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ASSESSMENT OF NEW POTENTIAL GRAPHITES AND NEEDS FOR HTR

by

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Summary

Graphite has been used as a neutron moderator in a variety of different reactors, and there has recently been a renewal of interest in High Temperature Reactors (HTRs) in the world. In particular the European Commission is supporting a number of projects for the development of HTR technology, with a view to creating the technological basis for the industrial emergence of HTRs in Europe by 2010.

Most of the available data on the irradiation behaviour of graphite have been obtained by irradiating small samples in MTRs. Unfortunately, most of the data have been obtained at temperatures <550^{o}C, whereas HTRs will be operating generally at temperatures >550^{o}C. In addition, almost all the graphites previously irradiated are no longer commercially available. As a result a planned graphite irradiation programme is being undertaken for the European HTR project. This will allow the ‘best’ graphite(s) to be chosen, and provide all the data necessary to allow a full core design to be carried out.

Five of the currently available graphites have been selected for the forthcoming irradiation programme. These cover the two main coke sources (petroleum and pitch), two of the main forming methods (extrusion and iso-moulding), and a range of grain sizes (1mm down to 10 µm). Under 5th Framework Programme funding, the graphites will initially be irradiated in a high flux MTR to a low/medium fluence. Hopefully, this will be continued to the full life peak fluence with funding from the 6th Framework Programme.

The graphite data requirements for a HTR core design have been presented, covering the initial specification, as-manufactured data, and irradiation data. The important aspects involved in selecting the ‘best’ graphite have also been given including dimensional stability, purity and costs.

1 Introduction

Graphite has been used as a neutron moderator in a variety of different reactors. These include the Advanced Gas-cooled Reactors (AGRs), Magnox Reactors, High Temperature Reactors (HTRs), RBMKs, Research Reactors and Materials Testing Reactors (MTRs). The amount of nuclear grade graphite currently manufactured worldwide is relatively small, and broadly consists of graphite for AGR fuel sleeves and prototype HTRs (one in Japan and one in China). However, there has recently been a renewal of interest in HTRs in the world. The design of the Pebble Bed Modular Reactor (PBMR), led by ESKOM (South Africa), and the Gas-Turbine Modular Helium Reactor (GT-MHR) led by an international consortium (Russia, USA, France and Japan) are at an advanced stage. The European Commission is also supporting a number of projects for the development of HTR technology, with a view to creating the technological basis for the industrial emergence of HTRs in Europe by 2010.

The behaviour of graphite in a reactor environment has been extensively studied since the early 1940s and a good understanding of the significant and complex property changes which take place in the material has been gained. Most of the available data have been obtained by irradiating small graphite samples in MTRs. Unfortunately, almost all the graphites previously irradiated are no longer commercially available. In addition, most of the irradiation temperatures investigated will have been $<550^{o}$C, whereas for HTRs the graphite temperatures will generally be $>550^{o}$C (a review of available data on the irradiation behaviour of different graphites at high temperatures was carried out in Ref. 1).

Therefore, in order to support the development of a future European HTR, it was first of all necessary to establish what graphites are currently available. From these, a number of suitable candidates would then be selected for an irradiation programme in a high flux MTR. The irradiation programme will be aimed at providing data for these selected graphites over the appropriate irradiation fluence and temperature range as required by the core designer. The selection of suitable graphites and information on the irradiation programme are given in Ref. 1. This report deals with the needs of a HTR in terms of initial properties of the graphite and its irradiation behaviour, and also an initial assessment of new potential graphites.

2 Nuclear graphite manufacture

Natural graphite is not plentiful and so there is a need to manufacture ‘artificial’ graphites for large-scale applications, such as electric arc furnaces and nuclear reactor cores. Modern graphite manufacture (Figure 1) starts with a high molecular weight hydrocarbon - often a natural pitch or a residue of crude oil distillation - which is first converted to coke by heating in the absence of air. This process is long and complex, both in the choice of initial stock and its subsequent thermal treatment, and can take weeks to perform. During the process, the carbon atoms form a ‘mesophase’, where they order themselves in extensive hexagonal clumps.

The coke is then calcined, crushed and screened to get a specific distribution of particle sizes - typically 1 mm or less. Next, the particles are mixed with a binder pitch (generally coal tar pitch) in heated mixers to obtain a plastic paste at a uniform temperature. The paste is then charged into an extrusion press or into a mould to form rough blocks of the shape eventually required.

One crucial property is now already determined. This is the anisotropy of the graphite, which is so vital in determining it's behaviour under irradiation (see Section 3). The crystal lattice in graphite can at best only be continuous over the coke particle dimensions - so if these particles are randomly oriented the aggregate will be macroscopically isotropic, despite the inherent anisotropy of the graphite's atomic lattice. However, coke particles are seldom spherically symmetric, and the directional forces used in moulding or extruding tend to align them in preferred directions, leading to anisotropy on the 'block' scale. For example, extrusion tends to align crystallite basal planes parallel to the extrusion direction, whereas pressing in a mould tends to align them perpendicular to the pressing direction.

The 'green' pieces from the forming stage are then baked in a furnace, at a temperature of ~1000^{o}C, for several weeks. After baking, the pieces are allowed to cool very slowly. The baking process changes the binder pitch into amorphous carbon. As the volatiles are released, an extensive pore network is created. As a result, the apparent density of the graphite is quite low, and so the baked article is generally impregnated with a suitable impregnant (pitch), and then re-baked (like baking, re-baking changes the impregnant pitch into carbon, but now the process is much faster). This procedure is carried out until the required density is reached. This may involve one, two or three impregnation/baking cycles. As well as increasing the density, there also a general improvement in mechanical properties, and a decrease in porosity and hence permeability.

Finally, the amorphous carbon material is transformed into crystalline graphite, at a temperature between 2800^{o}C and 3300^{o}C, in a graphitising furnace. The blocks are stacked in close proximity in the furnace and covered completely with carbon particles. A large current is passed through the bed to raise the temperature of the blocks and maintain it at the required level. After graphitisation, the pieces are allowed to cool very slowly.

For nuclear applications, the graphite has to be as free as possible from impurities. Most of the impurities present will become activated during the operating life of the reactor, which will give rise to operational problems, as well as decommissioning and final disposal problems. Most impurities, however, are volatile and so disappear during graphitisation. To remove as much of the remainder as possible, halogens are added generally during graphitisation to aid the conversion of metal impurities and boron particularly, to their more volatile halides (extremely low boron levels are important from a reactor physics point of view as it is a very strong neutron absorber).

3 Graphite irradiation behaviour

Graphite has been used extensively in the past as a fast neutron moderator and neutron reflector. The problem is that the fast neutrons cause significant damage to the crystal structure of the graphite, which in turn causes a change to the crystal dimensions and also in almost all the material properties of the graphite. The damage mechanism and the effect the damage has on the properties of the graphite are described below.

3.1 Damage mechanism

When a carbon atom is hit by a fast neutron, it is displaced from its lattice position and has sufficient energy to displace a large number of other carbon atoms. Each of these in turn can have sufficient energy to displace many other carbon atoms. Thus a single fast neutron/carbon atom impact can lead to a very large number of displaced carbon atoms. The fast neutron itself can go on to create many more displaced carbon atoms as it slows down, which in turn displace more carbon atoms as before. The displaced carbon atoms generally end up between the layer planes and can coalesce to form anything from sub-microscopic clusters of a few atoms up to large interstitial clusters containing many hundreds of atoms. The interstitial loops force the planes apart and so the crystals grow in the direction perpendicular to the planes (‘c’ direction). The displaced atoms will leave vacancies which can themselves combine to form large vacancy loops. This results in the crystals contracting in the direction parallel to the planes (‘a’ direction).

3.2 Effect of damage on graphite properties

The nett effect of the damage caused to a polycrystal is growth and shrinkage. This is extremely dependent however, on the type of coke used, the mean particle size, and the method of forming. For example, Pile Grade A (PGA) graphite, used in the UK’s Magnox reactors, was made using a needle coke and the blocks were formed by extrusion. This tended to align the crystal planes in the direction of extrusion and so when irradiated the graphite exhibited growth in the perpendicular direction and shrinkage in the parallel direction. The behaviour was thus very anisotropic. However, Gilsocarbon graphite, which was used for the UK’s AGRs was made using spherical gilsonite coke and the blocks were moulded in a press. This resulted in an isotropic graphite which when irradiated exhibited shrinkage in both the parallel and perpendicular directions.

Material properties are also affected by irradiation, the most important ones from a core design point of view being strength, Young’s modulus, coefficient of thermal Expansion (CTE) and thermal conductivity.

Figure 2 shows the dimensional change behaviour of a German graphite, ATR-2E. This is the general behaviour of a near-isotropic graphite i.e. there is an initial shrinkage phase followed by turnaround and subsequent growth. Figure 3 shows the variations in Young’s modulus with irradiation. Again this is a typical variation, with an initial rapid increase at low fluence, followed by a gradual increase and then a continual decrease. The particular temperature chosen for illustration purposes is 750^{o}C (the variation in these properties at other temperatures are given in Ref. 2).

4 Graphite data requirements for a HTR core design

4.1 Initial specifications

At a very early stage during the design process, a specification for each graphite to be used needs to be produced. The specifications should list particular physical and mechanical properties (e.g. density, strength, Young's modulus, CTE and thermal conductivity), and quote values for each which need to me met (or bettered) by the actual manufactured graphites. The properties and their variation with irradiation are used for the initial design assessment.

Also specified are chemical impurities, the most important of which are ash, boron, lithium, sulphur, chlorine, cobalt, iron and nickel. A few of the impurities are important from a reactor physics point of view as they are extremely strong neutron absorbers (e.g. boron). The others are important because they become activated during operation, which can give rise to operational problems during the lifetime of the reactor and to long term decommissioning problems (e.g. cobalt 60 and iron 55). It is important therefore that the quoted maximum concentration for each (in ppm) is met or bettered by the manufactured graphite.

4.2 As-manufactured data

Graphite manufacturers will publish booklets etc. which will contain data on the graphites they currently manufacture. These will generally give the relevant physical and mechanical properties of the different graphites and perhaps their range and/or variability. For nuclear applications, typical impurity levels will also be given. These will be the values which the manufacturers will claim they can achieve.

When a contract is placed, the manufacturer will be required to test a small number of blocks from each graphitising heat stage during the production run. These will be sectioned and the required quantity and type of samples produced. The physical and mechanical properties of the samples from a heat stage will be determined and the minimum, maximum and mean value for each recorded on a Heat Certificate. This will be issued to the Client with the results of the measurements and the values given in the specification (any improvements to the properties achieved for the as-manufactured graphite may be claimed in any safety assessment). Measurements of important impurities such as boron, cobalt and lithium are also given in the Heat Certificates. On a less frequent basis e.g. every 10^{th} heat, a full chemical analysis is undertaken. Figure 4 shows typical values for properties, and Figure 5 shows levels of major and minor impurities for the Gilsocarbon graphite used in the AGRs.

4.3 Irradiation data

Although initial properties are important, it is the way in which they vary with irradiation which will ultimately determine the safe operating life of a given core design. The most important of these is generally dimensional change as this will affect the overall behaviour of a core in terms of distortion, stability and whether or not components will crack within the design life.

As stated earlier, the variation with irradiation of the following properties are most important from a core design point of view - strength, Young's modulus, CTE and thermal conductivity. These are discussed in detail in Ref. 3.

5 Initial assessment of new potential graphites

Since the graphites used previously for the various core designs are no longer commercially available, there is a need to assess the currently available graphites in terms of their suitability for a HTR core design. First of all the graphites selected for the irradiation programme (from those currently available) are discussed. The 'ideal' graphite is then described and some reasons given why this cannot be achieved in practice. Next, other factors affecting the selection of the 'best' graphite are given. Finally, an initial assement of the selected graphites is given.

5.1 Selected graphites

Ultimately, the selection of the 'best' graphite for the design of a reactor core will be based on a number of factors including dimensional change behaviour and changes in physical/mechanical properties with irradiation, impurity levels and production cost. However, for the purposes of the irradiation programme, it was decided that a range of graphites should be tested, and the selection based on raw materials, grain size and manufacturing methods only (impurities and costs are discussed in section 5.3).

5.1.1 UCAR Carbon graphites

Of the ten potential graphite grades manufactured by UCAR, the grades put forward for selection were PPEA, PAEA, PCEA and a super-fine grade of PCIB (PCIB-SFG). The quoted density and Young's modulus for all four graphites are similar. The largest difference was in the strengths (tensile, compressive, bend). The strengths of the first three (which are all extruded graphites) are reasonably similar, although the first two (made from pitch cokes) have higher strengths than the third (made from a petroleum coke). For the fourth, which is an iso-moulded graphite, the strengths are significantly higher than all three extruded graphites. It was decided that two graphites would be selected and it was agreed that these were PCEA and PCIB-SFG. Although both are made from a petroleum coke, one is an extruded graphite and the other is an iso-moulded graphite (which is also of interest due to it having a very small grain size). The important physical/mechanical properties for these two graphites are given in Table 1.

5.1.2 SGL graphites

Of the three graphite grades put forward by SGL for selection, only two are currently being manufactured on a large scale. These are NBG-10 and NBG-25 (a third grade, NBG-20 is being developed as an economic alternative to NBG-10).

NBG-10 is an extruded graphite which is an upgrade on the AGR fuel sleeve material. It is made using a Japanese pitch coke on the industrial scale, but has also been produced using a USA petroleum coke on the laboratory scale, and using a South African (Sasol) coke on an industrial scale (the latter produces an isotropic graphite but has too much boron). NBG-25 is an iso-statically moulded graphite made using a USA petroleum coke on an industrial scale (NBG-20 is an extruded graphite made using a petroleum coke).

It was decided that the two currently manufactured grades would be selected. This would provide an extruded graphite made from a coal tar pitch coke, and an iso-moulded graphite using a petroleum coke. The decision also took into account the risks associated with the third grade not being available in time. The important physical/mechanical properties for these two graphites are given in Table 2.

5.1.3 Toyo Tanso graphites

Two graphite grades were put forward by Toyo Tanso. The first, IG-110, was used for the Japanese HTTR prototype reactor. It is an iso-moulded graphite made using a petroleum coke supplied by the Nippon Steel and Chemical Company (NSCC). An improved graphite grade, IG-430 has been developed and was also available. It was decided that IG-110 should be selected. The important physical/mechanical properties for this graphites are given in Table 3. The decision was based on the fact that it has previously been irradiated at high temperature, although only to a small/medium fluence. Nevertheless, the available data will be extremely useful for comparison with the data obtained from the 5th Framework Programme experiment. The behaviour of the graphite will then, hopefully, be determined up to the full life fluence in the 6th Framework Programme.

5.1.4 Additional graphites

Although five (major) grades of graphite have been selected for full testing in the experiment, it was decided that it would be useful to have an early indication of the irradiation behaviour of some of the other proposed graphites. These could be included as ‘piggy-back’ samples in the irradiation capsule. The (minor) graphites selected are UCAR grade PPEA, SGL grade NBG-20 and Toyo Tanso grade IG-430.

5.2 ‘Ideal’ graphite

The as-manufactured ‘ideal’ graphite should be reasonably isotropic, have a high thermal conductivity, a high strength, and a low Young’s modulus. It should also have high purity, have good machinability and have a low cost. However, there are a number of reasons why the ‘ideal’ graphite is not achievable in practice. For example, high strength generally goes hand in hand with high Young’s modulus. CTE also poses a difficulty since a low value of CTE will be beneficial in reducing thermal stresses, whereas a high value is generally thought to result in better dimensional stability.

Under irradiation, the ‘ideal’ graphite should exhibit low rates of dimensional change, and a small variation in properties. At the present time, the irradiation behaviour of graphites cannot be deduced quantitatively from a knowledge of the as-manufactured structure and property data, although it may be possible to predict some qualitative behaviour. However, these ‘rules-of-thumb’, such as the link between dimensional stability and CTE, have arisen in the past using data from previous graphites, and may not necessarily apply to the current graphites.

5.3 Other factors affecting choice of 'best'graphite

Other factors affecting the choice of the 'best' graphite include purity and cost. These are discussed below.

5.3.1 Purity

The purity of the graphites used is important for the operational life of the reactor as well as the post-operational/decommissioning stages. A few of the impurities are important from a reactor physics point of view as they are extremely strong neutron absorbers (e.g. boron). The others are important because they become activated during operation, which can give rise to operational problems during the lifetime of the reactor and to long term decommissioning problems (e.g. cobalt 60 and iron 55). It is important therefore that the quoted maximum concentration for each (in ppm) is met or bettered by the manufactured graphite.

The impurities are removed by a purification process which adds considerable cost to the graphite, and therefore if it is possible to use raw materials with low concentrations of important impurities, the need for purification may be eliminated altogether. In the past, it was recognised during the design stage that regions of the core such as the outer reflector and neutron shields would not require purified graphites as the doses received would be very small. Thus in an AGR core different grades are used in different regions (see Figure 6). For the active core and inner reflected a 'high' grade graphite was used, whereas for the outer reflectors and neutron shields, 'medium' and 'low' grades were used. This can reduce overall costs significantly.

5.3.2 Cost

The cost of the graphite for a particular core design is clearly an important part of the initial capital costs, and should ideally be as low as possible. Many factors affect the initial costs e.g. raw materials (pitch coke being much more expensive than petroleum coke), forming method (iso-moulding being much more expensive than extrusion, and purification (as mentioned above). However, it is important to realise that the long term economics of a plant will depend on its design life/predicted life. It might be found from the irradiation experiments that the more expensive graphites turn out to give property variations which allow a significantly longer life to be achieved than the less expensive graphites, or will significantly reduce decommissioning and final disposal costs. The higher initial cost could be far outweighed by the increased returns of a longer life of the plant, and the potential reduction in decommissioning and final disposal costs.

5.4 Initial assessment

Unfortunately it is not currently possible to qualitatively predict the irradiation behaviour of a graphite from its unirradiated structure/properties. However, work is currently underway in the UK to try and gain a better understanding of the variation in some properties, in particular dimensional change behaviour. At the moment, therefore, it is not only possible to give a meaningful assessment of the selected graphites. All that can be said is that they have been chosen from a broad range of graphites to cover the different types of raw materials, grain sizes, and forming methods available to the manufacturer.

Given the knowledge accumulated in the past, together with the data that will be obtained from the initial irradiation programme, it is hoped that a much better understanding of graphite behaviour will be gained in the future. This should be supplemented by additional work such as analysis of the microstructure of the graphites both before and after irradiation. Discussions between the manufacturers, physicists and core designers can then be targeted at developing the ‘best’ graphite for future HTRs.

6 Conclusions

Most of the available data on the irradiation behaviour of graphite have been obtained by irradiating small samples in MTRs. Unfortunately, most of the data have been obtained at temperatures <550^{o}C, whereas HTRs will be operating generally at temperatures >550^{o}C. In addition, almost all the graphites previously irradiated are no longer commercially available. As a result a planned graphite irradiation programme is being undertaken for the European HTR project. This will allow the ‘best’ graphite(s) to be chosen, and provide all the data necessary to allow a full core design to be carried out.

Five of the currently available graphites have been selected for the forthcoming irradiation programme. These cover the two main coke sources (petroleum and pitch), two of the main forming methods (extrusion and iso-moulding), and a range of grain sizes (1mm down to 10 μm). Under the 5th Framework Programme funding, the graphites will initially be irradiated in a high flux MTR to a low/medium fluence. Hopefully, this will be continued to the full life peak fluence with funding from the 6th Framework Programme.

The graphite data requirements for a HTR core design have been presented, covering the initial specification, as-manufactured data, and irradiation data. The important aspects involved in selecting the ‘best’ graphite have also been given including dimensional stability, purity and costs.

7 References

Ref	Title
1	M W Davies. Report on selection of graphites and testing requirements. HTR-M1-02/11-D-2.1.9. NNC Report C6857/TR/001
2	M W Davies and G Haag. State of the art review of graphite materials and behaviour. HTR-M-02/6-D-3.1.37. NNC Report C6463/TR/011
3	M W Davies. Report on database of graphite properties for use by designers. HTR-M-02/06-D-3.1.22. NNC Report C6463/TR/012.

Table 1 Typical properties of selected UCAR Carbon graphites

Property - Typical average		Units	Petroleum coke	
			Extruded	Iso-moulded
			PCEA	PCIB-SFG
Apparent density		g/cm^3	1.83	1.86
Young's modulus	WG	GPa	11	12
	AG	GPa	10	
Tensile strength	WG	MPa	20	43
	AG	MPa	16	
Flexural strength (4-point)	WG	MPa	26	53
	AG	MPa	23	
Compressive strength		MPa	67	98
Ceofficient of thermal expansion 20 - 100^{o}C (20 - 1000^{o}C)	WG	10^{-6}/K	5.1 (3.8)	5.4 (4.1)
	AG	10^{-6}/K	5.6 (4.3)	
Thermal conductivity		W/mK	165	120
Anisotropy factor			1.13	< 1.07

Table 2 Typical properties of selected SGL graphites

Property - Typical average		Units	Coal tar pitch coke	Petroleum coke
			Extruded	Iso-moulded
			NBG-10	NBG-25
Apparent density		**g/cm^3**	1.80	1.81
Young's modulus	**WG**	**GPa**	10.0	9.9
	AG	**GPa**	9.8	10.9
Tensile strength	**WG**	**MPa**	19	
	AG	**MPa**	20	
Flexural strength (4-point)	**WG**	**MPa**	27	44
	AG	**MPa**	27	48
Compressive strength		**MPa**	60	95
Ceofficient of thermal expansion 20 - 200^{o}C	**WG**	**10^{-6}/K**	4.2	4.3
	AG	**10^{-6}/K**	4.5	3.9
Thermal conductivity	**WG**	**W/mK**	155	112
	AG	**W/mK**	161	126

Table 3 Typical properties of selected Toyo Tanso graphites

Property - Typical average		Units	Petroleum coke	Coal tar pitch coke
			Iso-moulded	Iso-moulded
			IG-110	IG-430
Apparent density		g/cm^3	1.77	1.82
Young's modulus	WG	GPa	9.7	10.8
	AG	GPa		
Tensile strength	WG	MPa	29	37
	AG	MPa		
Flexural strength (4-point)	WG	MPa	40	52
	AG	MPa		
Compressive strength		MPa	79	90
Ceofficient of thermal expansion	WG	10^{-6}/K	4.1	4.2
	AG	10^{-6}/K		
Thermal conductivity		W/mK	130	145
Anisotropy ratio			1.07	1.10

Figure 1 Graphite manufacture

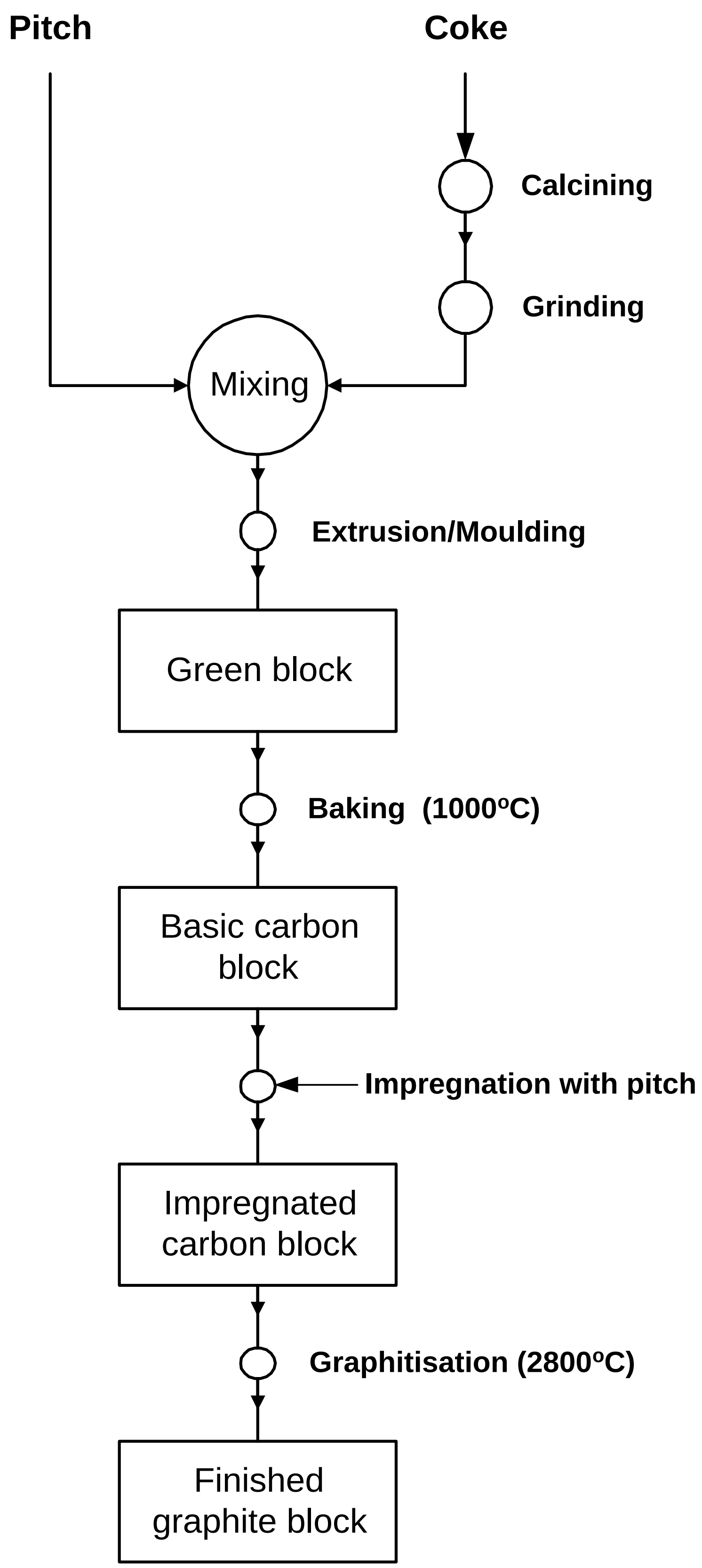

Figure 2 Dimensional change behaviour of ATR-2E graphite at 750°C

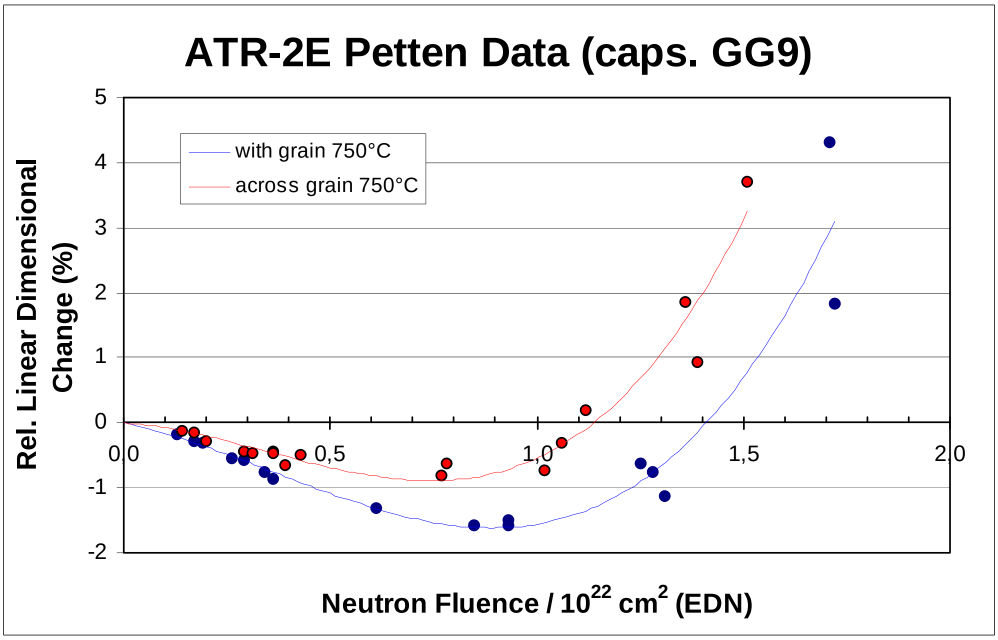

Figure 3 Variation in Young's modulus for ATR-2E graphite at 750°C

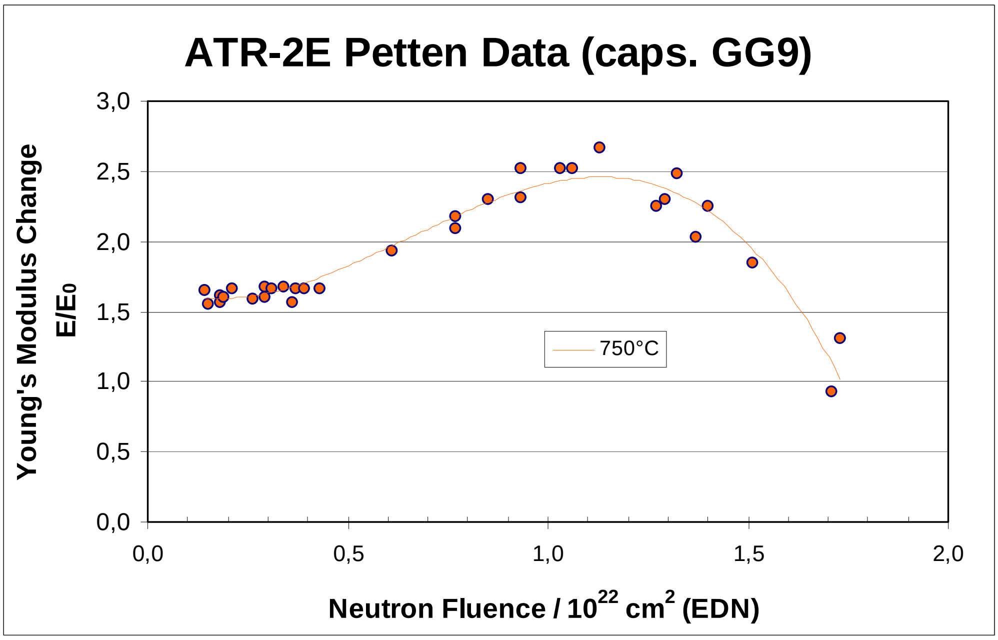

Figure 4 Typical properties for Gilsocarbon graphite

BRITISH ACHESON ELECTRODES LIMITED

TEST CERTIFICATE

Order No. 29RB90006/PRB
BNDC Specification No. 06/010 (Core)

BNDC Contract : 70040

Heat No: 7358
Item No: 1 & 2
Grade: GCMB
Size: 466 dia x 892 & 953 mm

		Guaranteed Values	Mean	Max.	Min.	n	Mean Periphery	Mean Centre
Neutron Absorption X Section mb/atom less boron		4.80 max	3.85			1		
		3.95 max	3.80			1		
Apparent Density Mg/m^2		1.80 min	1.83	1.85	1.82	12		
Specific Resistance (ohm cm x 10^{-4})	WG							
	AG	12.00 max	10.04	11.73	8.55	12		
Flexural strength (MN/m^2)	WG	23.00 min	23.28	24.21	21.31	12	23.53	23.01
	AG	24.00 min	24.88	26.90	22.76	12	25.30	24.46
Tensile strength (MN/m^2)	WG	16.00 min	16.56	18.11	15.53	12	16.28	16.83
	AG	18.00 min	19.20	21.32	17.19	12	19.53	18.87
Compressive strength (MN/m^2)	WG	65.00 min	69.97	79.30	58.62	12	70.83	69.11
	AG	70.00 min	74.35	87.92	72.41	12	74.71	73.99
C.T.E. ((20-120°C) x 10^{-6}/°C)	WG	4.00 min	4.63	4.69	4.54	4		
	AG	4.10 min	4.73	4.79	4.64	4		
Effective OPV (m^3/Mg x 10^{-2})		8.0 max	7.8	8.9	5.0	11	7.4	8.2
Air reactivity (g/g/hrx10^{-6})		5.0 max	5.0	6.0	4.0	4		
Youngs Modulus (GN/m^2)	WG		9.81	10.25	9.64	4		
	AG		9.58	10.47	9.24	4		
Strain/Fracture %	WG		0.23	0.25	0.21	4		
	AG		0.31	0.33	0.27	4		
Permeability (m^2 x 10^{-10})	WG		50	58	41	4		
	AG		75	75	74	2		
Diffusivity (radial)			0.00346	0.00408	0.00323	3		

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R.S. Shaw
Assistant Head - Quality Control
Engineering

Figure 5 Typical impurity levels for Gilsocarbon graphite

GILSOCARBON GRAPHITE

TYPICAL ANALYSIS

	Unpurified	Purified	Limit of Detection
Ash %	0.110	0.005	
Iron ppm	70	10	1
Sulphur ppm	130	< 50	50
Boron ppm	2.0	0.2	0.02
Aluminium ppm	14	1	0.01
Barium ppm	6	1	0.01
Bismuth ppm	0.3	< 0.01	0.01
Calcium ppm	220	1	0.1
Cobalt	10	1	0.01
Chromium ppm	1	< 0.02	0.02
Lead ppm	0.2	0.02	0.005
Lithium ppm	0.2	0.01	0.01
Magnesium ppm	0.2	< 0.02	0.02
Manganese ppm	0.1	0.01	0.01
Molybdenum ppm	20	0.1	0.01
Nickel ppm	80	1	0.01
Sodium ppm	3	1	0.01
Silicon ppm	70	5	0.1
Strontium ppm	3	< 0.1	0.1
Tin ppm	0.1	< 0.01	0.01
Titanium ppm	10	< 0.1	0.1
Tungsten ppm	1	< 0.01	0.01
Vanadium ppm	5	0.1	0.01
Zinc ppm	1	< 0.01	0.01
Dysprosium ppm	0.02	< 0.005	0.005
Europium ppm	< 0.004	< 0.004	0.004
Gadolinium ppm	< 0.013	< 0.013	0.013
Samarium ppm	< 0.018	< 0.018	0.018
Cerium ppm	0.1	< 0.04	0.04
Lanthanum ppm	0.1	< 0.003	0.003
Neodymium ppm	0.15	< 0.008	0.008
Scandium ppm	0.05	< 0.003	0.003
Ytterbium ppm	0.01	< 0.003	0.003
Yttrium ppm	0.07	< 0.003	0.003
Praseodymium ppm	0.03	< 0.018	0.018
Erbium ppm	0.01	< 0.005	0.005
Terbium ppm	< 0.01	< 0.008	0.008

Figure 6 Distribution of graphite grades in an AGR