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Materials for the Very High Temperature Reactor – results and progress within the Fifth and Sixth Framework Programmes

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Abstract. The Very High Temperature Reactor (VHTR) is one of six advanced fission systems of interest for meeting the Generation IV goals of attaining highly economic, safe, reliable, sustainable, proliferation-resistant systems. The VHTR offers significant advantages for long-term development of sustainable energy and for use in heat applications and can operate with either a direct or indirect cycle. Work on materials for the HTR and VHTR within Europe recommenced with the EU Fifth Framework Programme (5FP) projects HTR-M & M1 [1] and together with other 5FP projects (fuel, reactor physics, components, safety,..) and the establishment of the European High Temperature Reactor Technology Network HTR-TN, served as the main European platform for the coordination and development of HTR and VHTR issues.

The HTR-M & M1 projects addressed material requirements for the key components of the direct cycle HTR. The work specifically focussed on materials development for the pressure vessel, high temperature components (including turbine), and the graphite core. Alongside this, developments were undertaken on key component issues (HTR-E) associated with the gas turbine, the recuperator, and other system developments (e.g. tribology, corrosion, bearings, seals, etc.) concerned the operation and performance of the power circuit components. Within this paper the main highlights from the results of the 5FP programmes affecting material issues are reviewed and examined.

For the 6th Framework activities the main European research focus on VHTR is through the RAPHAEL-IP. The project was started in 2005 and addresses a range of issues (materials, components, fuel, code qualification, etc.), which are structured in a similar way to the corresponding GIF VHTR projects. The materials issues are addressed within one of the RAPHAEL-IP sub-projects with a focus on outstanding issues. The main emphasis on materials is for graphite development, materials for the heat exchangers, continuation of vessel qualification and work on design code requirements. The progress of the materials issues within the RAPHAEL-IP, which is now in its fourth year, will also be reviewed and the expected future orientations of the programme described.

During the RAPHAEL-IP a close link with the fission investigations within the EXTREMAT-IP has been possible. In particular the material needs of the VHTR have been brought to the EXTREMAT-IP with a view to investigating the potential of future advanced materials that could be used in the VHTR environment. Specifically work on carbon-carbon composite materials for the reactor control rod, the potential of high strength alloys for the heat exchanger and core support and graphites have been investigated within EXTREMAT for fission application. The progress and results from this exchange together with other potential spin-off benefits are also summarised in this paper.

1. Introduction. The VHTR modular reactor offers major advantages for long-term development of sustainable energy, such as heat applications and hydrogen generation. For Generation IV type reactors it is important to have a good understanding of the limits of the materials used and the behaviour of the main components. This paper aims to summarise the main achievements gained in the area of HTR component development within the Fifth Framework Programme (5FP) Projects

HTR-M, M1 and HTR-E [1-2], and the 6FP RAPHAEL-IP and to identify possible future activities in a future frame for the VHTR.

2. Material Development for the VHTR. The areas of work on materials development covered by the HTR-M & M1 and RAPHAEL IP are as follows [3]:

- Reactor Pressure Vessel
    - Review and database actions covering existing and new vessel material options
    - Tests on Mod 9Cr 1Mo steel welded joints under irradiated and non-irradiated conditions to determine suitability for vessel application. Investigation on the effects of aging.

Fabrication and the effects of irradiation/environment on the HTR vessel weld behaviour are crucial issues in terms of structural viability. These have been addressed in the programmes and provide key results for material selection development and qualification.

- High temperature materials (inc. turbine)
    - Review and database actions for the control rod and turbine
    - Review and database actions for the heat exchangers
    - Tests on selected materials (carbon fibre reinforced carbon (C/C) composites, high alloy steels) at temperature and under short and intermediate times in air, effects of aging and simulated carburising and de-carburising environments (Fig 1.)

Temperatures and environmental degradation are the main concerns for the direct and indirect cycle options. Fabrication, creep and the effect of helium on properties and strength are assessed for the materials investigated. Fabrication and effects of irradiation/environment are crucial issues for C-based materials seen as future candidates for control rods. Recommendations are made for future investigations and tests and for other component applications.

(a) (b)

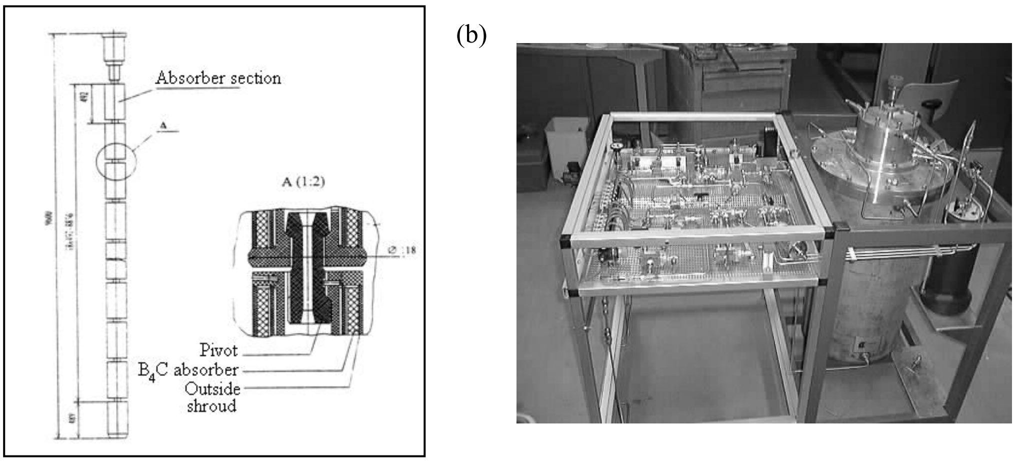

Figure 1: (a) Carbon fibre application to control rod (b) Carburisation test rig.

- Graphite core
    - Review of experience plus data base action for new graphites
    - Oxidation tests on graphites and C composites plus assessment of protective coatings
    - Selection of most promising currently available graphites and irradiation testing 750ºC plus testing at higher temperature (~950ºC)
    - Microstructural modelling & guidelines development [4]

These graphite actions are seen as important first steps in qualifying new graphites for future HTR and VHTR application, given that almost all the graphites previously irradiated are no longer manufactured. Recommendations are made with respect to a graphite selection strategy and the need for international collaboration (Fig. 2).

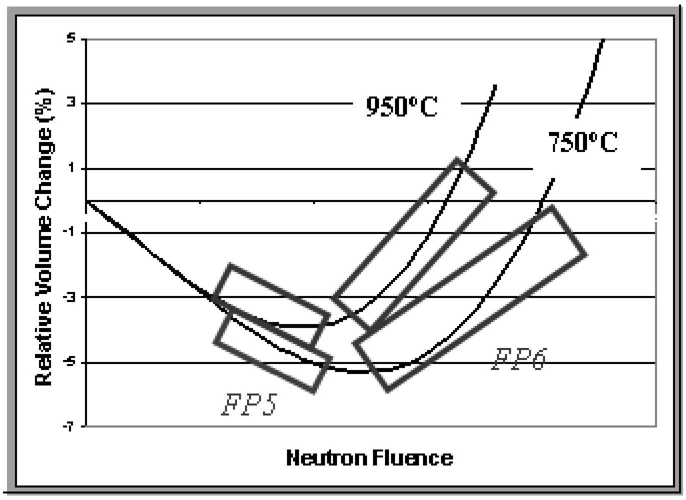

Figure 2: Stages in graphite irradiation tests

3. Component activities affecting material selection.

a) The Fifth Framework Project HTR-E was started at the beginning of 2002 with 14 partners. The main objective was to develop key components and systems needed for the HTR, which were selected by reference to existing projects at the time that envisaged a direct cycle concept (GT-MHR, PBMR). The main components and systems selected for the HTR-E were as follows:

- Helium Turbine
  Review of past experiences and feasibility of using a high efficiency helium turbine, inserted in the primary cycle. The feasibility of the helium turbine within the direct cycle is the most important technological issue for the components of the modern HTR. Although it is not safety classified, in the case of any potential incident causing deblading any fragments from the discs or blades have to be confined within the pressure containment.

- Recuperator
  Investigation of plate-type recuperator and testing of a mock up. The function of the recuperator is to recuperate a part of the remaining energy at the turbine outlet to preheat the helium at the core inlet, thus maintaining thermal efficiency. It is essentially a helium/helium heat exchanger inserted in the primary circuit.

- Tribology
  Review of past experience and development of facilities and representative tests on coatings and base materials. Sliding components (e.g. stator seal, hot gas duct seal…) of a modern HTR with a direct cycle are of particular concern, since sliding components can have a dramatic impact on the safety and availability of the reactor.

b) Component activities in RAPHAEL IP were initiated in April 2005, the main objective of the Sub-Project on Component Development (SP-CT) of RAPHAEL IP was to further develop innovative technologies needed for the main components and systems of a VHTR. The FP5 addressed the development of the components of a direct cycle. This sub-project addressed conceptual designs for key components of the indirect cycle. The effort was focused on the most challenging components:

- The Intermediate Heat eXchanger (IHX): the compactness for both tube and/or plate concepts and their integrity under the load. This is a real challenge since it is beyond existing industrial experience;
- Hot helium valves: the role is to isolate the reactor in case of failure of the IHX. Design studies based on past experience in Germany and from the AGR (UK) and existing technologies will be performed;
- Gas circulator: the design will be focused on large power for a 600 MWth reactor with low power consumption. Magnetic bearings will also be developed and tested in an IPM Zittau facility.

Moreover tribology and corrosion phenomena are key issues in the selection of materials and the design, operation and lifetime of components and systems in the helium atmosphere. Therefore a programme has been undertaken to study these phenomena for the different situations to be considered in the system focussing on VHTR conditions, which were not covered in the FP5 programme, in particular the graphite/metal, graphite/graphite and ceramic contacts that will be tested under closer representative conditions [3].

4. Conclusion & Summary. The main objectives for the HTR-M & M1 and the materials part of the RAPHAEL project was the substantiation and development of a materials platform in terms of data and re-instatement of materials knowledge and experimental capabilities in three key technological areas important to HTR and VHTR feasibility, namely for reactor vessel steels, high temperature materials, and the graphite core. Alongside these, issues connected with Codes and Standards development have also been addressed. The work on the vessel welds provides the first available results in terms of fabrication and influence of HTR irradiation levels on the properties of Mod 9Cr 1Mo steel for HTR and VHTR reactor pressure vessel application. The activities on high temperature materials for the turbine (and later for the IHX) have advanced understanding of the material requirements for such applications in terms of behaviour and the implications of corrosion on properties. The work on the graphite has helped to focus manufacturers and international graphite specialist’s attention on developing new materials for the reactor core. The results from the combined HTR-M1 programmes plus the follow-on tests in the 6th Framework Programme RAPHAEL are likely to be the only main source of full life fluence data available at 750^{o}C and 950^{o}C for application to the core design. Overall the results from these projects represents an important contribution to HTR and VHTR materials advancement and a valuable contribution to materials development within Europe and the Generation IV International Forum, and International Codes & Standards.

4. Acknowledgement. Acknowledgement is given to the contributions from HTR-M & M1 and RAPHAEL partners and the European Commission.

5. References

[1] D. Buckthorpe et al.; Materials for the VHTR: Progress of HTR-M & M1 Projects, EUROMAT05, Prague (Czech. Republic), 2005.
[2] E. Breuil, D. Besson (Framatome ANP). HTR-E project. High-Temperature Reactor Components & Systems. Last results from HTR-E project. Beijing (China), September 22-24, 2004.
[3] D. Buckthorpe et al.; Materials and Components highlights from the HTR FP5 and FP6 Programmes, ICAPP 2007, Nice (France), May 13-18 2007.
[4] J. Ali, C. Berre, P. Mummery: *Energy Materials*, 2006, **37**, pp 361-373