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High Temperature Reactor (HTR) Materials

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HIGH TEMPERATURE REACTOR (HTR) MATERIALS

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Abstract

Issues concerned with the material selection and behaviour of the main component reactor materials are examined for the Modular High Temperature Reactor. The work considers materials for the reactor vessel, certain high temperature regions including the control rod and turbine and the graphite core. The work is being performed within a European development initiative supported by the European Union Fifth Framework programme. This paper reviews the main elements of the materials work programme and presents some initial results. Future actions with regard to experiments and assessment are discussed.

Keywords: HTR, materials, irradiation, tests, steels, graphite, gas

Introduction

European Community Framework Programmes have been launched to consolidate and advance the modular HTR technology in Europe [1]. These involve six coordinated projects that look at important technological issues associated with its development in key technical areas (HTR-F, HTR-M, HTR-N, HTR-E, HTR-L and HTR-C). HTR-C deals with co-ordination of the collective whole, whilst the others cover issues on Fuel, Materials, Nuclear Physics, Equipment, and Licensing. The projects involve partnerships between principal industrial and research organisations from different countries of the European Union, and have the individual aim to develop and consolidate European expertise and experience in each of these areas.

The project on materials (denoted HTR-M & M1) deals with the selection and development of materials for the reactor pressure vessel, high temperature resistant alloys for the internal structures and turbine and graphite for the reactor core. The work started in November 2000 and involves eight partners from five European countries. The main elements of the programme have previously been reviewed and discussed with respect to feasibility and structural integrity requirement [2]. This paper gives a brief outline of the HTR-M programme and presents and discusses some of the initial results and ongoing actions.

Development of HTR Technology

The first commercial gas cooled reactor used for the generation of electricity was commissioned in 1956 at Calder Hall in the UK. This used CO_2 gas as the primary coolant. Over the next decades a total of 26 Magnox Stations and 15 Advanced Gas Cooled Reactors were built most of which are still operating today (the last station starting service in 1989).

Alongside this the helium cooled graphite moderated reactor was developed. The use of helium as a coolant meant that the reactor could operate at higher temperatures and increased efficiency. Such a reactor however called for a new approach to both the core design and the engineering structures. The concept used coated ceramic fuel particles and a dispersed graphite matrix and moderator. In the years 1960 to 1990 HTR prototypes were built and tested in Europe (DRAGON (UK) - 1964 to 1975, AVR (Germany) 1966 to 1988, THTR 300 (Germany) 1983 to 1989). The introduction of a commercial system seemed promising in the early 1980s with the HTR-MODUL plant developed in Germany for industrial process heat applications (based on the passive safety features and a side by side modular arrangement). However the decision to decommission the THTR-300 demonstration plant eventually led to the HTR programme being stopped.

Since that time two high temperature test reactors have been built and commissioned outside Europe, the HTTR in Japan in 1998, and HTR-10 in China in 2000. Two international industrial projects are also underway with the aim of commissioning prototype reactors before 2010. The PBMR led by ESKOM (South Africa) with participation of the UK (BNFL), Exelon and South African companies and GT-MHR led by a consortium (MINATOM, General Atomics, Framatome ANP and Fuji Electric). Both of these projects have a strong European involvement. The GT-MHR is being developed for burning Russian military plutonium and the PBMR as the first of a new generation of cost-effective and inherently safe power plants that use the modular approach.

In April 2000 a European HTR Technology Network (HTR-TN) was established to coordinate and encourage work-shared actions within European companies involved in HTRs. This would also serve as a channel for international collaboration [3]. This network involves over 20 organisations from industry, research and development, utilities and universities together with the Joint Research Centre (JRC) of the European Commission who have agreed to work collectively on longer term issues to established a firm basis for continued development of HTRs in Europe.

Objectives and description of the HTR Materials Projects

The development of Advanced HTR concepts requires material data information and an understanding of material behaviour under representative reactor operating conditions. For components important to the safety and feasibility of designs such as the main steel structures (vessel, internal structures, turbine) and the graphite structures (core), investigation of the different materials to be used and their behaviour in the reactor environment is an important necessary requirement for feasibility and design. The objective of the HTR-M programme therefore was to identify materials of interest for key components, establishing a database of information and support any unresolved technological issues with tests on the most promising options for future application. Two projects are ongoing (HTR-M & HTR-M1 -managed together) that cover three areas: the reactor vessel, high temperature materials (internal structures and turbine) and graphite structures (including oxidation). A description of the main activities and project time-scales is shown in Fig. 1. Since no new design work has so far been performed the programme aims to solve technological issues important to the future development of HTRs based on current understandings of the two international project concepts PBMR and GT-MHR.

<u>Reactor Vessel</u>

Design information is needed for the Reactor Pressure Vessel (RPV) under HTR conditions. For the vessel two design options exist:

(1) to keep the vessel temperatures at a similar level to PWR vessels by cooling (this option has been selected for the PBMR) or;

(2) allow the vessel temperatures to reach the core inlet temperature (option selected for the GT-MHR).

It is necessary to investigate and confirm the choice of candidate material options for these two concepts. It is important also to compile their design properties, in relation to both normal and accident conditions. The integrity of the welded joints is seen as a critical feasibility issue and information is needed on the behaviour of welded joints under the influence of the HTR environment. The programme on the vessel material is focused therefore on qualification through a series of tests to look at the integrity of welded joints under irradiated and non-irradiated conditions. An irradiation test of thick section welded joints is being prepared that will start at the end of 2002. It is planned to irradiate specimens in the High Flux Reactor (HFR) at Petten.

In summary the work (performed in HTR-M) on vessel steels covers the following:

- review of existing materials used in gas-cooled reactors and previous high temperature reactors;
- setting up of a materials database on design properties (which will lead to identification of data omissions for future R& D testing);
- carrying out of specific tests on welded joints under irradiated and non-irradiated conditions.

High Temperature Materials

For the HTR primary circuit components metallic and ceramic materials are possible. Some data exists on such materials but the information and experience for the HTR environment are not well established. The structures to be investigated include the control rods and the turbine. For the former carbon-carbon (C/C) composites provide an option for which some work has been performed [4]. For the turbine (disc and blades) high alloy steels are possible although the expected working conditions and environment are beyond current industrial experience (issues of endurance rather than temperature).

Work is underway to establish a short list of materials for the control rod and turbine that takes account of the experience from existing high temperature and gas cooled reactors and current manufacturing techniques.

For the turbine, the most critical stage is the first stage discs and blades. The most promising grades are to be investigated initially using short term mechanical tests (tensile, fatigue, short term creep and creep / fatigue tests (in air, vacuum, helium)). Within HTR-M1 the test programme includes intermediate term creep effects to confirm the suitability of the chosen alloys for longer-term high temperature exposure. The tests cover specific grades, fabrication routes, and heat treatments. Tests will also be carried out on aged material and damage analysis and lifetime modelling is planned (based on results from notched specimens) to gain a fuller understanding of failure mechanisms.

In summary the work (performed in HTR-M & M1) on high temperature materials covers the following:

- review of existing materials used in gas-cooled reactors and previous high temperature reactors;
- setting up of a materials database on design properties (which will lead to identification of data omissions for future R& D testing);
- specific tests on control rod, turbine disc and blade materials (carbon-carbon composites, high alloy steels) at temperature and under short term and intermediate times in air, vacuum and helium.

Graphite

The need for reliable graphite data is a crucial issue for existing and new HTR projects. Graphite plays an important role as a moderator and structural component and has important safety implications because of structural and other property changes that occur when it is irradiated. Its selection also has important consequences for future decommissioning activities. Oxidation resistance of graphites at high temperature requires special attention due to its relevance for safety analyses of air and water ingress accidents, licensing procedure and normal operation.

The HTR-M project provides a limited review of existing graphite information plus some tests on graphite oxidation. The review work focuses on graphite data and selection issues and future needs. Many graphites used in previous core designs are no longer manufactured commercially, and currently available grades limited to a few specific sources of raw materials. Very few of the grades may turn out to be suitable or desirable for a European based modular HTR. The graphite oxidation work involves tests to investigate the effect of oxidation from severe air ingress with core burning. It also looks at protective coatings and innovative C- based materials.

Recognising the shortage of and need for information, the HTR-M1 project concentrates on performing irradiation tests on new graphites for which no data is currently available. The work includes discussions with graphite manufacturers to provide samples and investigate the possibility of producing small quantities of alternative graphites (in the laboratory) which would have a better combination of desirable properties. Also tests to determine variations in physical and mechanical properties up to low / medium irradiation doses (making use of the results from HTR-M as a basis for estimation and extrapolation to higher doses). Although the project falls short of the ultimate selection criteria for the graphite, which will mainly be based on long-term irradiation behaviour, it does provide the groundwork for continuation of the irradiation programme on the most desirable graphite(s). It also makes use of the valuable diminishing experience from experts in design, experiments and testing of graphite within Europe serving to reinstall graphite irradiation and qualification methods within Europe while the available experience and facilities exists.

In summary the work (performed in HTR-M & M1) on graphite covers the following:

- review of graphite materials data identifying new graphites suitable for HTR and formulating a database of available information;
- selection of and performing of irradiation testing on new graphites;
- investigate graphite oxidation and the consequences of severe air ingress with core burning including the development of HTR models and data, protective coatings and innovative C-based materials.

Results from ongoing actions

The work is well into its second year with the emphasis so far on completing and assembling the review and database for the component materials and defining the needs and requirements for the experiments. The following sections provide the results to date from ongoing actions and the basis on which some of the decisions taken so far have been made.

Database information

The database is required to cover three main areas.

- The reactor pressure vessel (and other pressure vessels used to contain primary circuit components).
- The high temperature components focusing in particular for the reactor internals on the control rod system and for the turbine on the blades and discs.
- The graphite core and its components.

The work is considered to be well advanced in certain areas. The overall aims and composition of the database have been defined and Alloys-DB developed at JRC is being considered to house the resulting data. A few selected materials have been chosen for each category and an intermediate spreadsheet is being used to collect and assemble the information from the different partners. The key issues are ease of access, security, quality assurance, central control and the need for web access. The data is being input through a PC version of the software with updating of the web-based information being done in stages.

Reactor Vessel

The vessel review work has concentrated on materials used in new and developing plants to make sure that the most up to date vessel steels are considered. LWR type steel is proposed for the insulated design of the current PBMR and modified 9Cr 1Mo steel for the inlet temperature vessel design of the GT-MHR and both types of steel will be included in the database. The project resources however only permit one type of steel to be tested in the HFR. Since modified 9Cr 1Mo steel has the wider applicability and most uncertainties on database and fabrication experience (with respect to HTR vessel characteristics), this was chosen as the material for the irradiation test programme.

The irradiation tests will involve the use of the Lyra rig (Fig. 2), which allows accurate control of the temperatures and use of a helium atmosphere. The heaters in the rig will be used to correct the temperature levels obtained from gamma heating. Post irradiation tests will include tensile, creep, Charpy and CT toughness tests. The fabrication and characterisation of the welded specimens involves tests on 40 and 150mm thick plate. The former provides a suitable vehicle for trials using different weld bead lengths and different weld parameters before producing the final weld specimens with the thicker plate. The conditions used will simulate the accumulated dose at the end of life. For the tests the lowest temperature condition needs to be considered as higher temperatures are expected to act to anneal out any irradiation damage effects.

Work has started in defining the tests for post-irradiation and reference properties. The database analyses on modified 9Cr 1Mo steel weldments together with actions to bound the operating and design conditions will determine the final test selections and boundary conditions. The procurement of the material and fabrication of the thick section welded test pieces will be done following characterisation tests. These characterisation tests are underway. Test programme details are expected to be finalised by mid 2002 to allow the test programme to start at the end of 2002.

High Temperature materials

For the Work Package on high temperature materials, actions to establish representative design and operating information are in hand. This is needed in order to use the most appropriate conditions for the test. The material review and database activity on the control rod materials is underway with special attention paid to C/C Composite materials as an alternative to metals. The review and database work is expected to determine the candidate material for the tests. Actions needed to procure suitable material have started.

For the Turbine (disc and blades) the review and database work has shown a potential list of alloys which will be considered in detail before selecting the final list of materials for the database and before confirming the alloy to use for the experiments. Discussions are underway with a turbine materials manufacturer. Testing of turbine materials in helium will require some test facility development. Designs have been initiated and preliminary work is underway in order to have the facilities ready when the materials have become available. A decision on procurement of material is expected to be taken shortly to allow the short-term experiments to start in 2002. Intermediate creep testing of material is planned to start in 2002 under the HTR-M1 project and material selection will be made to maximise the amount of testing time available.

Corrosion problems are known in Helium atmospheres as a result of the decomposition of methane under extremely low oxygen partial pressures. Tests show that such atmospheres are heavily carburising with the carbon forming from water and hydrogen reactions. Such an effect on turbine disc and blade alloys may result in significant reductions in creep strength. Doping the atmosphere with carbon monoxide alleviates the carburising effect. Since carburising can also occur in the tests in helium, the choice of conditions used has to be made very carefully in order to ensure good representative results are obtained. The presence of alloying elements such as cobalt (which is in most of the currently available turbine disc and blade materials) is a further area of investigation. The main issues are the potential for plate out and lift off of particles and their activation and prevention of them flowing through the core.

The current view is to avoid single crystal materials for the blades and test three grades of material under tensile and creep conditions, at temperatures up to 850^{o}C. Manufacturing considerations are a major factor for the disc, producing large ingots without porosity and segregation is a major challenge for the size of disc being considered. The tests on the proposed disc material will be carried out at 700 and

750^{o}C. The ageing will be performed on one grade (that offers the best properties for blades) and post ageing mechanical tests will be performed (tensile and creep tests).

Graphite

The work on the graphite properties has so far looked at the current understanding of knowledge and considered the information available in the IAEA database. Activity has also started on the selection of graphites and for the experimental programme to be performed within the HTR-M1 project. Irradiation damage can have a significant effect on the physical and mechanical properties of graphite and the HTR-M1 project will test a small number of graphite types that are to be irradiated within the High Flux Reactor to identify such changes. Progress on this work is underway to set the characteristics of the test programme and shortlist the types of graphites and numbers of tests to be performed. The main graphite suppliers have already indicated their willingness to participate in the test programme.

The work on graphite oxidation involves tests in the THERA and INDEX facilities (Fig. 3). This work is well advanced with some early results in air available. Measurements have been taken on the kinetics of graphite in oxygen for temperatures between 550 and 750^{o}C and partial pressures of between 2 and 20kPa. Measurements in steam have required some improvements to be incorporated in the test rig. Oxidation resistance of three-selected Carbon-Fibre-Composites (CFCs) developed for the Fusion Reactor has so far been measured in air. Further tests in steam are planned for mid 2002 and results from the high flow rate facility expected by the end of 2002. Experiments are also being carried out to determine the thermal conductivity of such CFC materials, and so far reference measurements have been made in non-irradiated material with tests on irradiated samples to be completed in 2002.

Summary and Conclusions

This paper outlines the work program and reviews and discusses important issues concerning material needs for feasibility and results of some of the ongoing actions. Overall the project is progressing to programme with review and database investigations in hand and planning for experiments started. Graphite oxidation experiments are well underway and results available. The next phase of the work will involve decisions on materials and the setting up of the tests on the vessel material, the disc and blade high temperature alloys, and for the graphite irradiation tests to enable them to start as early as possible in the programme.

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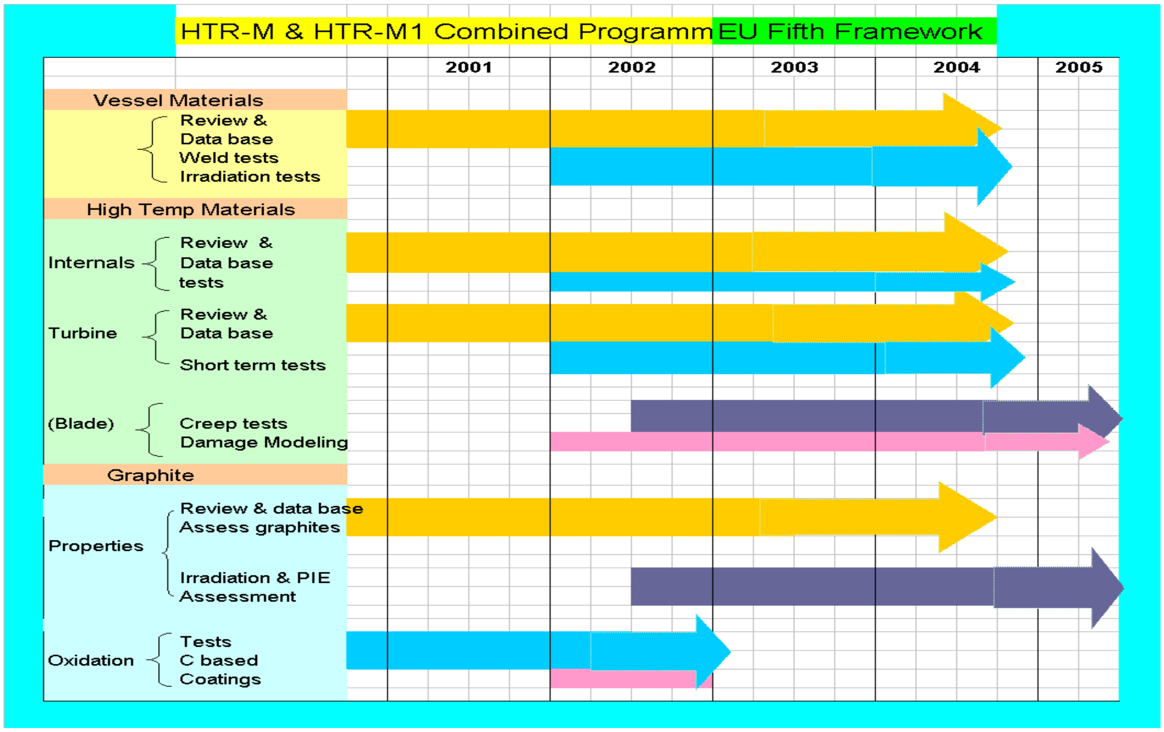

Figure 1 Description of Overall HTR-Materials Programme

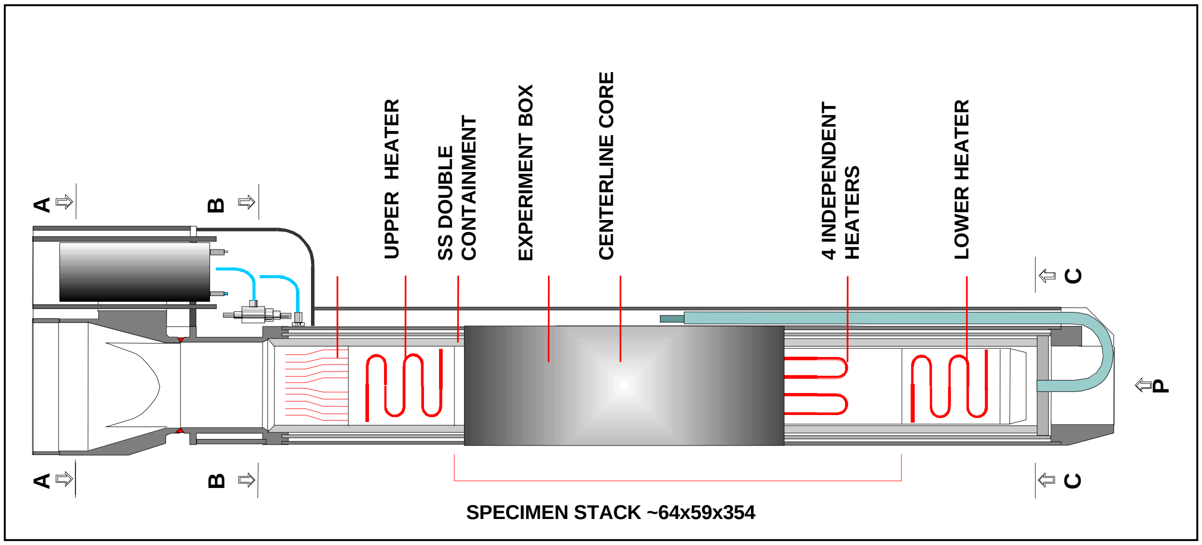

Figure 2 Lyra Test Rig

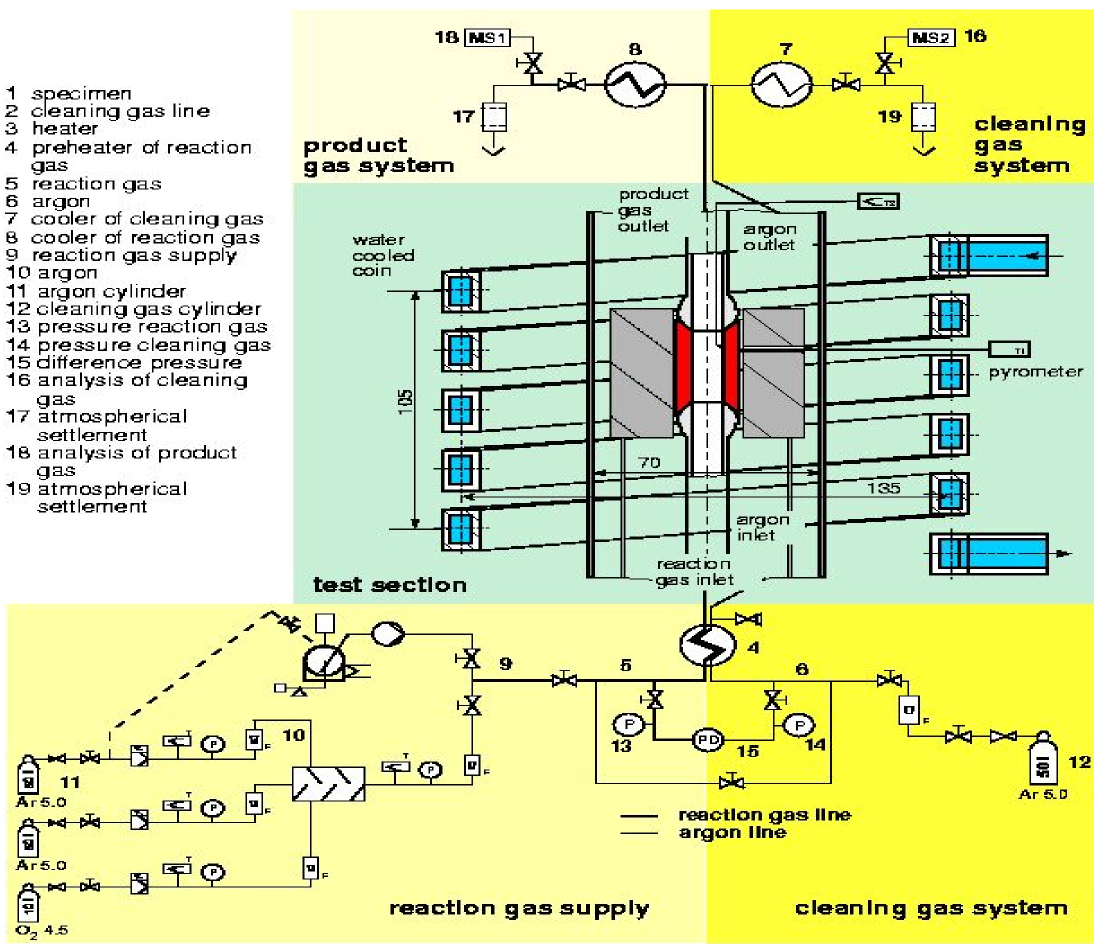

Figure 3 Schematic of the Oxidation Facility INDEX