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European Project on Materials for Modular HTRs

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EUROPEAN PROJECT ON MATERIALS FOR MODULAR HTRs

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ABSTRACT

Issues associated with material selection and behaviour are being examined for the main reactor circuit components of the Modular High Temperature Reactor. The work is being performed as part of a European development supported by the European Union Fifth Framework programme and under the review of the Network HTR-TN. This paper reviews the mid term progress of HTR-M & M1 projects on materials. These projects focus on requirements for reactor pressure vessel, high temperature resistant alloys, and graphite for the reactor core.

1. 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 industrial and research organisations from different countries of the European Union, with the aim to develop and consolidate European expertise and experience in each of these areas.

The projects on materials (denoted HTR-M & M1) deal 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. A description of the programme and its objectives has been summarised elsewhere (Ref. [2]). The work started in November 2000 and involves eight partners from five European countries. This paper reviews the progress of the HTR-M programmes and discusses some of the results to date.

2. HTR-M & M1 Project Objectives and Programme

The projects involve research into materials technology for three main component areas;
(i) vessel, (ii) turbine (blades & discs) and (iii) graphite (core). The main objectives and activities are as follows.

(i) Vessel

- Review existing materials used in gas-cooled reactors and previous high temperature reactors.
- Setting up 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.

(ii) Turbine

- 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 (C/C) composites, high alloy steels) at temperature and under short and intermediate times in air, vacuum and helium.

(iii) Graphite Core

- 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 C-based materials.

The work is nearing the end of 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.

3. Review of Progress

Materials Database

This is required to cover the three main component areas.

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

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 assembled for each component area to be 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.

Vessel

Design information is needed under HTR conditions. For the vessel two design options exist.

(1) The case where the vessel temperatures are kept at a similar level to the PWR by cooling (this option has been selected for the PBMR).

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

The integrity of the vessel welds is seen as the main structural issue. Fracture, fatigue and creep-fatigue (depending on temperature) are the main damage mechanisms with compatibility aspects (metal loss and carburisation) not expected to have a significant impact on material choice. The programme on the vessel material is focused on qualification through a series of tests on welded joints under irradiated and non-irradiated conditions. The intent is to pre-irradiate specimens in the High Flux Reactor (HFR) at Petten and then to perform a series of tests under controlled conditions in order to determine the effect of irradiation on properties.

The vessel review work concentrates on materials used in new and developing plants to make sure that the most up to date vessel steels are considered. Design Codes such as ASME and RCC-MR have been examined from the point of view of availability of properties (joint coefficients, fast fracture, LBB) and procedures. Some improvements are deemed necessary to confirm their suitability for the HTR application. The property information on vessel steels is being assembled throughout the duration of the project for inclusion in the database. Such materials as C-Mn steels (as used in the UK Magnox and AGR types), SA 508 Grade 3 Class 1 (LWR) or its European equivalent, 2¼Cr 1Mo steel as used on HTTR and modified 9Cr 1Mo. The database will cover provisions, products & parts, test results, design data and effect of environment. Significant amounts of data exist for these steels and the main focus is on comparisons and assembling relevant design data.

The project resources allow one type of vessel steel to be irradiated. Modified 9Cr 1Mo was considered to have the most uncertainty on data and fabrication experience with respect to HTR and also potentially to have a wider applicability and was selected for the test programme in the High Flux Reactor (HFR). The irradiation tests involve the use of the Lyra test rig, which allows accurate control of the temperatures and use of a helium atmosphere. The heaters in the rig are 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 plates. 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 is considered, as high temperatures are expected 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 is well underway. Test programme details are expected to be finalised shortly to allow the commencement of the irradiation tests early in 2003.

High Temperature Materials

The work on high temperature materials concentrates on alloys for the blade and disc of the turbine and C/C composites for the control rod. These areas are seen as presenting the most difficult challenges with respect to reliability and endurance in the hot flowing helium gas environment. For the turbine, the most critical part is the first stage discs and blades. The most promising grades are to be investigated within the HTR-M contract using short term mechanical tests (tensile, fatigue, short term creep and creep / fatigue tests (in air, vacuum, helium) and within HTR-M1 with intermediate term creep tests to confirm suitability for longer-term high temperature exposure. The tests are to cover specific grades, fabrication routes, and heat treatments. Tests on aged material and damage analysis for lifetime modeling are also included. For the control rod the main aim is to assess the potential of C/C composites and to gain experience in the behaviour of these materials at temperature. Only non-irradiated tests are planned within the HTR-M project. Tests under irradiated conditions will be considered at a future date possibly within a future framework programme.

The review work on turbine disc and blade materials short listed five disc materials and thirteen blade materials for inclusion in the database. For the disc, few materials have the potential of meeting the manufacturing requirement and the high temperature endurance strength (60,000h) necessary for an un-cooled design. Discussions with a turbine materials manufacturer have identified potential candidates for temperatures of around 700^{o}C but it is unlikely they will have the necessary endurance strength at 850^{o}C. The review considered UDIMET 720 as the best available candidate. Manufacturing considerations are a key factor and 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. For the turbine blade materials the current view is to avoid single crystal materials for the blades and test two grades of material (IN 792 DS, CM 247 LC DS) under tensile and creep conditions, at temperatures up to 850^{o}C.

The review of available C/C composite materials for the control rod identified a range of information under irradiated and non-irradiated conditions. The main source of information coming from Fusion applications particularly with respect to thermal properties. The review showed that properties of many C/C composites were largely an-isotropic. Also for C/C composites as with all carbon based materials (i.e. graphites), property values can be severely degraded by neutron irradiation, the level of degradation being dependent on irradiation condition and temperature.

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.

For the turbine materials, decisions on procurement of material have been taken and short-term experiments are expected to start late 2002. Intermediate creep testing of material is also planned to start in 2002 or early 2003 under the HTR-M1 project to maximise the amount of testing time available. 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). For the C/C composite the test programme is still under review pending the decision on identification of a suitable supplier and the procurement of representative material.

Graphite

Graphite has been used as a neutron moderator in a variety of reactors. These include the Magnox Reactors, Advanced Gas-cooled Reactors (AGRs), High Temperature Reactors (HTRs), RBMKs, Research Reactors and Materials Testing Reactors (MTRs). The amount of nuclear grade graphite currently manufactured worldwide is relatively small. The properties of graphite in a reactor environment have been extensively studied since the early 1940s and a good understanding of the significant and complex property changes that 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 available. In addition, most of the irradiation temperatures investigated will have been <550^{o}C, whereas for HTRs the graphite temperatures will be >550^{o}C. The behaviour of currently available graphites will therefore have to be determined by experiments in a MTR over the appropriate irradiation dose and temperature range. In the past, only a small number of irradiation programmes were aimed at determining the irradiation behaviour of graphites at high temperatures, i.e. >600^{o}C. Two of the most significant were for the European Dragon HTR programme, and the German HTR programme. For the review and database work on graphite properties the available information from these two programmes and the IAEA database have been considered.

The work on the selection of graphites and for the experimental programme to be performed within the HTR-M1 project is well advanced. The HTR-M1 project will test a small number of graphite types that are to be irradiated within the HFR to identify changes in properties. Work is in hand to set the characteristics of the test programme and numbers of tests to be performed, shortlist the types of graphites and characterise specimens ready for irradiation testing. Two main graphite suppliers have been involved in this selection process and are fully supportive of the tests being planned.

The work on graphite oxidation involves tests in the THERA and INDEX facilities at FZJ. This work is nearing completion with some results in air and steam available. Measurements have been taken on the kinetics of graphite for temperatures between 550 and 750^{o}C and partial pressures of between 2 and 20kPa in air and between 900 and 980°C at $P_{[H2O]}$ =1 in steam. This includes oxidation resistance of three-selected Carbon-Fibre-Composites (CFCs) developed for the fusion reactor also being measured. Experiments have also been carried out to determine the thermal conductivity of CFC materials in irradiated and non-irradiated samples.

Summary and Conclusions

This paper discusses results of some of the mid term results from the materials projects HTR-M & M1 within the EU Fifth Framework programme. Overall the project is progressing well with review and database investigations and planning for experiments well advanced. Graphite oxidation experiments are nearing completion and results are available. The next phase of the work will focus on the planned experiments and the irradiation of samples in the HFR. The expectation is to start the experiments as early as possible to maximise the value of the time dependent data to be obtained.

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