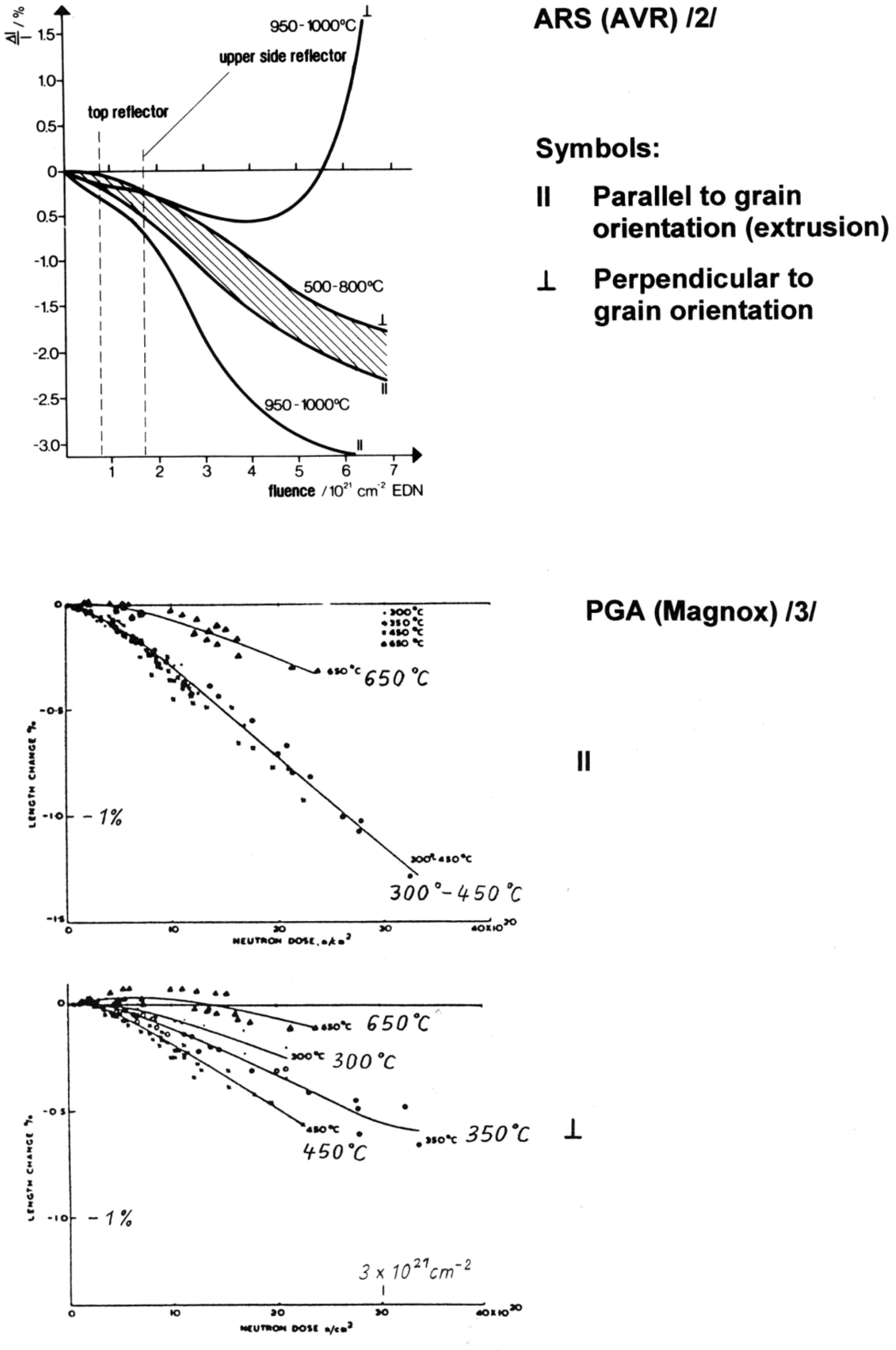
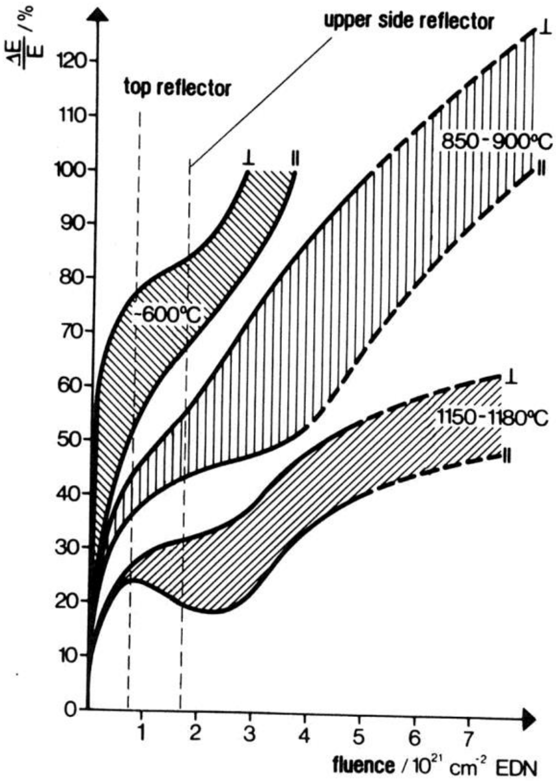


Figure 4: Dimensional changes of ARS /2/ and PGA /3/ under neutron irradiation



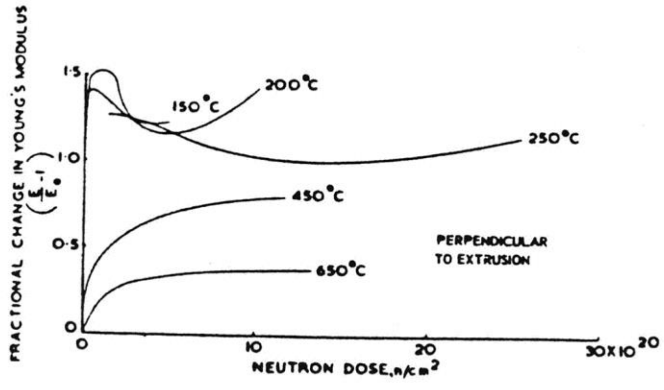
ARS (AVR) /2/

Symbols:

II **Parallel to grain orientation (extrusion)**

⊥ **Perpendicular to grain orientation**

PGA (Magnox) /3/



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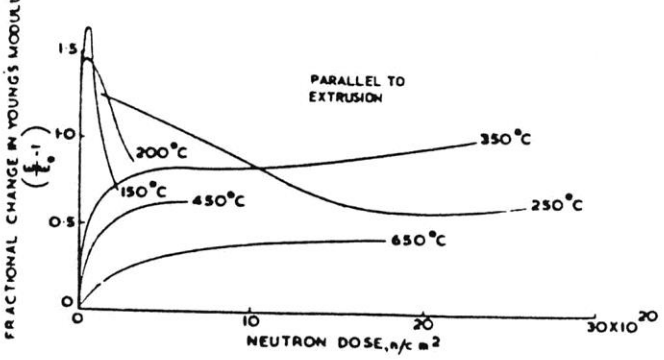

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Figure 5: Irradiation-induced changes of Young's modulus at different irradiation temperatures

Behaviour in the Reactor

In contrast to many operational results on the pebble graphite matrix behaviour and despite the long-term operation of AVR, only very limited information is available on the performance of the graphite structures due to the lack of direct access to the core itself due to the pebble bed design. Replacement, maintenance or repair of the reflector was not provided for as the maximum neutron fluence was kept low enough.

Indications on the integrity of the graphite reflector were given by the fact that only a few graphite parts not attributable to broken pebbles were found in the scrap that was removed from the pebble recycling system.

Another indirect hint was given by the post-examination of very old fuel and graphite pebbles that did not show any obvious property changes due to corrosion or material wear even after having stayed for more than 10 years in the core.

Certainly, the most spectacular insights were gained in 1984 during a video inspection of the top reflector and the upper side reflector when a TV camera was introduced through the feed lines of the pebble recycling system. The pictures revealed a completely unaffected structure after 16 years of operation as widely reported in the past /4, 5, 6/. It is worth to recall that even very small irregularities on the surface such as tiny scratches that had been documented by photographs taken during core assembling were still visible and unchanged. This is even more remarkable as the top reflector has experienced temperatures of at least 1280°C for about one year (unexpected and detected by melt-wire experiments) and more than 1000°C for many more years.

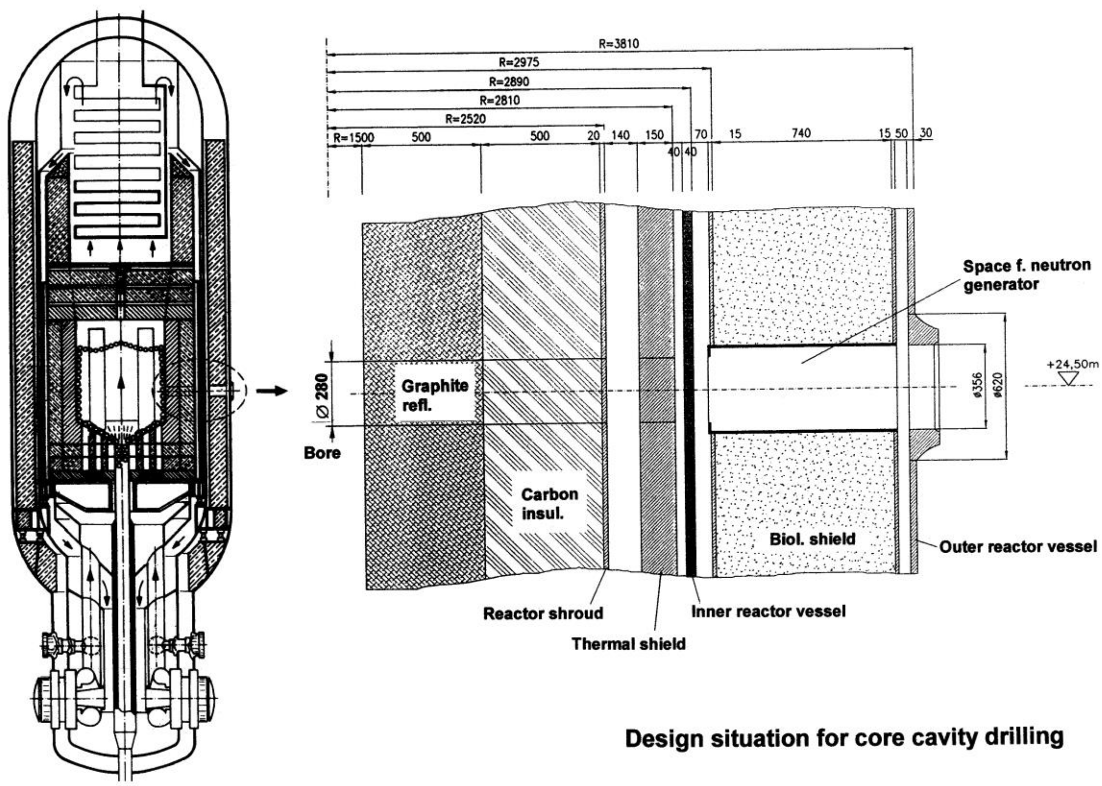

Figure 6: Radial Inspection Drilling

Additional hints concerning the behaviour of the graphite structures have been gained during decommissioning activities to date. In 1999, after the removal of the fuel elements, a radial bore-hole was drilled through the whole side wall structure at core mid height (see Figure 6) right into the core cavity as an access for the inspection of the core bottom in terms of remaining fuel elements. That part of the core could naturally not be investigated in 1984 since the fuel elements stayed in place. Drilling through the carbon insulation wall and the graphite reflector blocks of 0.5 m thickness went smoothly and in full accordance with recent experience from simulation tests of machining fresh material.

The occasion was also used to take graphite samples to verify site characterisation data for the future green-field decommissioning. However, since in the early 1990s an extensive post-operational investigation programme was turned down for lack of funding, there were no solid graphite samples available for physical properties investigations, but only drilling powder which serves to determine radioactive contamination and to develop waste treatment methods as underway in the European HTR programme. The reduction of the investigation programme should be reassessed in the light of increasing world-wide interest in HTR technology.

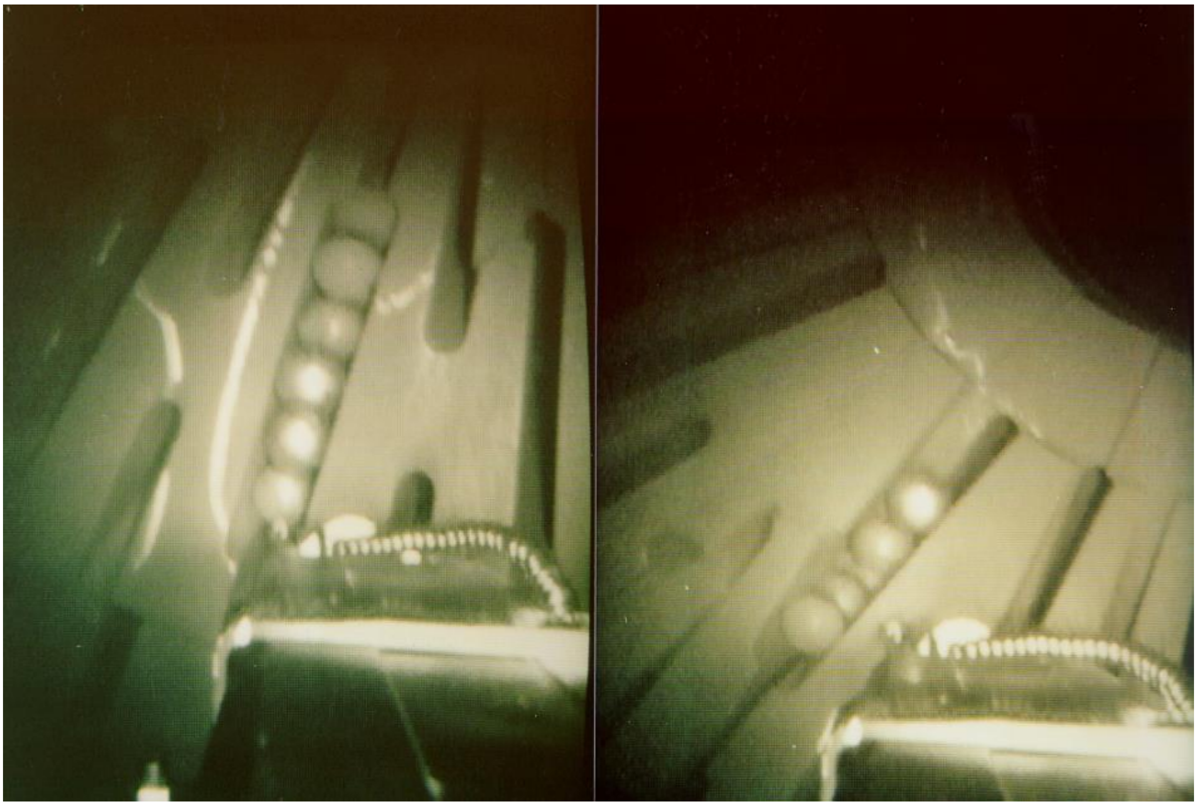

Figure 7: Damaged Bottom Reflector

The inspection for remaining fuel elements mentioned above, however, revealed cracks of the bottom reflector structure with pebbles gone into the slits for the coolant gas, as can be seen from Figure 7 , described in /7/. In this region, these damages can clearly be attributed to the layer design of the bottom reflector (see Figure 1), and in no way to changes in material properties of the graphite. Even at the bottom of the core, the graphite surfaces appear unchanged as compared to the appearance during build-up , and edges are still in a good i.e. as-machined shape. However, it has to be considered that irradiation temperatures in the bottom reflector did not exceed 300°C (except in some short specific tests), whereas in future HTR designs the flow direction of the cooling gas will be inversed (from top to bottom).

Fast Neutron Fluence in the AVR

Because of the relatively low reactor power of 46 MWth, and the low power density, the accumulated fast neutron fluences are also rather low. Table 1 shows data for the end of AVR operation being deduced from core physics calculations /8/.

Location	**Temp. / °C**	**Fast Fluence / $10^{25}m^{-2}$**
Graphite noses, core midheight	550	8.6
Side reflector, core midheight	650	7.0
Bottom reflector	300	3.2
Top reflector	1050-1300	1.3

Table 1: Maximum fast neutron fluence (E>0.1 MeV) of the AVR reflector graphite

From Table 1 and Figure 4 it can be assumed that the AVR graphite has not been irradiated beyond turn-around. The top reflector experienced by far the highest irradiation temperatures up to 1300°C in some places whereas the fluence remained low. The upper side reflector also was exposed to rather high temperatures which are estimated to about 800°C. Here also, the fluence is rather low; it is estimated to be comparable to that in the bottom reflector (~ 3 * $10^{25}m^{-2}$).

Using the diagrams in Figures 3 to 5, the fluence can be converted by using the relation /9, 10/:

$$\textit{Fluence (EDN)} \approx 0.57 \times \textit{Fluence (E>0.1 MeV)}$$

With this correlation some final fluences of AVR are entered into the above mentioned diagrams. These values show some significant differences in comparison to the former assumptions. They illustrate that despite the large anisotropy the AVR could have been operated over a much longer period, or at a much higher power, without reaching any critical limits.

Conclusions

In some respect, the situation of modern HTGR projects is similar to that during the design and construction phase of the AVR. First of all, there is no well tested nuclear graphite available at present. Therefore, the design of graphite components that are exposed to significant fast neutron fluences must be based on more than 40 years of experience rather than on existing data. Nuclear graphite should exhibit low anisotropy, high strength, good homogeneity and high purity. The demand for high purity can be fulfilled by using pure raw materials, thus excluding some coke sources, e.g., containing too much boron. Low anisotropy means that the ratio of the linear thermal expansion coefficients perpendicular and parallel to the preferred orientation of the filler particles should not exceed a value of 1.15. Good homogeneity requires careful investigation of optimum production parameters. In case of manufacturing large size graphite blocks special equipment may be necessary. Strength is a very delicate quantity relying on special features of filler coke, sufficiently high density, appropriate pressing technique and again careful manufacturing. However, it must be taken into account that high strength may be accompanied by fracture mechanical problems resulting from brittleness which, e.g., makes a crack running through the whole component rather than being stopped after a relatively short distance.

Altogether, it can be stated that there is a good chance for present and future HTGR projects to use the best graphite that has ever been manufactured for nuclear purposes. However, a suitably high effort may be necessary to revive appropriate manufacturing techniques, to dig out approved irradiation equipment and methods, and last but not least to install as soon as possible a graphite irradiation testing programme flanking the design, construction, and operation of graphite moderated reactors under consideration.

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