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Material Challenges of the new Advanced Gas Cooled Systems

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1 ABSTRACT

For new Generation IV gas cooled systems such as the HTR/ VHTR and the GCFR, industrially established materials are at, or near, their limits in certain applications and new materials and an understanding of the behaviour of existing materials under more severe environmental reactor conditions are required. For these systems, metals, ODS alloys, ferritic-martensitic steels, and some super-alloys offer solutions but some require significant R & D in terms of their properties and behaviour under component conditions. Such systems may also require the deployment of non-metallic materials (e.g. high-temperature fibrous insulation, composites and ceramics) as alternatives to metals for different applications and components. The present understanding and progress in interpreting and establishing property and behaviour information on these materials for the VHTR and GFR systems is reviewed together with key findings from experimental work undertaken in the RAPHAEL and EXTREMAT EU 6th Framework projects. Cross-cut information from similar situations in Fusion is also considered. The paper summarises the main achievements so far and the needs in terms of future R & D activities in Europe for these systems, taking account of expected inputs from the Generation IV International programmes and from ongoing national programmes.

2 INTRODUCTION

Gas Cooled Reactor (GCR) projects have been launched within the European Union Framework Programmes (FP's) to consolidate and advance the very high temperature reactor (VHTR) and gas cooled fast reactor (GCFR) technologies within Europe. The VHTR and GCFR are two of six advanced fission systems of interest for meeting the Generation IV goals of attaining highly economic, safe, reliable, sustainable, proliferation-resistant systems. Previous programme details and intermediate results have been presented for the HTR system (Buckthorpe, 2003). The modular HTR/VHTR offers significant advantages for the longer-term development of sustainable energy and in particular for heat and process applications and hydrogen generation. The GCFR combines fast neutrons and high temperature and proposes an attractive alternative to liquid metal cooling for fast neutron reactors, with advantages associated with helium properties, safety (favourable reactivity effects) and in service inspections (optical transparency). In the GFR development plan the Experimental Technical Demonstration Reactor (ETDR) is an important first step towards an electricity-generating prototype which has a planned operation around 2020 and is expected to progress towards the development of a much larger demonstrator for around 2030. The (V)HTR

demonstration on the other hand is potentially much nearer term and in addition to further component technology development, there is also an important need (which is being addressed in the 7th Framework project, EUROPAIRS) to investigate the coupling requirements of potential process heat applications and encourage the direct involvement of process industries.

For the 6th Framework activities the main European research focus on VHTR has been through the RAPHAEL-IP and to a lesser extent within the EXTREMAT –IP. The RAPHAEL project started in 2005 following on from a series of smaller technology focussed projects on fuel, safety, materials, components aimed at consolidating past knowledge and providing a platform for future development. The RAPHAEL-IP addresses a range of issues (materials, components, fuel, code qualification, etc.) in one single project and is structured in a similar way to the corresponding GIF VHTR projects. The materials issues are addressed within one of the RAPHAEL sub-projects with a focus on outstanding issues for the reactor core, the vessel and the heat carrying/ generating components. The GCFR investigations in the 6th Framework were performed through a GCFR STREP launched in 2005 to address design and safety challenges and the qualification and benchmarking of numerical codes for transient analysis. Material requirements were not specifically investigated, as these came through a collaboration with the VHTR activities (RAPAHEL) with respect to main circuit and its components and through some specific advanced material developments (for components such as the control rod) within the EXTREMAT-IP. The GCFR requirements for the core are being addressed in a future 7th Framework proposal, GofastR.

The materials involved include composites, metallics and high temperature resistant alloys and ceramics. This paper will review the findings from these past Framework Programmes and discuss the major materials challenges that lie ahead for these systems.

3 MATERIALS FINDINGS AND CHALLENGES FOR THE REACTOR BLOCK

Key reactor block components include those associated with containment or confinement of the coolant and the support and functioning of the reactor core. The materials within the reactor unit have to withstand high levels of neutron fluence and temperature. Normal operating temperatures range from room temperature up to around 850°C and are higher (<1600°C) under accident conditions. The irradiation levels vary from <1 for VHTR to 1 to 2 dpa for GFR outside the neutron shielding layers and from 6 to 25dpa for the control rod and core components of the VHTR and 150 dpa for the core and fuel cladding of the GCR (163 dpa for the SiC). Helium gas is used as the coolant for both systems hence the materials have to be tolerant to this atmosphere.

3.1 VHTR core

The core is a key component that affects safety and operability of the reactor. For the HTR the material used is graphite. It provides structural support, coolant channels, moderation, and shielding while operating in a high temperature helium environment. Its performance is critically dependent on the graphite properties, which are irradiation dependent. The most important considerations are component integrity and changes in core geometry, both of which are affected by the dimensional change. Many of the graphites used in previous core designs are no longer available and there has been a serious decline in ability to manufacture nuclear grade graphite in large quantities, the main questions concern the availability of the coke and the manufacturing procedure. Current HTR projects - HTTR (Japan) and HTR-10 (China) - use a Japanese graphite (IG-110), which, with its high strength, is suitable for exchangeable core components where low fast neutron fluences and hence low total fluxes are applicable.

Work has been performed on the review and collection of graphite properties including the accessible information on the IAEA database, internal information, and published information at seminars and conferences. The data relevant to the irradiation temperature and neutron fluence domains for new HTR's will however largely come from new tests and be built up for each graphite grade and sample orientation. These will need to contain information on the graphite grade, manufacturer, coke source, grain size, and manufacturing method. For nuclear applications, the graphite has to be as free as possible from impurities since these will become activated during the operating life of the reactor leading to operational problems, as well as decommissioning and final disposal problems. Most impurities, however, are volatile and so disappear during graphitization. The selection of nuclear grade graphite for the next demonstration HTR's will necessarily involve the present day graphite suppliers and within the RAPHAEL materials programme,

three key suppliers have been involved and have recommended major and minor graphite grades for investigation (see Table 1).

Table 1: Selected graphite grades: a) major and b) minor grades

Grade	Manufacturer	Coke	Process
PCEA	GrafTech	Petroleum	Extrusion
PPEA	GrafTech	Pitch	Extrusion
NGB-10	SGL	Pitch	Extrusion
NBG-18	SGL	Pitch	Vibro-moulding

a) major

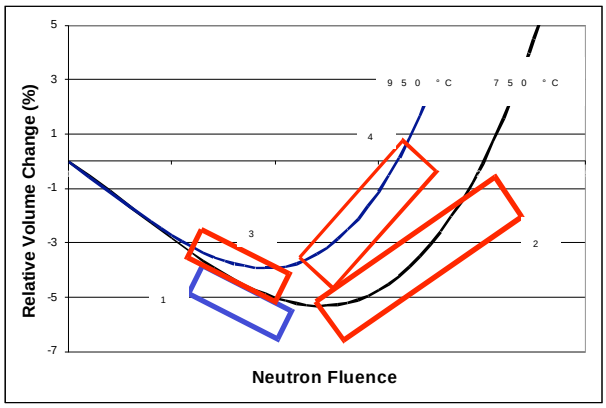
Grade	Manufacturer	Coke	Process
PCIB-SFG	GrafTech	Petroleum	Iso-moulding
BAN	GrafTech	Needle	Extrusion
NBG-25	SGL	Petroleum	Iso-moulding
NBG-17	SGL	Pitch	Vibro-moulding
IG-110	Toyo Tanso	Petroleum	Iso-moulding
IG-430	Toyo Tanso	Pitch	Iso-Moulding

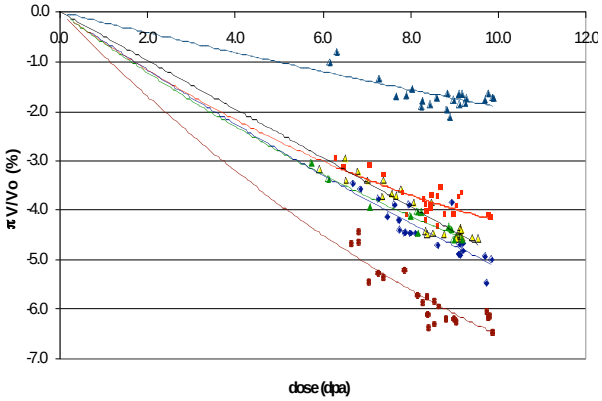
b) minor

The EU HTR Programme was therefore established to include test work on these and other graphites covering graphite irradiation, graphite oxidation (including coatings used for pebble bed graphites), micro-structural modelling and the development of guidelines for design. Available commercial graphite grades were investigated and selected and irradiation tested in the HFR at Petten to develop curves of irradiated properties, which can be used for design and to confirm selection. The selection of the graphite grades for the test programmes was based on factors such as properties, impurity levels and availability. Five major grades were chosen for the first test so as to cover a variety of microstructures, raw materials (coal tar, pitch coke, and petroleum coke) and manufacturing methods (extrusion and iso-moulding). Three graphite manufacturers were approached Graftech and SGL, who are major graphite suppliers in Europe, and Toyo Tanso, who is a major graphite supplier in the far-east. The latter provided IG 110 samples (to be used as a reference) and IG 430 samples for comparison. From discussions a test programme was identified as presented below and summarised in Figure 1.

For an HTR, the temperature range of interest for the main structural core graphite was considered to be between 550-950^{o}C. The peak fluence will be at around the mid-range temperature of 750^{o}C and so this was chosen for the first experiment. An additional higher temperature was also needed for VHTR requirements and the nominal temperature for these tests was defined as 950^{o}C. Within the experiments provision was made for including intermediate temperatures of approximately 100^{o}C lower so that some additional indications of behaviour at other temperatures could be obtained. The irradiation of the graphite samples was carried out using the INNOGRAPH test rig (four and three column designs were used depending on temperature), inserted in the core of the HFR. The rig design requires the stacking of up to 150 samples, 8mm diameter (either 6 or 12mm in height), covering the two main directions parallel and perpendicular with grain (15 samples per grade per direction). The specimens were placed in four stacks with 60mm stacking height per drum and separated from surrounding TZM alloy with graphite foils. Characterization tests were carried out prior to loading in the test rig to determine properties before irradiation.

The maximum dose of interest was considered to be around 25 dpa (estimated end of life dose for the pebble bed design) at 750^{o}C and 16 dpa at 950^{o}C. One irradiation would only give information between 16 to 25dpa (at 750^{o}C) taking account of the radiation buckling distribution of the HFR reactor, which would be insufficient to construct a design curve. It was decided therefore to have two irradiation experiments to produce each design curve. The first experiment was targeted at 1/3rd of the maximum dose and the second , which contains fresh un-irradiated samples and irradiated samples from the first experiment is targeted at two thirds of end of life dose. In this way data is generated at a 1/3, 2/3 and 3/3 of end of life dose and data points between these levels will be obtained by making use of the flux buckling of the reactor. The first test was not expected to yield properties up to 'turn round' behaviour but provided information on whether the graphite is useful or not thereby providing a first sorting of the available graphites and as the experiment progressed there is the possibility of replacing those that are unsuitable with alternatives.





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1. INNOGRAPH - 1A: 750°C, low/medium dose (FP5)
2. INNOGRAPH - 1B: 750°C, high dose
3. INNOGRAPH - 2A: 950°C, low/medium dose
4. INNOGRAPH - 2B: 950°C, high dose

Results form the INNOGRAPH 1A experiment

Figure. 1 Graphite Irradiation tests in RAPHAEL

The irradiation programme was performed on selected graphites to determine the variations in their physical and mechanical properties (dimensional change, Youngs' Modulus, thermal expansion coefficient, conductivity) over low/ medium/ high irradiation dose. PIE investigations have been completed on specimens from the INNOGRAPH 1A and 2A experiments and the phase 2 experiments are currently within HFR and expected to complete their irradiations by the spring of 2010. The achievement of these first phase tests and the insertion of the second phase experiments in the reactor was a major milestone in this work and for the substantiation of graphite selection for an HTR in Europe. The work is also a major input to the collaborative programme of the Generation IV International Forum. Alongside this work, investigations on the oxidation potential and micro-structural modelling of the different graphite grades within these experiments has also been performed to help understand behaviour and to provide appropriate selection criteria from which the development of future processes and graphite grades can be based. The results from the RAPHAEL programme are likely to provide the only high dose results for the current grades of available graphites in the foreseeable future and will become an important set of results on which future developments will be based. Codes and Standards developments are underway within ASME and this will be an important need for future acceptance and development of these developing graphite grades. The challenge for the HTR core will be the development of graphites in sufficient quantities with appropriate properties and irradiation behaviour capable of providing the required security of supply for a large numbers of modular HTR's able to meet the requirements of the process heat and electricity industries.

3.2 GFR Core

The in-core materials for the GFR range from those considered for liquid metal fast reactors (LMFR's) such as chromium and nickel based austenitic steels (M316, CW 316 Ti, CW-15-15Ti), high nickel alloy steels (e.g.PE16) and ferritic-martensitic and ODS steels (EM12, FV548, W.Nr.1.4914) to materials such as SiC, ceramic + ceramic fibres which are being considered as possible alternatives. For GFR assemblies a selection of ceramics, monolithic or composites (associating two ceramics or one ceramic and one metal) are also possible. The selection of these materials presupposes studies in manufacturing, joining, characterizing and controlling these materials (microstructure, thermal and mechanical properties, corrosion resistance, etc.). The same range of studies is needed for the reflector material, for which a candidate is an intermetallic compound of Zr and Si. The fuel clads for the GFRs will have to withstand operating temperatures of between 850 to 1600^{o}C and high fast neutron fluences (doses up to 150 dpa). Swelling behaviour and embrittlement, permeation of rare gases, helium, diffusion of volatiles, semi-volatiles, non volatiles are concerns specific to the clad which for the GFR application needs to have a lifetime minimum of around 6 years and be dimensionally stable and resistant to creep damage. All of these materials are required to be manufactured (and quality controlled) in the form of streamlined items, which should show a minimal toughness, and be able to be applied to the inlet as well as at outlet core temperatures. The development of suitable materials and manufacturable core components for the GFR core is a key challenge for European Research and the much larger International Generation IV programme.

3.3 Materials for the Control Rod

The control rod compensates for fuel burn-up and power variation reactivity effects and is used to control the reactor operation under normal operating modes as well as shut down the reactor system when required. Control rod materials have to withstand high gas temperatures, high irradiation fluence levels and resist the thermal strains arising from power changes and load following requirements. For the VHTR and GFR control rod metallic materials can be at or near their operational limit with regard to environment and design code acceptance. Within the RAPHAEL and EXTREMAT EU programmes collaborative actions have been focussing on the development of a suitable composite material that could replace the first choice Incoloy 800H material where its limits are exceeded. These collaborative actions have been in form of development and investigation (in conjunction with a manufacturer) of the effects of architecture (with respect to fluence and temperature) through experimental and micro-structural modelling. The activities within RAPHAEL and EXTREMAT have been complimentary providing the opportunity to study the selection criteria and perform preliminary experimentation. The EXTREMAT investigations also cover a much wider scope of applications which includes feedback from specific fusion and non-nuclear (e.g. space) developments as well as providing the opportunity for irradiation testing (which is due to be completed in 2010) at temperatures up to 900^{o}C and examination of some initial materials. The control rod for the GFR operates at lower temperatures than the VHTR but higher levels of irradiation and the challenge within the EU and Generation IV programmes is to develop a diversity of options capable of meeting the range of temperature and irradiation conditions for these systems which is likely to include both metallic (HTR) and carbon based (VHTR and GFR) alternatives.

3.4 Reactor Pressure Vessel

For the reactor pressure vessels (RPV) assurance of safety is of paramount importance. Key issues for the RPV are manufacture and welds and resistance to irradiation. HTR and GFR vessel materials can operate at temperatures higher than 450^{o}C and information on materials behaviour during manufacture, in the operating environment (neutron-irradiation fluence, operational temperature, and helium environment) and for welding are needed for assurance of integrity. The main safety and structural integrity concerns for the RPV are at the vessel welds, at thicker sections, hot spots, the belt line and regions important to functionality. Fracture, fatigue and creep-fatigue (depending on temperature) are the main damage mechanisms and degradation mechanisms (irradiation, thermal aging and corrosion) the main environmental considerations. Most designs of future plant for the VHTR make use of the either an LWR type steel or a Cr-Mo type steel. These materials have similar strength levels at temperatures up to 370°C. Two vessel options have been considered in the technological survey for the VHTR system namely a cooled option similar to PBMR (using a ferritic material similar to that adopted for LWR's) with temperatures are kept at LWR temperatures and a non-cooled option similar to ANTARES (the choice of Cr-Mo steels with modified 9Cr-1Mo steel grades similar to ASME Grade 91 as the prime candidate) where the vessel experiences normal operating temperatures similar to the inlet gas temperature which is held below the creep limiting temperature of the material (around 400- 425^{o}C). Note that Mod 9Cr1Mo steel allows for higher temperatures with only a gradual reduction in design strength at temperatures up to 450°C and above 450°C allowable stresses for all materials fall off rapidly.

The effects of irradiation on the toughness of LWR steels have been studied extensively, the major effect being an increase in the ductile brittle transition temperature (DBTT) due to the combined effects of matrix hardening and grain boundary weakening associated mainly with the residual elements P and Cu. For warm vessel options, no data were available for Mod 9Cr 1Mo steel irradiated under conditions expected for the HTR. However information at much higher doses (≥1dpa) concluded that there is an important effect of irradiation temperature in the range 250-450°C. There was no information on the behaviour of modified 9Cr-1Mo steel welds at the irradiation dose levels expected for the HTR and GFR systems.

The work of HTR-M and latterly RAPHAEL has been to investigate the effects of irradiation and environment on representative RPV Mod 9Cr 1Mo steel welds to check the effects of HTR levels of irradiation on weld strength. The research and development included the manufacture of thick section (150 mm) weld sections manufactured using a narrow gap TIG process with a double V weld preparation and post weld heat treatment. At first this showed a significant number of micro-cracks in the weld metal, which were neither expected (the selected filler had the lowest tendency to hot cracking among the products tested) nor detected initially but seen when performing a micrographic examination. These heat cracks in parts of the weld were later eliminated through adjustments to the welding procedure. This fabrication work

represented a significant achievement and step forward in using this material for the HTR vessel and showed the importance of optimising the filler material composition and welding procedures to avoid cracking and to maximize strength. Subsequent development work continued and was able to explain the reasons for the phenomenon and to help with the selection of a future filler material that would avoid the problem.

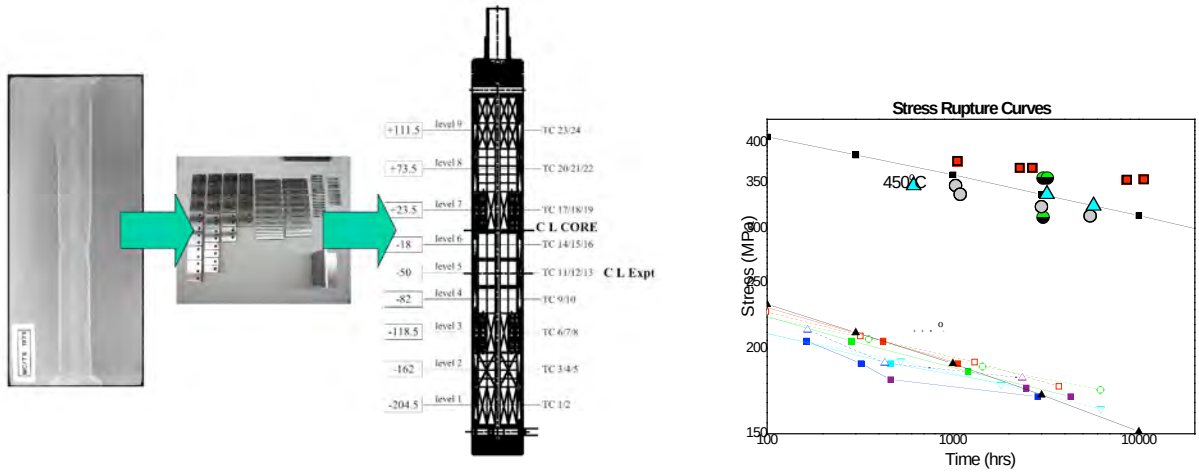

Figure. 2 Irradiation (LYRA) tests in HFR

Specimens were cut from the weld and tested in the main stress directions with tests carried out both for the reference condition and End of Life (EOL) conditions. The mechanical tests included impact, tensile, creep and facture toughness (CT) tests. Four conditions were selected: plate material in the parallel and perpendicular directions (with respect to rolling), the heat affected zone (HAZ), and the weld metal (WM). The specimens were loaded into the LYRA test facility and the irradiation, which was started at the beginning of 2004 and took place in the poolside facility of the High Flux Reactor (HFR) at Petten was carried out at a temperature of 375°C and an average fluence of $9.44 \cdot 10^{22}$ n/m^2, E>0.1 MeV (~5.8 mdpa). Comparisons were made with other available non-irradiated data and also for creep with non-factored values from the RCC-MR Code. The results showed the weld metal to have the highest ductility and the cross weld (CW) specimens the lowest. The only systematic influence of the irradiation was seen in the CW tests where testing times were longer and minimum strain rates lower. The work confirmed the effects of irradiation to be small for the range of HAZ, WM and cross weld tests covered and also that the RCC-MR weld factor Jr = 0.9 for Mod 9Cr 1 Mo steel weldments was applicable to these tests.

Sixteen pre-irradiated specimens were held over for the RAPHAEL-IP programme and creep tests were performed (with and without irradiation effects) at 450°C to cover conditions closer to normal operating or design (and negligible creep) conditions and to provide confirmation that the effects of irradiation on creep strength are still negligible at this condition. The results showed again that the changes due to the irradiation were within the batch to batch variations of the material. The results from the base metals tests and the weld tests also showed (as previously) the base-metal results to be above the RCC-MR minimum curve with a different slope for both reference and irradiated material. Also (as previously) the weld metal specimens and the cross weld specimens are below the RCC-MR minimum curve (Figure 2). Translating these results to GFR will be dependent on the extent of shielding used in the design and the threshold level above which the effects of irradiation become significant. It is likely that repeat tests may be needed when GFR vessel and core design parameters are set.

With regard to the effects of aging, the most likely location of concern is the coarse-grained HAZ. Cold vessels operate at temperatures below the aging embrittlement range and so aging might only be important during transients involving exposure to higher temperatures for tens or hundreds of hours. Warm vessels however may be more prone to aging throughout their lifetime and therefore this is of greater concern to vessel integrity. Within RAPHAEL aging tests have been performed on Mod 9Cr 1Mo at 450°C for up to 5000h with impact and tensile tests carried out at ambient and at the temperature of the heat treatment to assess the effects of the aging on strength. The results show good behaviour for the welded joint with no significant difference between the PWHT microstructure and the microstructure after aging for 5000 h at 450°C. With regard to other environmental effects such as vessel metal losses due to either controlled carburisation in cold wall vessels and decarburisation combined with internal oxidation in warm wall vessels (as a results of helium impurities) these are considered less important given a beltline wall thickness in the

range 140-200mm. Metal loss is only likely to become significant if breakaway corrosion or metal dusting can occur which is considered unlikely in HTR or GFR helium conditions.

To help develop models on weld behaviour a series of creep tests have been performed in RAPHAEL on reduced scale cylinders that feature a representative mid height circumferential weld which are loaded under internal gas pressure (150 bar) and at elevated temperature (625°C). The tests will aim to provide a more accurate interpretation of weldment creep factor, which is dependent on loadings and geometry and to build on the results of the small specimen tests already performed. Two base metal (a thermal mock-up and a reference mock-up) and two circumferentially welded samples were tested and all except the thermal mock-up failed following leak detection, with longitudinal cracks located in the welded zone for samples bearing a circumferential joint. The temperature gradients were also found to be more significant than expected. The variation in temperature (around the circumference) of around 5°C had a larger effect on behaviour than the presence of the weld. The results have been assessed against small specimen data and using 2-D and 3-D Finite Element to model an understanding of behaviour and conclusions were reached with regard to modelling interpretations and future testing. The thickness of the tube and width of the HAZ are key parameters driving the size effect on creep life of the welded cylinder at 625°C.

In terms of challenges of RPV materials for gas cooled systems, the development using Mod 9Cr 1 Mo steel for the HTR vessel is well advanced however future effort should concentrate on very representative samples, with the base material ideally from prototype forged parts and the welded joints representative of HTR/VHTR and GFR vessel fabrication route with regard to weld metal properties and welding procedures. In addition effort needs to be channelled towards inspection issues and in particular inspection of welds and In Service Inspection (ISI) requirements. Such methods for thick section Mod 9Cr Cr1Mo steel plate and forgings will need to be developed, as currently most applications for this material are in thin sections such as for heat exchangers. Such NDE method development is considered a high priority by Regulators and will be particularly important to demonstrate a first of a kind vessel.

3.5 Reactor Internals

For the internal reactor components (core support and core barrel) austenitic stainless steels and Mod 9Cr-Mo alloys are currently the most promising for temperatures up to 550-650°C in view of their previous experience in LMFR's. Other possible materials include Oxide Dispersion Strengthened (ODS) steels but these require significant research and development. For the GFR (as for HTR and VHTR), the components used to support the core would normally be designed to operate below the material creep threshold temperature (370-400°C) whereas for the core barrel, this could operate at much higher temperatures reaching levels above 850°C for short periods during transients. It is also likely that these two components could be joined (by welding) and therefore required to be of the same material to avoid the sighting of a dissimilar weld in an area that is not capable of inspection. Materials considered for the internals of the VHTR are also expected to be suitable for the GFR, although GFR temperatures are likely to be lower, and levels of irradiation higher. Although the effects of the increased irradiation needs to be assessed in terms of consequences on fracture toughness (core support) and creep strength (core barrel), the difference in conditions is not expected to lead to the need for an improved material for the GFR system. Corrosion due to the impurities within the helium coolant also needs to be assessed, there will be few problems at moderate temperatures but for the higher temperatures of the core barrel this needs to be checked. Work with RAPHAEL and EXTREMAT on ODS steels has focussed on effects of thermal and irradiation creep. At temperatures above about 600°C the usual Norton-behaviour is found, at temperatures below 600°C irradiation can lead to deformation which is almost independent of temperature. Investigations on the latter however using ion implanted thin tensile samples in an accelerator showed that even at 500°C and assuming a total dose rate of 10 dpa /60 years the thermal creep is still expected to be dominant.

4 MATERIALS FINDINGS AND CHALLENGES FOR THE HELIUM CIRCUIT

The main components requiring important material advances include the heat exchangers (Inc. IHX) and the turbine (direct cycle application). Other components such as the circulator and hot gas duct are well developed and will require less material innovation in order to achieve an effective design. For the helium circuit components resistance to temperature and corrosion are key requirements. Maximum temperature levels plus temperature gradients due to transients must not be excessive and although these components are not directly subjected to neutron irradiation, environment induced degradation from impurities in the helium

or due to oxidation can be important. Aging effects too are important for long-term exposure as are welding and fabrication aspects, which are dependent on the individual design details. Within the RAPHAEL and EXTREMAT programmes selection of suitable high temperature materials includes Hot Gas Duct application. The duct is usually insulated to increase efficiency and limit thermal loads. Its lifetime is the same as that of the reactor with normally no repairs or maintenance required except in unforeseen circumstances. Materials considered include high strength alloys such as Alloy 800H, ODS materials and composites. The design can be horizontal or vertical with co-axial flow (hot on inside, cold on the outside) and experience in Germany on past HTR's includes investigation of a ceramic system for temperatures above 900^{o}C and a lifetime in excess of 140,000h. Gas circulation in the GFR and VHTR is required for a number of different purposes (e.g. turbo-compressors / turbo-generators for direct cycle helium gas turbine plants, start-up blower system for the turbo compressor, etc.). For indirect cycles, the design of the gas circulator impeller, electric motor and bearings (e.g. (electromagnetic bearings + catcher bearings and/or permanent magnetic bearings) are important under normal operation and also external loads from the process transients. For the power rotor, benefit can be taken from the materials investigations on the turbine. For the VHTR of 600 MWth a blower power of 10 to 15 MW is required which is much higher than in former HTRs.

4.1 Heat exchangers

This section discusses gas to gas heat exchangers including the IHX and the recuperator. The function of a heat exchanger is to transfer the heat generated from the nuclear fission process through the use of efficient high conductivity materials. Its sizing and fabrication is dependent on issues such as corrosion, corrosion allowance, tube-plate manufacture, joining procedures, etc. as well as compactness and efficiency. The materials have to resist the temperatures, thermal gradients and pressures that give rise to stresses and distortions during normal operation and transients. Both the plate and tube concepts are possible and the design lifetime needs to be comparable with that of the reactor minimising the need for repair or maintenance. The VHTR the GFR heat exchangers are not directly subjected to neutron irradiation but must be compatible with potential applications and for processes where heat has to be delivered at very high temperatures (>850^{o}C) for hydrogen generation this is one of the most challenging components. The recuperator is a gas/gas heat exchanger inserted in the primary circuit to recuperate a part of the remaining energy at the turbine outlet by pre-heating the gas at the core inlet. This component function is to increase the efficiency of the gas cycle as much as possible. Important issues include leak tightness between cold and hot high and low pressure cavities, maintenance of flow path, integrity to avoid failure and debris blocking flow or causing damage to rotating machines further down the circuit. For VHTR under normal operating conditions gas temperature differences between inlet and outlet are around 380-430^{o}C and pressure: 40-60bar. Under transient conditions maximum temperatures can reach 650^{o}C and pressure differences 70bar. The recuperator is not normally safety classified unless its failure leads to damage of other safety related equipment. For VHTR potential designs are helical and finned tube and the plate type. For the gas to water heat exchangers the main concerns are to ensure there is no leakage of water into the system, and resistance to corrosion and thermal stress gradients. Currently available materials below 850-950^{o}C include alloys such as Hastalloy-XR, IN 617, Haynes 230. Above 950^{o}C materials such as ceramics and Fe based ODS materials may be needed. The significance of alloying elements, corrosion and potential for cracking are important issues as is resistance to degradation, oxidation and stress corrosion cracking and other mechanisms within the reactor operating environment. The potential for using coatings or and/bonded layers are also important possibilities.

Within the RAPHAEL programme the work has focused on identification of suitable industrial materials able to fulfil the requirements plus the performance of a simplified test programme to confirm aspects of suitability. The test programme focussed on Alloy 230 and investigated the effects of cold work and aging, which can affect creep properties including strength, lifetime creep rate and rupture ductility. The test programme was selected giving careful consideration to existing national programmes (within Generation IV) to maximise the effectiveness of the output. For EXTREMAT the focus was on identification of longer-term materials both for improvements in efficiency (heat transfer) and performance under higher temperatures (i.e. adoption of TiAl, ODS steels). The results for Alloy 230 suggest that the steady state creep rate and rupture ductility are strongly affected by cold work at 850°C and 950°C. Cold work at 850°C produces hardening reducing the transient creep stage and the steady state creep rate. The effect of 10% cold work on time to rupture seems to be beneficial whereas a scatter in time to rupture was observed on 17 % cold worked specimens. At the higher temperature of 950°C, only the10% cold work has a beneficial effect on steady state creep rate and life time and the 17 % cold work induces a dramatic drop in

creep resistance and time to rupture. For the evolution of mechanical properties with aging at temperatures up to 1000°C, a reduction of strength was observed which could be related to the carbide morphology. The results suggest a stabilization of properties (e.g. impact values) after 1000h at temperature, however to confirm this trend, aging treatment for longer durations are required. Further investigation of advanced alloys such as TiAl and ODS steels at temperatures exceeding 950°C using 200m thick specimens has been performed and compared with information on Ni based alloys and found to give increased creep strength compared with Alloy 617. The assessment showed the TiAl material to be a factor of 2 stronger in terms of creep rupture stress and although this is a promising conclusion a number of issues remain to be addressed including micro-structural stability, longer term data and data scatter, and production routes. For ODS steel the results at 850°C and 1100°C for a 100h creep rupture strength showed an increased value compared with Alloy 617 but at temperatures below 700°C, the creep rupture strength is lower. For this material, despite its potential for increased strength, there are many additional investigations required particularly with respect to manufacturing capabilities. Codes and Standards and database developments for the industrially established materials such as IN 617 (<850°C) is a key requirement and is advancing as a result of recent interest in the Generation IV gas cooled systems. There appears to have been little demand however over the last few decades for development of these higher temperature materials and much is still required with regard to their acceptance and application to large-scale component manufacture. Its unlikely that a nuclear renaissance involving gas systems will be sufficient to fuel a surge in demand hence the challenge in the short term will be to maintain and target the R & D towards specific systems (such as the VHTR/GFR IHX) where higher temperature application needs to be encouraged (for large scale hydrogen generation) and where the R & D may be sufficient to maintain the interest of potential and future manufacturers.

4.2 Gas Turbine (direct cycle)

For the turbine, the ability to withstand high temperatures (850°C) and provide long-term endurance (60,000h) are key material requirements especially for the first row of discs and blades. The main concerns are creep and the influence of the environment. The results of a review of potential materials (which was carried out in conjunction with component development work and a turbine materials supplier) identified Udimet 720 as the best available (large diameter) disc material and DS IN792 (Cr-oxide former) and CM 247 LC DS (Al-oxide former) as two options for the blades. Subsequent tests to confirm properties and behaviour in air were performed and the better blade material in terms of strength and life was CM 247 LC DS. For the large diameter rotor (>1.2m) disc material good forging properties were required. Micro-structural examinations showed a larger variability in grain size, which was heterogeneous with bands of coarse (500μm) grains separated by areas where the grain size did not exceed 50μm. This duplex grain size was thought to arise from the combined result of forging and heat treatment. Fatigue results for the disc material were dependent on grain size but nevertheless better than expected.

With regard to the effects of corrosion, depending on the partial pressure of the impurities the resulting atmosphere can either be oxidizing or carburizing for the selected materials with damage either at the surface or diffusing to significant depths in the metallic matrices (internal oxidation or carburization or decarburization). For the blade materials both Al and Cr formers were selected with phase diagrams used to determine the neutrality of the chemical activity and to determine whether compatibility issues are likely to have a strong impact on materials selection. The presence of a corrosive layer was thought to result in a loss of mechanical properties and along with aging tests, a series of environmental tests were undertaken using a specialist rig (at JRC) to investigate its influence on creep strength. The tests were performed in argon at 850°C for times up to 9000h with the individual specimens heat treated to provide either fully carburized and fully decarburized conditions as well as the equivalent heat treated condition. The results suggested a significant influence of carburization on the creep strength, which would need to be taken into account in any design evaluation. These tests provide a lower bound estimate for design and while they may be conservative, offer an alternative evaluation to performing large numbers of expensive tests in test loops at different impurity levels which would be very difficult to control within the loop test section area.

5 CONCLUSIONS

Materials research and development (R & D) issues has been investigated for the developing HTR, VHTR and GFR systems. The VHTR system operates at potentially higher temperatures and therefore acts as a pilot for many of the issues that also need to be addressed by GFR. However there are additional requirements for the GFR (e.g. fast fluence, high transient temperatures, higher inlet gas temperature), which

may impact on materials selection and require further R & D. The EU Framework programmes provide a means for addressing these materials issues and key technology developments that can be further evaluated on an international scale within Generation IV. Some of the important activities with regard to future material challenges for the new advanced gas cooled systems are summarised as follows:

- selection and development of graphites for the HTR core with desirable irradiation properties in sufficient quantities to provide security of supply for a large numbers of modular HTR's that are able to meet the requirements of the process heat and electricity industries.
- development of manufacturable new materials for the GFR able to meet the high temperature and fast fluence of the core environment
- for the Mod 9Cr 1Mo vessel future effort should concentrate on very representative samples, with the base material from prototype forged parts and the welded joints representative of HTR/VHTR and GFR vessel fabrication route focusing on the remaining qualification issues including inspection
- for the IHX and other helium circuit components to focus on meeting the needs for formalization within codes & standards and progressing the industrialization of alternative high strength alloys to enable designs to progress to higher temperature applications.

Materials investigations performed within the 5th and 6th Framework projects such as RAPHAEL has seen significant progress in developing materials technology for advanced gas cooled systems including the development of a Mod 9Cr 1Mo steel for vessel application, investigations on high temperature metallic and C-based materials for heat exchangers and other components and the material property data for the graphite core. These results provide an important contribution to materials development within Europe and a valuable input to the Materials Research Programme within the Generation IV International Forum. There are still many challenges to be faced and these need to be overcome if these systems are to provide an important contribution to future power, process heat, and electricity requirements in the decades to come.

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6 REFERENCES

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EXTREMAT- New Materials for Extreme Environments sixth Framework Project: www.extremat.org

GCFR STREP - Gas Cooled Fast Reactor European sixth Framework Project: http://www. gcfr.org