EUROPEAN COMMISSION

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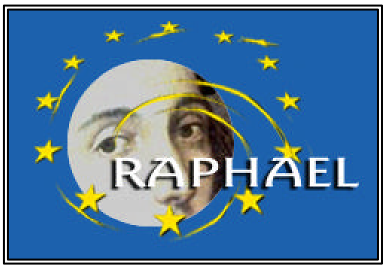
Contract Number: 516508 (FI6O)



DELIVERABLE (D-ML4.1)

Development of Design Data and Guidelines for Carbon Composites – Scope and Planning

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Reporting period: e.g. 15/04/2006– 14/04/2007

Date of issue of this report : 30/06/2006

Start date of project : **15/04/2005** Duration : **48 Months**

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)		
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ReActor for Process heat, Hydrogen And ELectricity generation (RAPHAEL)		
Sub-project: SP-ML **Work package:** 3	**RAPHAEL document no:** RAPHAEL-0606-D-ML4-1	**Document type:** D=Deliverable / M=Minute / P=Progress report / S=Support
Issued by: NNC(UK) **Internal no.:** 12820/TR/018		**Document status:** Final

Document title

Development of Design Data and Guidelines for Carbon Composites – Scope and Planning

Abstract

Within the RAPHAEL-IP framework, there is a requirement to develop design data and guidelines for the design of those parts of the reactor that require the use of carbon-carbon composites. This report reviews the current situation with regard to the selection of C-C composites, the requirements for irradiation testing, and outlines the overall scope and planning requirements for the development of a database, and for producing guidelines on design methodology for components made from C-C composites for the European (V)HTR programme,

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
00	dd/mm/yyyy	First issue	Name, Organisation	Name, Organisation *Signature*	Name, Organisation *Signature*	Name, Organisation *Signature*
01	30/06/2006	First issue	Mike Davies NNC	Derek Buckthorpe NNC	Derek Buckthorpe NNC	E. Bogusch

DOCUMENT ISSUE RECORD
(engineering documents)

Adding value through knowledge

Document Title :	**Development of Design Data and Guidelines for Carbon Composites – Scope and Planning**
Project Reference:	12820

Purpose of Issue : For use

Security Class : Commercial-in-Confidence

Issue	Description of Amendment	Originator/ Author	Checker	Approver	Date
01 Draft	First draft for comment	M W Davies	D E Buckthorpe		
01	Checker comments incorporated	M W Davies (signed)	D E Buckthorpe (signed)	A Cheyne (signed)	

Total number of pages:	Intro:	1 - 7	Text	8 - 14	Tables		Figures		Appendices	

Previous issues of this document shall be destroyed or marked **SUPERSEDED**

Distribution: SINTER, HTR-M1 Parteners (via SINTER), NNC: M W Davies, D E Buckthorpe, EDMS

3050aJan01 Controlling procedure - QP11, QP40 *Docprodref*

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1 Introduction

In order to be able to carry out the initial design of the graphite core in a (Very) High Temperature Reactor (V)HTR it is essential to have reliable graphite data and a proven design methodology. These aspects are covered in Ref 1. However there may be regions of the core, or specific items, which may have to be made out of carbon-carbon (C-C) composites, because the normal operating temperatures or potential fault condition temperatures may preclude the use of metallic components. There is therefore a need to establish what candidate C-C composites are available, and to qualify them for use in the environment to which they would be subjected. This is likely to include fast neutron irradiation and/or high temperature. Therefore for the C-C composite(s) selected, it is important to have a full characterisation of the as-manufactured material(s) as well as a complete set of information on how particular properties vary with fast neutron irradiation and irradiation temperature over the required range. Such experiments are planned for the High Flux Reactor (HFR) at Petten. The oxidation resistance of the C-C composites at high temperature also needs to be determined due to its relevance during normal operation and for air and water ingress accidents. Few may turn out to be suitable for a modular VHTR and there may therefore be a need to develop improved materials in the future.

In the past, the design of graphites cores has generally been carried out by the countries in which the reactors were built, using their own developed methodology and data on their particular graphites. The countries in question were the UK, USA, France, Germany and Russia. However, very few if any C-C composites have been used, and so in addition to the knowledge of their irradiation behaviour being limited, so is the experience in designing components for reactor applications made from them. Therefore, for the European (V)HTR R&D activities, there is a need to develop suitable methodologies for the design of reactor components made from C-C composites. Methodologies for core design are being addressed through the American Society of Mechanical Engineers (ASME). A Project Team has been established and is developing a consensus design code for graphite components. It is also the remit of this Project Team to develop methodologies for components designed using other ceramic materials such as C-C composites.

This report reviews the current situation with regard to the selection of C-C composites, the requirements for irradiation testing, and outlines the overall scope and planning requirements for the development of a database, and for producing guidelines on design methodology for components made from C-C composites for the European (V)HTR programme,

2 Carbon-carbon composites

2.1 Material properties

The most important class of properties of C-C composites is their thermal properties. C-C composites have very low thermal expansion coefficients, making them dimensionally stable at a wide range of temperatures, and they have high thermal conductivity. C-C composites retain mechanical properties even at temperatures (in non-oxidizing atmospheres) above 2000°C. They are also highly resistant to thermal shock, or fracture due to rapid and extreme changes in temperature. The material properties of a C-C composite vary depending on the fibre fraction, fibre type selected, textile weave type and similar factors, and the individual properties of the fibres and matrix material. C-C composites are available as unidirectional (1D), and 2-D and 3-D reinforced.

Fibre properties depend on precursor material, production process, degree of graphitisation and orientation, etc. The tensioning step in fibre formation is critical in making a fibre (and therefore a composite) with any useful strength at all. Matrix precursor material and manufacturing method have a significant impact on composite strength. Sufficient and uniform densification is necessary for a strong composite. Generally, the elastic modulus is very high, from 15-20 GPa for composites made with a 3D fibre felt to 150-200 GPa for those made with unidirectional fibre sheet. Other properties include low-weight, high abrasion resistance, high electrical conductivity and non-brittle failure. C-C composites are very workable, and can be formed into complex shapes.

However, the chief drawback of C-C composites is that they are much less resistant to fast neutron damage than graphite, and that they oxidise readily at temperatures between 600-700°C, especially in the presence of atomic oxygen. A protective coating (usually silicon carbide) must be applied to prevent high-temperature oxidation, adding an additional manufacturing step and additional cost to the production process. Some investigative work on oxidation of selected composites was carried out in the HTR-M Project (Ref 2)

2.2 Selection of candidate materials

An investigation into suitable candidate materials for the (V)HTR Control Rod and other applications is underway (Ref 3). For use as the former, information on irradiation resistance is needed and it is planned to carry out some irradiation testing for this within the Extremat project (Ref 4). There is a need therefore to select candidate C-C composite materials for such irradiation experiments. No materials have been selected at the current time but initial indications suggest that one or more from the family of materials referred to as ®SIGRABOND may be suitable. This is the trade name used by SGL Carbon for a high strength composite material consisting of a carbon or graphite matrix with carbon fibre reinforcement. This combination of carbon or graphite with carbon fibres produces a material with both the favourable properties of fibre composites and those of graphite.

2.3 Irradiation experiments

It is planned to perform experiments to determine the irradiation behaviour of the selected C-C composites relevant to VHTR application in the HFR at Petten as part of the EXTREMAT-IP. However, due to the much lower resistance of C-C composites to fast neutron irradiation compared to graphite, there is a need to carefully select the appropriate fluence ranges for each stage of the experiment. This is to guard against any specimens disintegrating before the first stage is completed. There is also a need to decide on what the most appropriate shape and size is for the specimens, and what orientations need to be tested.

For the graphite irradiation programme, the specimens are cylindrical, 8 mm in diameter and either 6 or 12 mm in length. Due to the anisotropy of the materials, it was necessary to machine half of the specimens with their length axis in the 'with-grain' direction(s) and the other half with their length axis in the 'against-grain' direction(s). However, for C-C materials, which carbon fibres aligned in a number of different ways depending on the weave etc, the anisotropy is much larger. The various mechanical and thermal properties can have significantly different values parallel to the fibre compared to those perpendicular to the fibre or layer. It is certain that the irradiation behaviour will also be significantly different in the different directions.

2.4 Irradiation data base

2.4.1 Graphite materials

A database for the selected graphites being tested in the HFR at Petten has already been developed and populated with pre-characterisation data, and data from the first stage of the irradiation (Ref 5). Due to the large amount of data and grades of graphite it was decided to produce a single spreadsheet for each graphite grade. Measurements were made of their initial dimensions, mass, dynamic Young's modulus (DYM), coefficient of thermal expansion (CTE) and thermal conductivity (via measurements of thermal diffusivity). From these, their volumes and densities were calculated. The pre-characterisation (i.e. unirradiated) data are contained in the first part of the spreadsheet, the irradiated measurements are contained in the second part of the spreadsheet, and the fractional/percentage changes are calculated in the third part. The latter are used to produce graphical plots of the changes with respect to fluence (Ref 6). This can either be in terms of displacements per atom (dpa) or Equivalent DIDO Nickel Dose (EDND). These will be the 'design curves' for the properties in question and polynomial fits to the data can be used for computational models used to calculate through life stresses in components.

2.4.2 C-C composites

An equivalent database is required for the C-C composites. This will include data on the pre-characterisation and the irradiation measurements so that the necessary fractional/percentage changes in properties can be determined.

2.5 Tests on oxidation under accident and normal operation conditions:

The limited oxidation resistance of porous C-based materials causes potential problems when in contact with oxidising atmospheres. During accident conditions this can for example lead to a localised reduction in strength at exposed surfaces. The necessary safety analyses on graphite oxidation therefore require a detailed knowledge of the oxidation kinetics. Some rapid oxidation tests have been performed on the selected graphites and composites in the FP 5 HTR M / M1 programs [Ref 7 and 8] and further investigations are proposed on graphites within RAPAHEL. These are necessary to determine the behaviour of the different graphites under accident conditions. Similar experiments will be required to determine the behaviour of the different C-C composites under accident conditions. Some additional oxidation investigations are being conducted on composites within EXTREMAT-IP which will be used to support any further work within RAPHAEL.

Oxidation of the graphite also takes place during normal operation due to impurities in the cooling gases. In this case however the oxidation rate of the graphite is extremely low. Nevertheless it will be necessary to determine the appropriate oxidation kinetics so that through life predictions of component oxidation distributions can be determined for different level of impurities. Similar experiments will be required to determine the behaviour of the different C-C composites under long-term oxidation conditions.

3 Design methodologies

3.1 Requirements for calculations

In order to design components made out of a C-C composite material the following basic calculations are required

(i) Calculation of fluence distributions in the components

(ii) Calculation of temperature distributions in the components

(iii) Calculation of oxidation distributions in the components

(iv) Calculation of loadings generated in the components

With this information, together with the known irradiation behaviour of the material, it will then be possible to carry out the following through life calculations:

(v) Calculation of irradiation induced stress distributions in components

(vi) Calculation of irradiation induced distortions in components

(vii) Calculation of component integrity

Most of the above require special computer codes to be developed, which need to be verified where possible against other codes, and validated where possible against experimental data.

3.2 Existing design codes

There are two draft graphite core design codes in existence, one produced by ASME in the USA and one produced by the KTA in Germany. The ASME code for graphite cores (Ref 9) was produced primarily for the US High Temperature Gas-cooled Reactor (HTGR) programme, but was never progressed further due to the cancellation of the US programme. Around the same time a draft design code for graphite components (Ref 10) was also under development in Germany, again primarily for the country's HTGR programme, and again this was not progressed any further due to the cancellation of the German programme.

After the construction of the last two AGRs in the UK, a document entitled 'The Compendium of AGR Core and Sleeve Data and Methods' was developed which contains all the graphite data and methods needed. It is a live document and is updated as required to reflect improvements in methodology and revisions to the graphite data. The data sheets cover Young's modulus, strength, dimensional change, coefficient of thermal expansion, thermal conductivity, irradiation induced creep, specific heat and stored energy, gas transport properties (diffusivity ratio and viscous flow coefficients), virgin bulk density and open pore volume. The method sheets cover the calculation of fast neutron fluence, temperature and radiolytic oxidation distributions in components, brick geometry changes, core loads, brick internal stresses and external (load applied) stresses, brick integrity and core geometry.

The problem is that none of the above deal with the design of components made out of C-C composites. However, this should be covered by the ASME code being developed (see Section 3.3 below).

3.3 ASME code development

An ASME Project Team, initiated in 2004, is currently developing a design code for graphite core components for HTGRs. It is also planned to cover components made from other ceramic materials, such as C-C composites. The Project Team has members from the USA, UK, France, South Africa and Japan. The code when completed will include rules for materials, design, fabrication and testing, including the quality control requirements for fabrication and installation. It is expected that a completed draft of the code will not be available until 2008, and that it will take until at least 2010 before it has undergone complete peer review and will become fully operational.

3.4 Proposals for RAPHAEL (V)HTR Code Activities

It is proposed at this stage that the C-C composite data and design methodology developed within RAPHAEL for the (V)HTR be contained in a Compendium similar to that produced by the UK for the AGRs. However, not all the data and methodology sections will be required. The data sections will contain all the necessary data for the C-C composites selected as being the best overall. The selection will be based on a number of factors including the irradiation behaviour obtained from future experiments, the material availability and cost. Aspects of the methodology contained within the ASME graphite code currently under development will be referenced as required.

4 Scope and planning

The scope of the work required regarding the development of C-C composite data and design methodology is as follows:

(i) Determine unirradiated material properties for selected C-C composites

(ii) Determine irradiation behaviour at specified temperatures over the full fluence range (includes dimensional change, Young's modulus, strength, CTE and thermal conductivity)

(iii) Populate database and produce design curves

(iv) Produce compendium of C-C composite data and design methodology

The planning will have to take into account the timescales for obtaining the necessary irradiation behaviour and also the development of the ASME design code.

In the event of insufficient irradiation data becoming available for specifically identified composite materials or the timescales for obtaining actual reliable data becomes extended beyond the current RAPAHEAL project, then an initial approach will be developed based on generic/ published information.

5 Conclusion

In order to be able to carry out any initial design of the components made from C-C composites in a (Very) High Temperature Reactor (V)HTR it is essential to have reliable data and a proven design methodology. The necessary data on the irradiation behaviour are to be obtained from some initial experiments to be carried out in the future in the HFR at Petten (within EXTREMAT-IP), and the oxidation behaviour from experiments to be carried out at FZJ. It is proposed that C-C composite data and the development of design methodology within RAPHAEL for the (V)HTR be contained in a Compendium similar to that produced by the UK for the AGRs. Aspects of the methodology contained within the ASME code currently under development will be referenced as required.

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