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Materials for Advanced Gas-cooled Nuclear Systems

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Abstract.. The VHTR modular reactor 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 in particular for heat applications and hydrogen generation. This system can operate with either a direct or indirect cycle and makes use of the high efficiency brayton cycle. The GCFR system, which features a fast-spectrum helium-cooled reactor and closed fuel cycle is also capable of delivering electricity, hydrogen, or process heat with a high conversion efficiency. Again this system can operate with either a direct or indirect cycle. The reference concept for the GCFR uses a direct-cycle helium turbine. For the VHTR both the pebble bed (e.g. PBMR) and block type (e.g. ANTARES) are under development. For such new 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 under the expected operating requirements. Within these system requirements there are also significant synergies with the materials developments for the Fusion Reactor. All three systems use helium as a coolant, joining processes involving the bonding of similar and dissimilar materials developed initially in the Fusion industry are becoming increasingly used in advanced fission heat exchanger design for economy and compactness. The synergies between Fission and Fusion are especially visible in the EXTREMAT-IP which benefits from the close involvement of a wide range of applications (fission, fusion, aerospace, automotive, etc.). For the advanced fission reactors the work within the EXTREMAT-IP addresses the potential of new materials for the reactor control rod (irradiation resistance), for high temperature components such as the heat exchangers, and for protection against corrosion damage (barrier materials). Within the EXTREMAT-IP the main materials addressed for these applications are carbon composites, ODS steels and graphites where a database to store the results of irradiation resistant materials tests is also being developed and implemented

Introduction

This paper provides information on potential applications for new and developing materials for advanced gas cooled fission and fusion reactor systems. For the Fission industry, the main needs are for protection against corrosive actions in a high temperature environment. This can be in the form of coatings or further development of the material itself to resist gaseous and/or liquid chemical processes. The focus is on the materials for the main reactor components and the power conversion systems. The listed cases include the reactor core and its associated components, the heat exchanger and turbine (where applicable) and high temperature piping. The main material needs focus on Carbon based materials (composites, graphites, SiC) for the core itself, control rod and supporting straps; advanced metal alloy requirements for cladding, wrappers that are resistant to the environment (including irradiation); Oxide Dispersion Solidified (ODS) materials for the core support, hot gas duct, heat exchangers and turbines; specialised coatings or materials for areas exposed to corrosion and oxidation, carburisation (e.g. turbine blades). Specific applications for bonding are given for the case of the Cu-bonded heat exchanger for the LMR. Material Processes have to be consistent with the economics of component geometry and supply. In most cases the requirement is for high temperature strength and a creep endurance of 6 years for replaceable components (wrappers, control rod, etc.) and 60 years for the main components with the minimum maintenance and/or repair. For Fusion applications improved materials are needed for the ITER and DEMO developments. These include plasma facing compounds and materials for the Divertor. Requirements include carbon fiber composites, SiC matrix materials, W-based materials. Thermal properties and resistance to irradiation, oxidation and erosion plus resistance to the several thousand plasma pulses (fatigue) expected throughout the component lifetime are the key requirements.

Extremat IP Project

The main purpose of the Extremat-IP is to investigate and develop new materials for "Extreme environments." The materials covered include both carbon based (composites & graphite) and metals (steels, alloys, ODS materials, inter-metallics, nano-structured materials) with specific applications for advanced Fission, Fusion and other applications. The project considers four main areas of activity: 1) Barrier/ protection materials (e.g. coatings), 2) Heat sink materials (e.g. for heat exchanger applications), 3) Irradiation resistant materials (e.g. fission & fusion applications) and 4) Compounds/ bonded structures (e. g. Cu bonded heat exchanger)

Advanced Fission applications - VHTR/HTR

HTRs and VHTRs ([Very] High Temperature Reactors) are gas cooled thermal fission reactors well suited for use as either stand alone power plants for production of energy, or in the case of VHTRs, in conjunction with hydrogen production power plants providing the heat for the H_2-production process. HTR's and VHTRs operate at temperatures up to and beyond 1000^{o}C. The components reviewed in this section are the reactor unit (core, control rod, core support & internals), the hot gas duct, the heat exchangers and the turbine.

Reactor Structural Material Applications. Reactor structures include components constructed from both metallic and carbon (C) based materials [1]. Within the reactor core the metallic components (e.g. stainless or Cr-Mo steels) usually provide the structural support for the (graphite) core and such components are often not replaced for the lifetime of the reactor (40 operating years). The main C-based materials are the reactor core, part of which is replaceable, and the control rods, which is replaced approximately every four to six years. Other applications include straps for support for the core under (seismic and other) loads.

Internal metallic structures The internal reactor metallic structures concern the core support and core barrel, grids, plus any restraint mechanisms used to accommodate external loads such as seismic events. For such metallic internal components austenitic and some ferritic steels can be used. Such materials have an established capability at temperatures up to 550^{o}C and have been used within the reactor block of other high temperature reactor projects (e.g. Advanced Gas Cooled Reactor in the UK, the European Fast Reactor Project and High Temperature Reactor Projects such as AVR). For higher temperatures however, nickel based and Fe-Cr-Ni Alloys need to be considered also Oxide Dispersion Strengthened (ODS) Steels and nano-structured steels and alloys. For very high temperatures C-composite materials could also be used particularly for the control rods.

Graphite core Future high and very high temperature reactors will use industrial graphite for the neutron reflector. The core has to cope with extreme environmental conditions, temperatures ranging from 600 – 1100^{o}C or more. The fuel matrix itself has to withstand temperatures up to 1600^{o}C. Its performance is critically dependent on the graphite properties, which are also irradiation dependent. Thermal neutron fluxes of up to 10^{15} n/cm^2/s and damage levels up to 30 dpa are anticipated.

Control Rod The control rods and core structures in the VHTR have to withstand extreme environmental conditions. The temperature range is approximately 500 – 1200^{o}C and thermal neutron fluences occur up to the equivalent of around 5 dpa damage. Also within the reactor gas impurities are present such as H_2O, CO, CO_2 that can give rise to corrosive actions that will impair the integrity of the materials. The currently favoured materials are on C/C composites, SiC/SiC composites and C/SiC composites. Such materials need to have a minimum lifetime of around 6 years, be dimensionally stable, be resistant to creep damage and show no surface degradation. Tests are needed to validate such materials under realistic reactor conditions

Hot Gas Ducts. The Hot gas duct is used to transfer the hot helium from the reactor core to the power conversion circuit components such as heat exchangers and turbines. Materials that could be considered include high strength alloys, ODS materials and composites.

Heat Exchanger materials. The heat exchanger is an important component in any nuclear power plant and its efficiency and compactness is particularly important for the VHTR. The intermediate heat exchanger for indirect cycle and process heat applications (in particular hydrogen production) is one of the most challenging components, as it is required to exchange 600 MW at 900-1000°C. Currently available materials for temperatures below 950°C include high temperature 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.

Turbine components (discs & blades) Material selection criteria are based on a safe operation period of up to 60,000 h with upper temperature limits of approximately 850 to 950^{o}C (or more for the VHTR). The main material considerations are concerned with creep and environmental compatibility. For the disc and first row of blades potential materials are high temperature alloys capable of robust manufacture and resistance to corrosion and long term creep. For the turbine disc, considered materials include: A286 (Cr Ni Fe), Waspaloy, IN 706, IN718, UDIMET 720 and an oxide dispersion alloy MA6000. For the blade materials, directionally solidified (DS) or single crystal (SC) Ni based alloys are potential options. Candidate alloys for the blade materials include Inconel MA 6000, DS IN 792, DS CM 247 LC, etc.

Advanced Fission applications – GCFR

Gas-Cooled Fast Reactors (GCFRs) are currently undergoing renewed international interest [2]. They are different from HTRs and VHTRs in that they utilise fast, as opposed to thermal neutrons. GCFR's are of particular interest at the moment because they can re-use or burn up radioactive waste. Operating temperatures of the GCFR are up to 850°C, but temperatures can rise to around 1200^{o}C during accident conditions.

Reactor Material Applications. Materials within the GCFRs will have to withstand a high level of neutron fluence compared with VHTR's but less severe temperatures (similar to HTR). Operating temperatures range from room temperature to 850^{o}C. Irradiation doses from the fast neutron fluence range from 5 to around 30dpa for the internal structures and to150 dpa for the fuel cladding. Helium gas or CO_2 can be used as the coolant hence the materials have to be resistant to oxidation and corrosion. For the internal reactor components, similar materials to the VHTR (Oxide Dispersion Strengthened (ODS) Steels, W-based alloys and Ni-based alloys) are candidates for the higher temperature components. Austenitic stainless steels and the 9Cr-Mo alloys are currently the most promising for temperatures up to 550-650^{o}C

Heat exchanger and other power circuit components. As with the VHTR the compactness and efficiency of the heat exchangers are important requirements. Heat exchanger design and materials selection have to consider the temperatures, thermal gradients and pressures that give rise to stresses and distortions during normal operation and transients. Currently available materials for temperatures below 950^{o}C include high temperature alloys such as Hastalloy-XR, In 617 and Haynes 230. Above 950^{o}C new materials (ceramics and Fe based ODS alloys) may be needed. The significance of alloying elements, corrosion and potential for cracking are important issues that need to be investigated and new materials capable of resisting degradation, oxidation and stress corrosion cracking and other mechanisms within the reactor operating environment need to be developed. The possibility of coatings and bonded layers are also important possibilities.

Fusion applications - ITER and DEMO

The International Thermonuclear Experimental Reactor (ITER) will be the first machine that generates thermal power. It is planned that ITER will be followed by DEMO, which will be the first fusion machine to generate electrical power. The materials development undertaken during the design of ITER has led to solutions suitable for ITER. However, the material solutions are not ideal for because a significant factor in their selection is the availability based on current industrial production. Further work is now needed to identify better materials, specifically chosen for their application for fusion, with a view to their future use in commercial reactors. An overview of the ITER design and materials selection/development is given in [3].

Plasma facing components (PFCs) ITER is designed around a long pulse hydrogen plasma operating at over 100 million °C, which will produce a DT fusion power of 500 MW for a burn length of 400 s, with the injection of 50 MW of auxiliary power. The plasma is contained within a toroidal vacuum vessel surrounded by superconducting toroidal and poloidal field coils that magnetically confine, shape and control the plasma. Plasma facing components are the first line of defence within the vessel against the severe thermal and irradiation loadings emanating from the plasma. A summary of the fusion material applications are summarized in the table below.

	Blanket	**Divertor**	**Strike zone**	
Current choices				
Protection material	Be	W	CFC,:SEBCARB NB31, Concept 2	
Form and dimensions mm		Tiles	Tiles	Tiles
Heat sink material	CuCrZr (IG) or DS Cu (IG)			
Structural material	Austenitic Stainless Steel Type 316LN (IG)			
Future systems				
Protection material	W-Si –dopant (self passivating)		CFC-dopant, (self passivating)	
Product form	Coating	Coating or Tile	Tile	
Heat sink material	Cu alloy, W or improved structural material (ISM)			
Structural material	ISM			

Development of Irradiation Resistant Materials Database

Development of a web-based database to store the results from the Extremat IP irradiation resistant materials test programmes, has been developed. The database will store all aspects of the irradiation programmes, specimen geometries and test methods, and are available to all the Extremat IP partners via a website called BSCW

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