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Materials for Internals and Heat Exchangers and test programme

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RAPHAEL *(ReActor for Process heat, Hydrogen And ELectricity generation)*

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Abstract

A review of available materials for the key high temperature components (internals, hot gas duct, heat exchangers) of the VHTR plus a short list of most promising materials for evaluation has been made. This is preliminary investigation from which a more detailed study is initiated to prepare for a joint exchange with SP CP on requirements for High Temperature Material components. From this work candidate materials are to be selected for testing and further investigation. A recommendation on a generic test programme (short term plus ageing tests) has also been made.

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
01	31/01/2006	First issue	Jean-Marie Gentzbittel CEA	Jean-Marie Gentzbittel CEA	Derek Buckthorpe NNC	E.Bogusch, AREVA NP

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1 Introduction

VHTRs are gas cooled nuclear fission reactors for future co-generation plants for sustainable production of electric energy and heat for hydrogen production or other high temperature processes. To achieve high efficiencies of 70% or more gas outlet temperatures close to 1000°C are required. Materials for long-term structural applications in such plants must be explored to allow efficient safe and reliable operation of such advanced plants

The search for materials for use in the Very High Temperature Reactor requires extending the knowledge of existing materials beyond their present industrial experience and/or exploring new innovative materials capable of meeting the more demanding and increased VHTR requirements. These investigations mainly concern metallic materials, graphite, ceramics and composites. For the metallic materials work within Raphael-IP WP2 will cover the selection and confirmation of materials for the internals, hot gas duct and heat exchangers for VHTR operation. Complimentary short term testing and ageing tests will be performed to help with the selection and to establish a database of suitable materials information

2 Objectives

The purpose of this report is to review available materials for the key high temperature components (internals, hot gas duct, heat exchangers) of the VHTR and provide a short list of most promising materials for evaluation. From this review candidate materials will be selected for testing and further investigation. A generic recommendation with regard to the main issues for the test programme (short term plus ageing tests) is also to be made.

3 Issues concerning material selection

The selection of materials for developing advanced high temperature components for VHTRs for the heat exchangers, hot gas duct, internals, are dependent on the potential of prospective materials to meet design and service requirements and to be fabricated and assembled according to design and performance specifications. The capability of the selected material to meet these requirements is determined by mechanical, physical and corrosion properties as well as susceptibility to forming, shaping and bonding by feasible means.

The mechanical properties of metallic alloy components are highly dependent on the chemical composition , thermal treatment and the resultant metallurgical microstructures.

A brief overview of issues concerning the selection of materials for VHTR high temperature metallic components is given in Appendix A. Reference design data for the ANTARES plant supplied by SP SI are given in Appendix C.

The following sections address issues for the IHX, Hot Gas Duct and Reactor Internals.

3.1 General requirements for high temperature materials for VHTR components

3.1.1 Intermediate Heat Exchanger Materials selection and issues

The conditions that affect the material selection for these components are summarized in Table 1. For the indirect power generation cycle, the normal operating temperatures range from 350°C to 1000°C. The mechanical load is from the pressure (1 to 10MPa) however the difference from primary to secondary circuit is small since the IHX will be contained within a vessel. In addition thermal transient and thermal stresses should be taken into account

Environmental induced degradation of the metals from impurities in the helium is a concern. Ageing effects are important for long term exposure since embrittlement could affect the performance of the IHX during thermal transients. Welding and fabrication issues are important factors and these will depend on the IHX design details.

3.1.2 Metallic reactor internals and Hot Gas Duct Materials selection and issues

The core internals of a VHTR are composed of a variety of components. These can be metallic or carbon based materials such as graphite and composites C-based materials. Metallic materials provide structural support and protection for the core and for the lifetime of the plant (60 years). Depending on the specific component, the normal operating temperatures range from 600°C to 1000°C. However the maximum temperature estimated for accident conditions ranges from 600°C to 1100°C and higher.

With regard to loading conditions, these components are not pressure boundary components. In some cases the weight loads can be significant. Compatibility with the coolant gas is a requirement for core metallic internals. In the materials selection, irradiation and thermal aging effects on properties are an important consideration, also fabrication and joining requirements. The conditions that affect the material selection of these components are briefly summarized in table 1 below:

Table 1 Conditions affecting materials selection for high temperature metallic VHTR components.

Condition	Core Internals	Hot Gas Duct	IHX
Normal temperature ^oC	600	600	350-1000
Maximum temperature ^oC	700->1100	700-1000	1000
Loading	Core weight	Self weight	1-10MPa thermal transient
Environment issues	Helium + impurities	Helium + impurities	helium/helium nitrogen
Radiation issues	negligible	None	none
Aging issues	significant	significant	significant
Joining issues	significant	significant	significant
Manufacturing issues	None/ some	significant	significant

Potential candidate materials for the internals as well as for the other high temperature components likely to be constructed from metallic alloy are listed in table 2. These materials include alloys for which there is significant information. In addition, new state of the art alloys are being investigated for high temperature application in other programmes such as EXTREMAT-IP.

The leading candidates for service above 760°C are Alloy 617, Alloy X (XR); Alloy 800H. These alloys are favoured because they have been developed for use in earlier gas cooled reactor projects. Other Nickel based alloys are also being considered such as Alloy 230 which is a relatively “recent” alloy compared to the other listed nickel alloys. Oxide Dispersion Strengthened (ODS) alloys could also be an alternative for service in components that might experience temperature excursions above 1000°C.

Table 2 Possible materials selection for high temperature metallic VHTR components.

Components	Core internals	Hot Gas Duct	IHX
Material	Alloy 800H, Alloy 617, Alloy X Alloy XR Alloy 230 ODS Alloys.	Alloy 800H	Alloy 617, Alloy X AlloyXR Alloy 230 ODS Alloys

3.2 Short review of commercial metallic candidate materials

Two nickel base alloys have been used in the past for heat exchangers in gas cooled high temperature technology: Alloy 617 and a modified Alloy X (commonly called Alloy XR). In addition Alloy 230 and Alloy 800H have been proposed for this application from the French HTR selection and qualification programme, where Alloy 800 H has already been used in the German THTR. For increased outlet temperature of up to 1000°C or higher the use of ODS alloys should be considered.

3.2.1 Chemical composition of the candidate alloys

The chemical analysis as specified by ASTM for these four alloys are given in table 3 along with the American National Standard Number (UNS number). The chromium contents are similar also the carbon contents (0.05-0.15%). Alloy 617 contains around 12,5% cobalt, 9% molybdenum and a limited iron value.

The alloying elements for Alloy X are molybdenum (around 9 %), iron (19.5%), tungsten (0.2-1%) and cobalt(0.5-2.5%). The alloy XR (Hastelloy XR) has a similar composition for the major constituents to that of Alloy X, however the contents of specific minor elements have been optimized: Mn and Si are adjusted in the optimum ranges while cobalt, aluminum and titanium are reduced to the possible lowest levels (Al<0.05; Ti < 0.03).

The main alloying element for Alloy 230 (after chromium) are tungsten (13-15%), molybdenum and cobalt. Cobalt is specified in a large authorized range and some batches that have been tested present relatively low cobalt contents compared to the 5% authorized figure. The content of the aluminum specification is limited (0.2-0.5%), higher than in alloy X but much lower that in alloy 617.

Alloy 800H (HT) is an iron-nickel-chromium alloy having the same basic composition as INCOLOY alloy 800 but with significantly higher creep-rupture strength. The higher strength results from close control of the carbon, aluminum, and titanium contents in conjunction with a high-temperature anneal.

	Cr	Mo	W	Fe	Co	Mn	Si	C	Al	Ti	B	Ni
Alloy 617	20-24	8. – 10.0	-	≤ 3%	10.0 15.0	≤ 1	≤ 1	0.05-0.15	0.8 – 1.5	≤0.6	≤ 0.006	Bal
Alloy X	20.5-23.0	8-10	0.2-1.0	17.0-22.0	0.5-2.5	0<1.0	<1.0	0.05-0.15	-	-	-	Bal
Alloy 230	20.0-24.0	1.0-3.0.	13.0-15.0	<3.0	<5.0	<1	0.25-0.75	0.05-0.15	0.2-0.5	-		Bal
Alloy 800H	19.0-23.0	-	-	39.5 min		<1.5	≤ 0.75	0.05-0.10	0.15-.06	0.15-0.6		30.0-35.0

Table 2 : Chemical analysis of candidate alloys

The delivery condition for the four alloys above for IHX application is solution annealed:
1150°Cto 1230°C for Alloy 617
1177 to 1246 °C for Alloy 230
around 1180°C for Alloy X
over 1150°C for Alloy 800HT

3.2.2 Microstructure

The initial microstructure of the different alloy is a solid solution with different intra or intergranular precipitates. The strength of these alloys comes from the carbides and solid solution.

3.2.3 Comparison of physical and mechanical properties (in air)

3.2.3.1 Physical properties

The thermal expansion (mean coefficient between 20°C and temperature, and the thermal properties Cp and λ reported for these alloys are given in Table 3.

The differences between them is not sufficiently significant as to make the selection on this basis.

	θ °C	Cp J/kg.K	λ W/m.K	α 10-6 K-1	E GPa
Alloy X	700	605	22.8	15.6	161
	800	640	24.6	15.9	
	900	675	26.4	16.3	145
	1000	715	28.2	16.7	135
Alloy 617	700	586	23.9	14.8	166
	800	611	25.5	15.4	157
	900	645	27.1	15.8	149
	1000	662	28.7	16.3	139
Alloy 230	700	574		14.8	171
	800	595		15.2	164
	900	609		15.7	157
	1000	617		16.1	150

Table 3 : Physical properties & Young Modulus of nickel based alloys for HTR applications

3.2.3.2 Mechanical properties

The elevated temperature mechanical properties data base developed for alloy 800H and Alloy 617 in Germany is very extensive, especially the data base for tensile, creep, low cycle fatigue and creep fatigue and for the effect of environment exposure at the expected service temperature on mechanical properties. The experimental data obtained by investigations of Alloy 617 and Alloy 800 H are compiled and published in the draft version (1992) of the technical rule KTA 3221.1, 3221.2 and 3221.3 applicable for HTR'S, materials design and QA. Additionally a draft ASME code Case for Alloy 617, based on Code Case N47-28 that provides design rules for very high temperature reactors was issued in 1989. Alloy 800H and Alloy X are regulated in some specific German Standards and also in European Standards, as e.g EN 10302. Alloy XR has a manufacturers specification.

3.2.3.3 Tensile properties

Tensile properties have been measured for a large range of product forms for Alloy 617 and Alloy X. The data concerning Alloy 617 have been provided in a large part from the past German work on HTR's in order to qualify Alloy 617 for this application. Results for the yield and tensile strength data of Alloy 230 are more limited, nevertheless a first comparison (conducted in France) shows that the yield and tensile strength of Alloy 230 are slightly higher than the strength of Alloy 617. This trend is limited to temperatures above 850°C. The yield strength of Alloy X appears to be in the lower part of the strength of Alloy 617, however the key points of the design to consider for selection will be the highest temperature range capability and the strength properties to provide a long service life time.

3.2.3.4 Creep properties

Creep property information for different products of alloy 617 are numerous in the selected temperature range [700°C-1000°C] and for long duration (some tests up to 50,000hours).

The data for Alloy XR are given by the supplier and available from some Japanese program results or other works. They cover the temperature range [700°C-900°C]. Limited creep data exists on Alloy 230 in air and extrapolations are available beyond 10,000 hours at 950°C.

From a brief analysis the following points are noted:

There are numerous creep data on alloy 617 available but they present a large scatter and the long-term stress to rupture at the highest temperatures has to be confirmed

There is a need for long-term tests on Alloy 230 and data from different heats or products. This is necessary to improve the knowledge and reliability of the long-term extrapolations and to fulfil the requirements for the development of technical rules and standards.

3.2.4 Thermal ageing behaviour

Considering the requirement for a long service life and a high operating temperature level for the IHX and other metallic VHTR components, thermal ageing effects on the long term behaviour (mechanical or corrosion) of selected material properties has to be evaluated.

3.2.5 Effect of the VHTR helium environment on metallic candidate alloys

The primary coolant is helium, which passes through the hot graphite core structure. The Helium contains slight amounts of impurities: i.e H_2, H_2O, CO, N_2 and CH_4. The interactions between structural materials in the helium atmospheres associated with gas-cooled reactors have been the subject of numerous investigations and it has been demonstrated that small changes in impurity levels, high temperature in combination with the gas flow can cause oxidation, carburization or decarburization of the metallic materials. Carburization, via the subsequent precipitation of carbides can lead to a significant embrittlement of the Ni-Cr alloys at low temperature and to a strong degradation of their creep ductility but can also increase creep strength. De-carburization, which is the dissolution of the initial carbides acts to degrade the creep properties of the carbide hardened alloys.

Extensive studies have carried out in the 1980's in Japan and Germany in simulated impure HTR environments on a number of different NiCr and Fe-Ni-Cr alloys. Tests on Alloy 617 and Alloy X, were performed considering the environmental effects on chromium oxide as defined by the Quadakkers stability diagram. The comparison involved a close control of the sensitive helium environment, which was difficult. Some more recent corrosion work performed on the three Ni-Cr alloys exposed under a slightly oxidizing Helium atmosphere has shown that Alloy 617 is more oxidized at 950°C than Alloy X or Alloy 230 [Ref 2].

3.2.6 Fabrication and joining

No major differences are expected between the alloys for the fabrication of for e.g. a tubular IHX. There is a large experience in Japan for Alloy XR and in Germany for Alloy 617. Other IHX design options such as the plate IHX require additional fabrication, machining and more especially specialised joining techniques (Diffusion Bonding). Limited data are available today on the ability of the alloys to cope with these joining techniques other than for fusion welding.

3.2.7 Summary comments on the selected alloys

Nickel -Chrome solid solution alloys such as Alloy 617, Alloy 230 , Alloy X, Alloy XR and Alloy 800H are the most promising candidate materials for the VHTR Internals, Hot Gas Duct and Intermediate Heat exchanger. Other alloys such as ODS alloys will be considered due to their high thermal stability and creep strength.

Currently the two main candidates for the IHX are considered to be Alloy 617 and Alloy 230. Alloy 617 already has a very large database with numerous mechanical properties and creep data measured in air and a helium plus impurities atmosphere. An ASME draft code case for this material was developed in the LATE 1980's. The data obtained in the German R & D programme were put in the specifications for HTR applications, the KTA 3221.x series, draft version 1992. But then the work stopped as the need and the interest in HTR'S disappeared.

4 Information requirements for VHTR - IHX material selection (see Appendix B)

The main areas of information gathering for the selection of candidate materials can be summarised in the following stages:

Compile the appropriate operating conditions/ parameters
Compile the load cases to be considered
Short list the materials
Identify metallic materials information already examined/assembled in the scope of past HTR's
Define the material properties to be determined
Define the test methods and conditions
Evaluate available data and compare with what is needed
Pre-select the most promising candidate materials
Define the test and examination matrix
Begin the test work and evaluate the results
Draw conclusions on the value of the increased knowledge in relation to VHTR IHX applicability

Appendix B provides a development scheme for compiling the available information for the materials comparison. Issues such as loading data, properties, failure modes, environment and design data are addressed with a table format proposed. Work over the next months is to assemble the necessary information in order to make an assessment prior to confirming the test programme. Issues of procurement, test conditions, etc. are to be addressed in parallel where this is practical.

The requirement to cope with high temperatures and to provide a long service life (60 years /420000hours) at these temperatures means that whatever material is selected for the IHX there is a specific need to evaluate the long term properties at high temperature. There is therefore a need to evaluate creep and stress to rupture properties of representative products that will be used in design and to later confirm/reinforce their application through longer time test data. This need includes the evaluation of the effects of thermal ageing, which at IHX temperatures may also have a marked effect in the short or medium term. Section 5 below presents an outline of a generic test programme, which at the moment can be applied to any of the identified candidate materials.

5 Generic outline of Test programs

A test program should be proposed in order to improve the knowledge of high temperature mechanical properties and microstructure of selected high temperature metallic alloys. The requirement is to advance the understanding and evaluation of high temperature long-term properties through a series of tests including creep and thermal aging in the temperature range [700°C-1000°C]

5.1 CEA test program

The aim of CEA test program is to improve the understanding and data from different heat or products forms in order to improve the reliability of long term extrapolation and to fulfil the requirements of developing technical rules.

CEA intends to perform tensile and creep test at high temperature (850°C and 950°C) on a selected material (Alloy 230 and/ or Alloy 617) and for each temperature three creep stress levels are to be explored. Microstructure observations of initial material and after thermal ageing (short term 1000hours - at the same temperature as the creep tests) are to be performed. Tensile and Charpy impact properties are to be derived after ageing.

The test evaluation methods to be applied include : Hardness, tensile, Charpy impact, creep and thermal treatments, metallography, microstructure characterization. It is planned to procure the materials samples and adapt the available creep facilities over the next 9 months.

5.2 EdF test program

The EdF programme is devoted to investigation of aging of industrial products for the heat exchanger. The tests considered currently are to investigate thermal aging of Alloy 230 for durations 1000h and 5000h at temperatures of 850^{o}C and 950^{o}C. Short tests (1000 h) at very high temperature (1000 °C) will also be performed, to study the behavior of the material in accidental conditions.

Mechanical tests will be performed (tensile tests, Charpy tests), as well as microstructural examinations (SEM + TEM), according to the test matrix presented in Table 4.

Additional data will also be provided from the VHTR-CORBA project (Grant for Cooperating with Third Country from EURATOM for Dr. Arkadiusz Dyjakon). These additional data are not funded by RAPHAEL. Corresponding data are presented in Table 4.

<table>
<tr><th>Alloy</th><th>State / Thermal aging duration</th><th>100 h [1]</th><th>300 h [1]</th><th>500 h [1]</th><th>1000 h</th><th>5000 h</th></tr>
<tr><td rowspan="4">Alloy 230</td><td>As Received</td><td rowspan="4">SEM + EDS</td><td rowspan="4">SEM + EDS</td><td rowspan="4">SEM + EDS</td><td rowspan="4">Charpy tests
Tensile tests
SEM + TEM</td><td rowspan="3">Charpy tests
Tensile tests
SEM + TEM</td></tr>
<tr><td>Aged at 850 °C</td></tr>
<tr><td>Aged at 950 °C</td></tr>
<tr><td>Aged at 1000 °C</td><td>-</td></tr>
<tr><td>Alloy 617</td><td>Exposure under corrosion environment</td><td>-</td><td>Exposure under benign and decarburizing atmospheres</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Table 4 : EDF tests and examination matrix

6 Conclusions and Further Work

A brief review has been made of the issues concerning selection of high temperature materials for VHTR application

The most promising candidate materials have been identified: Alloy 617, Alloy 230; Alloy X, AlloyXR and Alloy 800 H. These materials are to be investigated more fully (including comparison of available data) with a view to identifying the materials and test matrix to be used in the Raphael test programme.

A proposal (format) has been made – see Appendix 2 to assemble the needed information for discussion and evaluation. This information is to be collected over the next few months.

A joint meeting has planned with Raphael SP CP on component development to discuss the needs for the high temp[erature components and the results of the assembled information in order to identify the best material and test matrix to use.

[1] Additional data coming from the VHTR-CORBA project (not funded by RAPHAEL)

Appendix A: Brief Overview of VHTR high temperature metallic materials

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 heat , 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 main components of a VHTR are:

- reactor (pressure vessel, core internals),
- piping, valves, heat exchangers,
- generator, for direct cycle (gas turbine)

The areas reviewed below are the reactor unit (core, control rod, core support & internals), the hot gas duct, the heat exchangers and the turbine. Other components will equally benefit from any materials development.

Reactor Structural Material Applications

Reactor structures include components constructed from both metallic and carbon (C) based materials. 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 – 60 operating years). The main C-based materials are the reactor core, part of which is replaceable, and the control rods, which can be replaced approximately every four to six years. Other applications include straps for support for the core under (seismic and other) loads.

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 (see below).

Control Rod

Existing test reactors use Alloy 800H for the control Rod material.

At present there is significant interest in the use of carbon-carbon (C/C) composites for control rods, however susceptibility to oxidation at high temperatures is a limiting factor and further development in this aspect is required.

Work has been done to increase the oxidation resistance of C-based materials for example using silicon (Si) which has the effect of increasing density and decreasing porosity. The resistance to oxidation is achieved by the formation of a SiO_2 layer which is impermeable to oxidants.

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 Duct

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 (in the case of the direct cycle). The duct is usually insulated to increase efficiency and limit thermal loads.

The lifetime of the hot gas ducts is the same as that of the reactor with no repairs or maintenance required, the option to repair or replace the component reserved for unforeseen circumstances. Materials that could be considered include high strength alloys, ODS materials and composites. Some investigations have been made in the past using such materials and these need to be extended taking full advantage of new and potential material developments.

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 designs must be compatible with potential heat applications proposed for the plant like desalination or district heating using energy extracted by a water circuit for example. 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. For cost effectiveness, high performance and compactness, innovative materials and components must be developed. The function of the heat exchanger is to convert the heat generated from the nuclear fission process (gas/gas, gas/steam, gas/ water) and this can be enhanced and/or size of the heat exchanger reduced through the use of efficient high conductivity materials. Materials selection and design have to consider temperatures, thermal gradients and pressures that give rise to stresses in the materials. Two kinds of concepts are often considered: i.e. the plate concept and the tube concept. Heat exchanger design lifetimes are the same as that of the reactor with provision for repair or maintenance to be carried out only under unforeseen circumstances.

Currently available materials for temperatures below 950°C include high temperature alloys such as Hastelloy-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 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 considerations.

Turbine components (discs & blades)

For the Direct cycle VHTR a turbine is introduced into the main cooling circuit.

The turbine is housed within the power conversion circuit of the HTR and used to convert the thermal energy of the primary coolant into mechanical energy for power generation and other purposes. The current designs of HTR such as proposed for the PBMR use cooled discs and 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.

Two basic requirements dictate the design of gas turbine blades and discs, the cycle temperature and the maintenance of critical dimensions (clearances) throughout the service life. For turbine discs it is necessary to limit the permanent growth and distortion to within typical design life targets. This is usually achieved by maintaining a greater part of the disc cross section within elastic limits. Critical regions for the disc from the point of view of potential creep and fatigue failure are invariably the hottest parts. These are at the disc neck because of unrelieved high localised stresses giving rise to undetected growth; and at the rim, due to the additional geometric effects of the blade root slots and possibly cooling holes. Careful material selection and control of localised stress/temperature conditions can avoid creep-fatigue interaction problems in these areas.

The selection of turbine blade designs is limited by the high temperature creep properties of the material (i.e. non-cooled blade). For turbine blades the gas radial temperature variation peaks typically in the middle third of the blade with steep temperature gradients across the blade section, varying according to the transient and steady state conditions. All regions of the blade profile therefore undergo complex stress-strain cycling with reversed plasticity in some areas. For material selection, a close understanding of some important parameters such as creep rupture strength, creep ductility and creep rates are needed. Typically for nickel based super-alloys the time dependent effects of creep and oxidation on cyclic crack growth rates are important for design, and hence an understanding is needed of creep crack growth behaviour as well as the interaction between creep and fatigue during both tensile and compressive dwells. The awareness of the role of grain boundaries in high temperature fracture was important for the development of single crystal super-alloys that can give beneficial an-isotropic material properties. For the HTR turbine blades such advanced blades are not thought to be necessary, for the VHTR more advanced material development may be needed.

The effect of impurities within the helium environment is a critical issue that affects both the blades and the discs. The main concerns were corrosion effects on strength. Corrosion can cause a significant shortening of the material creep life and acceleration of creep crack growth rates. Helium impurities can influence creep properties due to oxidation and carburisation mechanisms. Below about 575^{o}C corrosion of such alloys is limited. Between 575 & 900^{o}C chromium rich oxide scale can form also carburisation and de-carburisation due to chemical action. For such temperatures there is a need to consider optimisation of alloy composition and coatings to limit damage to the blades. Application of suitable coatings can arrest creep reduction tendencies, however their use requires an understanding of the potential for interfacial cracking at the coating layer to avoid the development of more significant cracking from the interface. Use of coated materials can potentially allow a significant increase in operating temperature for a chosen blade material.

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. Waspaloyhas been hich used extensively in the past, it is now being replaced by IN 718 and UDIMET 720. IN 706 with additional Mo and Nb allows for the manufacture of large discs but the process is very complex. The introduction of Hot Isostatically Pressed (HIP) material currently being investigated for the Fusion Reactor also offers the possibility of producing near finished sized components. There is some interest in ceramic forgings in Japan but tests have shown poor rotating properties. The most likely materials to be considered are IN 718 and UDIMET 720 however these are only expected to have a temperature ceiling of around 700^{o}C.

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.. For the advanced HTR and VHTR reactor developments both aluminium and Cr oxide formers are being considered as levels of impurities in the reactor coolant are not easily predicted at this stage in its development.

Coating of the blades is considered necessary for long life. A base material with adequate corrosion resistance is also needed even in the case of a coated blade. Coating must be of the same type (chromium oxide former or aluminium oxide former) as the base alloy.

For turbines aluminide coatings have been developed for resistance to oxidation. Metal, chromium, aluminium and ytrium coatings (MCrAlY, metal M being nickel, cobalt or iron) are used for hot corrosion. Thermal barrier coating (TBC) involving a second porous coating can be used to give an additional temperature advantage (of up to 100°C). Deposition of such coatings is done using vapour deposition (EP-PVD) or plasma spray.

The choice of the best coating remains to be made for HTR and VHTR helium environment.

Appendix B: scheme for selection of Candidate Alloys

General

Within the European project RAPHAEL work in the package ML 2 deals with metallic materials suitable for the application in VHTRs, for components as e.g. intermediate heat exchangers (IHX), pipes, nozzles and support structures. The basic operation environment may be defined as temperatures in the range of 650°C up to 950°C, continuous loads superimposed by transient loads in an environment composed by mainly Helium and impurities of water, carbon-monoxide, hydrogen and some carbon-dioxide, oxygen and nitrogen.

For metallic material this environment sets a fundamental challenge for the demanded properties as creep strength at a high level (e.g. 10 MPa creep rupture strength at 950°C for a 100.000 operation hour design) and resistance (on a technical judgement) to environmental interactions on properties.

For the proper component's design the respective properties of candidate material shall be available and, on the other hand, suitable design codes and design equations considering the general behaviour of materials in this temperature regime and, specific material grade related characteristic properties shall be generated.

In the following an assessment is made to compile the demanded properties and related test procedures in order to provide a guideline for the selection of a candidate material.

On the other hand, the list of features may be used to establish a kind of "reputation portfolio" for materials where the already known properties are being compiled and, the characteristics to be determined can be drawn off then from the appearing differences in the list (= remaining needs/required tests and examinations).

Development Scheme

The work in the project's subtask may follow the subsequent scheme:

- Compilation of operation conditions/parameters (e.g. temperature, stress, environment, etc.)
- Compilation of related load case schemes
- Compilation of possibly applicable metallic materials ("candidate materials")
- Compilation of metallic materials already examined within the scope of HTR R&D (or other) investigations
- Definition of the material properties to be determined
- Definition of the test methods and test conditions

- Evaluation of the available data and comparison with the data needed
- Judgement/evaluation in order to pre-select most promising candidate materials
- Definition of test and examination matrix
- Initiation and control of subsequent activities

Information on Load Cases and Failure Modes

In the following some load cases and possible failure modes for materials/parts operating in the creep regime with superimposed environmental effects (e.g. corrosion) are compiled in order to provide reference to the respective property item to be known.

Loading:

- Temperature
- Mechanical Loading
- Transients
- Environment/Chemistry
- Neutron Irradiation

Reaction of Material:

- Microstructural Instabilities
- Creep Deformation and Creep Damage
- Fatigue Exhaustion and Crack Initiation
- Corrosion (crack initiation)
- Crack Growth
- Ageing Process (Loss of Deformability)

Failure Modes:

- Ductile and Brittle Fracture due to Short Term Loadings
- Creep Rupture due to Long-Term Loadings
- Creep Fatigue Failure due to Cyclic Loadings
- Excessive Strain due to Incremental Deformation or Creep Ratcheting
- Loss of Stability due to Short-Term Loadings and Long-Term Loading
- Loss of Stability due to Long-Term Loading
- Environmentally Assisted Degradation (excessive corrosion)
- Fast Fatigue due to Instable Crack Growth

A more close consideration on the influence of the time to the failure mode is summarized in the following Table:

Time In-dependent Failure Modes	Time Dependent Failure Modes
Ductile short term rupture	Tough creep rupture
Brittle short term rupture	Non tough creep rupture
Fatigue failure	Creep fatigue failure
Buckling	Creep buckling
Gross distortion due to ratcheting	Gross distortion due to creep ratcheting
Loss of function due to excessive deformation	Loss of function due to excessive deformation
Environmental effects	Environmental effects

In the ASME Code NH, a technical rule for the design of nuclear components operating at temperatures where time-dependent properties have to be put into consideration, the definition is as follows:

6 (six) time-dependent failure modes are considered:

- Creep rupture under sustained primary loading
- Excessive creep deformation under sustained primary loading
- Cyclic creep ratcheting due to steady primary and cyclic secondary loading
- Creep fatigue due to cyclic primary, secondary, and peak stresses
- Creep crack growth and non-ductile fracture
- Creep buckling

Besides these effects also the definition of environmental effects by quantification (“environmental factor”) is requested.
This means that e.g. the influence of corrosion to the design data has to be defined by e.g. numbers, control of environment, wall thickness allowance, protective coatings or other suitable methods.

Compilation of Requested Properties and Available Information

Generally, data for following properties have to be compiled:

- Physical properties
- Creep rupture tests
- Relaxation tests
- Tensile tests
- Fatigue tests
- Fracture mechanics

Clearly these properties shall be available for a certain set of temperatures, loads and, also, for a certain set of structural conditions (e.g. aged) in order to provide information for “plant life time assessment”. Also the number of heats and product forms to be tested in order to fulfill the qualification requirements of common technical rules (e.g. ASME) and, environmental aspects has to be added.
The Table below only gives the “summary” of properties, a more detailed “requirement schedule” has to be prepared that includes the requested test temperatures, stress levels and e.g. requested minimum creep times and permitted extrapolation factors by numbers.
Only an example on what it could look like is given here.
More details will be given in a later stage of this work inside the RAPHAEL project.

In the following Table, an example list of needed property terms is compiled. This table is “designed” to provide short information on “reputation”. Details of available information shall be compiled in another Table.

Property / Property Term	**Material Grade (Available Data)**			
	Alloy 617	**Alloy XR**	**Alloy 230**	**Alloy NN1**
Tensile Strength Properties → f (Temperatures)				
Yield Strength	*RT – 1000°C*			
Ultimate Tensile Strength	*RT – 1000°C*			
Elongation at Fracture	*RT – 1000°C*			
Toughness Properties				
Impact Strength				
Creep Properties				
1% Creep Strength	*700 – 1000°C,*			
Creep Ruture Strength	*700 – 1000°C, up to 55.000 h*			
Minimum Creep Rates	*...*			
Fatigue				
Creep Fatigue				
Aging				
Structural Investigations				
Time-Temperature-Precipitation Diagram				

Tensile Test Properties (Yield Strength, Ultimate Tensile Strength, Elongation at Fracture)				
Impact Strength/Toughness				
Creep Properties				
Creep Fatigue				
Fracture Mechanics				
Modulus of Elasticity				
Coefficient of Thermal Expansion				
Thermal Conductivity				
Poisson’s Ratio				
Stress-strain curves (average and minimum)				
Stress vs time to 1% strain (average, minimum)				
Stress vs time to onset of tertiary creep (minimum)				
Continuously cycling fatigue life as a function of strain range at a fast strain rate				
Creep-fatigue cyclic life involving cycles with various strain ranges and hold times (average)				
Fracture Mechanics (KIC, Jc values and J-Rcurves)				
Supplementary Tests for Component’s Behaviour Description and Constitutive Equations				
Environmental Effects				
Ageing (see above)				
Corrosion				
Design Data				
Technical Specifications				
Design Equations				
Constitutive equations for conducting time- and temperature-dependent stress-strain analysis				

Miscellaneous

Aging

Since materials undergo structural changes by operating time at elevated temperatures and, change of structure is depending on both, time and temperature range, it is important to have information about the respective material grade on the Time-Temperature-Precipitation diagrams.
Information will be suitable to characterize the behaviour of an IHX material as the IHX operates “in-situ” at different temperatures (e.g. 850°C inlet, 250°C outlet and, all temperatures in between this range).

Corrosion

Although corrosion resistant materials will be used, the materials are altered by e.g. forming and growth of the protecting scale and, other effects inside the material (e.g. carburizing due to the impurities in the environment) may happen.
Influence of these effects to the mechanical properties unless “compensated” by wall thickness allowance shall be considered and investigated, respectively.

The influence of atmosphere on the data set achieved shall be considered for applicability to other environments as tested (e.g. it is well known that creep rupture strain will be different when specimens are tested in air (more) compared to tests in protective atmosphere).

Appendix C: Reference VHTR Plant Design Data ANTARES

	Opt 1	Opt 2
Reactor power	600 MWt	600 MWt
Core inlet temperature	400°C	400°C
Core outlet temperature	950°C	950°C
Primary pressure	5.0 MPa	5.5 MPa
Number of primary circulators	2	1
IHX type	Tube	Plate
Reactor vessel material	9 Cr	9 Cr
Secondary fluid	He	He

Table C1 Reference VHTR Plant Design Data ANTARES

Opt 1 tube IHX	Primary	Secondary Helium
IHX outlet temperature	390°C	900°C
IHX inlet temperature	950°C	340°C
IHX inlet Primary pressure	5 MPa	4.5 MPa
Flow rate (kg/s)	210	210
IHX Max pressure loss	2 %	2 %
IHX Power	610 MWt	
IHX Effectiveness	90 %	
Primary circulators (2) pressure head	0.15 - 0.2 MPa	
Primary circulators (2)	Around 10 MWt	
Primary circulators (2) inlet	390 °C	
Primary circulators (2)	400°C	

Table C2 Reference VHTR Plant Design Data ANTARES (IHX (Tube Design)

Opt 2 plate IHX	Primary Helium	Secondary Helium
IHX outlet temperature	390°C	900°C
IHX inlet temperature	950°C	340°C
IHX inlet Primary	5.5 MPa	5.0 MPa
Flow rate (kg/s)	210	210
IHX Max pressure loss	2 % (1.5 % for IHX	2 % (1.5 % for IHX
IHX Power	610 MWt	
IHX Effectiveness	90 %	
Primary circulator pressure head	0.15 - 0.2 MPa	
Primary circulator	Around 10 MWt	
Primary circulator inlet	390 °C	
Primary circulator	400°C	

Table C3 Reference VHTR Plant Design Data ANTARES (IHX (Plate Design)