EUROPEAN COMMISSION

Community Research

RAPHAEL

Contract Number: 516508 (FI6O)

DELIVERABLE (D-CT3.1)

Review of tribology and corrosion conditions of components for HTR and VHTR

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Reporting period: P2 (15/04/2006-14/04/2007)

Date of issue of this report : 24/10/2006

Start date of project : **15/04/2005** Duration : **48 Months**

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)		
Dissemination Level (place an X in the appropriate cell)		
PU	Public	
RE	Restricted to the partners of the RAPHAEL project	**X**
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ReActor for Process heat, Hydrogen And ELectricity generation (RAPHAEL)		
Sub-project: SP-CT **Work package:** 3	**RAPHAEL document no:** RAPHAEL-0608-D-CT3-1	**Document type:** D=Deliverable / M=Minute / P=Progress report / S=Support
Issued by: Carole FALCAND ANP-F & B.C. FRIEDRICH ANP-D **Internal no.:** NFTM R06.1043		**Document status:** Final

Document title

Review of tribology and corrosion conditions of components for HTR and VHTR

Abstract

Based on available information concerning the present design for ANTARES, this re-view points out the tribological operating conditions of main components presenting wear exposed localizations for e.g. control rods, internal equipments, IHX (intermediate heat exchanger), hot gas duct and other components.

This report shall provide the available information concerning the environmental conditions (temperature, pressure gas, nature of gas (impurities)..) and tribological conditions such as the type of contact motion (sliding, bearing, fretting,…), the typical contact conditions (contact pressure, displacement, speed, …) and will specify whether these occur in normal operating or transient conditions (start or outage periods, control rod drop,..).

This document has been initiated by ANP-F, completed by ANP-D, and checked by NNC. It is sent to J.Pirson (Tractebel Engineering) for the safety condition examination.

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
00	24/10/2006	Final issue	C. FALCAND, ANP-F B.C. FRIEDRICH, ANP-D	C. FALCAND, ANP-F	D. BESSON, ANP-F	E. BOGUSCH, ANP-D

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ISO 9001 VERSION 2000
N° QUAL/2002/18692c

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NTT-F R06.1043

MODIFICATIONS	
INDICE	DATE
0	24/10/2006

RAPHAEL IP – DELIVERABLE D-CT3.1

REVIEW OF TRIBOLOGY AND CORROSION CONDITIONS OF COMPONENTS FOR HTR AND VHTR

KEY WORDS

Tribology
Corrosion
HTR
RAPHAEL IP
Review

DISTRIBUTION
Niveau de protection
~~NORM (normal)~~
FILT (filtré)
~~CONF (confidentiel)~~

N° Réseau : 181006

DIFFUSION	FONCTION	NOM	VISA	DATE
D. BESSON (NEELFD) D. VERRIER (NEPL-F) O. GELINEAU (NEELFM) J.-Ph. VERNOT (NTT-F) G. BRINKMANN (NESS-G) D. BUCKTHORPE (NNC) L. CACHON (CEA) G. LAFFONT (CEA) W. VON LENSA (FZJ) J. PIRSON (SUEZ TRACTEBEL)	Rédacteurs	C. FALCAND	CFalcand	17/07/2006
	Rédacteurs	B.C. FRIEDRICH		
	Vérificateur	J. Ph. VERNOT		19/10/06.
	Approbateur	G. BERTHOLLON		24/10/2006

SIEGE SOCIAL : TOUR AREVA - CEDEX 16 - 92084 PARIS LA DEFENSE - FRANCE

REVISIONS

Ind.	***Date***	***Parag.***	***Page***	***Appen-dix***	***Revision object***
0					Document edition

ABSTRACT

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This report shall provide the available information concerning the environmental conditions (temperature, pressure gas, nature of gas (impurities)..) and tribological conditions such as the type of contact motion (sliding, bearing, fretting,…), the typical contact conditions (contact pressure, displacement, speed, …) and will specify whether these occur in normal operating or transient conditions (start or outage periods, control rod drop,..).

This document has been initiated by ANP-F, completed by ANP-D, and checked by NNC. It is sent to J. Pirson for the safety condition examination.

TABLE OF CONTENT

1. REFERENCE DOCUMENTS

[1]	HTR-E-02/11-D-5-1-2	D38 – Review and identification of typical HTR tribology conditions of components
[2]	Borel, M.O. et al.	The Tribological Behaviour of Tube Supports in Helium Heat Exchangers, Nuclear Technology – Volume 66 n°3 – September 1984 – Page 512 - 517
[3]	Voisin, J. M.	Méthodologie pour l'étude de l'endommagement d'un contact tube-grille – Thesis 1992 (*Methodology for the study of a grid-tube contact*)
[4]	Li, C.C.	Characterization of Thermally Sprayed Coatings for High Temperature Wear Protection Applications, Thin Solid Films, 73 (1980), Page 59-77
[5]	HTR-E-05/12-M-0-0-9	Minutes of HTR-E 9th PMT meeting

2. INTRODUCTION

The objective of RAPHAEL-IP SP-CT work package 3 is to realise an up-dating of the tribological problems met in former HTRs, to review and identify the corresponding tribological environments and finally find possible materials or coatings able to bring a reliable answer to these situations through elementary tests in a representative and tribological Helium environments close to identified components such as control rods, stator seals or hot gas duct. The aim of this deliverable D-CT3.1 is to make a point on the different tribological conditions which can be met by VHTR // ANTARES components in operating conditions.

Components designed by moving parts and function (e.g. control rods, blowers, …) of a modern HTR with indirect cycle are particularly affected by tribological issues. It must be noted that poor operation of these wear exposed components can dramatically impact the safety and availability of the reactor.
These issues have been fully mastered in the reactors built in the past, but with lower temperatures, different materials and different configurations. This legacy cannot therefore be simply extrapolated to present possible designs and materials and least of all to fulfilling the requirements of VHTR operating conditions. Therefore qualification tests will be carried out in this WP, with representative conditions, considering VHTR conditions (Temperature, Loads, Pressure, Velocity, etc.), and with a test facility allowing a large range of tribological contacts, long-term tests and coupling of mechanical, tribological and corrosion tests.
Some tests relative to the new graphite grades will be also carried out. For possible extrapolations for even higher temperatures (> 1000°C), ceramic materials will be also investigated.

3. DESCRIPTION OF D-CT3.1

The title of the document is "Review of tribology and corrosion conditions of components for HTR and VHTR".
Based on available information concerning the present design for ANTARES, this review will point out the tribological operating conditions of main components presenting wear exposed localizations for e.g. control rods, internal equipments, IHX (intermediate heat exchanger), hot gas duct and other components.
This report shall provide the available information concerning the environmental conditions (temperature, pressure gas, nature of gas (impurities)..) and tribological conditions such as the type of contact motion (sliding, bearing, fretting,…), the typical contact conditions (contact pressure, displacement, speed, …) and will specify whether these occur in normal operating or transient conditions (start or outage periods, control rod drop,..).

4. ORGANISATION OF D-CT3.1

The organisation of the document can be found in Table 3. The involved partners are AREVA NP GmbH and AREVA NP SAS. This document is available on SINTER network.

5. RESULTS OF D-CT3.1

The main results of the work are the following:

5.1. Feedback from HTR-E [1]

5.1.1. PBMR type reactor

5.1.1.1. Description

The PBMR type reactor is being developed in South Africa as the first of a new generation of cost-effective and inherently safe power plants that uses a modular approach. It consists of a helium cooled graphite moderated reactor core coupled to a power conversion unit that uses a gas turbine driven by the reactor coolant gas. The reactor system is based on an annular pebble bed core design and uses a solid central column of graphite. Fuel spheres are loaded from positions on the periphery, through the top reflector to form an annulus, which enables the required power output to be achieved within the fuel safety margin. The process cycle used is the Brayton cycle with a closed circuit water-cooled inter-cooler and pre-cooler.

Separate turbo-compressors and power turbine are used in the power conversion unit (PCU) with magnetic type bearings to avoid contaminants in the helium circuit and limit maintenance.

The high efficiency power system is achieved from a 900°C reactor gas outlet temperature combined with a high efficiency recuperator. Helium leaves the pebble bed reactor and flows through the high and low pressure turbines and these drive the associated compressors. Power control is achieved by adding or removing helium to the volume inside the main circuit, which increases primary circuit pressure and mass flow rate without changing temperatures and pressure ratios. The reactor systems are placed inside a Reactor Pressure Vessel with the PCU components located separately. The whole plant is housed in a single building.

5.1.1.2. Localisation of problems

The published information on this reactor design is limited. There are little or no details available on components and no information on loading and tribology.

Components working at T < 600° C are heat exchangers, low temperature part of recuperator, low temperature part of control rods mechanism, core conditioning system with essentially a sliding motion.
The components operating at 700-900° C are the high temperature part of CRDM, of recuperator, turbine power.
This review is a preliminary assessment based on the few references located and using NNC's experience in gas reactor operation and on the Dragon reactor. The conclusions reached should therefore only be taken as an indicator on where possible future investigation may be needed.

A recapitulative table of components with potential problems, type of motion and temperature, is provided with Table 4.

5.1.2. GTMHR type reactor

5.1.2.1. Description

The GTMHR is a Helium cooled graphite moderated reactor core coupled to a power conversion unit using a gas turbine driven by the reactor coolant gas. The reactor system is based on an annular core design using hexagonal graphite blocks as moderator, channels with fuel microspheres under a compact shape, and channels for Helium circulation, control rods, ... The gas outlet temperature is 850°C (pressure 70 bar), with a 490°C inlet temperature.
The characteristics of the GTMHR are given by:

- the same shaft for the turbine, alternator and compressors

- heat exchangers Helium / water
- a recuperator which enhances the thermal efficiency.

5.1.2.2. Localisation of problems

- AREVA focused its study on control rods drive mechanism and tubes or structures subject to vibration.
- CEA focused its study on hot gas duct, stator seals and internals. The studied motion for hot gas duct was the motion due to thermal compensation unit against metallic tube, and sealing strips. It does not include the insulation jacket.

For both studies, the results are given under the shape of charts summarising all the known operating conditions per component (see Figure 2 to Figure 5). The detailed filling cards giving general information on each component, parts which are in contact with their dimensions, tribological and environmental conditions … are available in document [1].

5.1.3. Conclusions of D 38

The bibliography showed that the data are not totally known, due to the evolution of design of GTMHR or difficulty to obtain data (PBMR). Particularly, information concerning the typical contact parameters (contact pressure, displacement, speed …) cannot be clearly specified because of the lack of reliable and accessible data concerning this topic.
Nevertheless, potentiality of solicitations like impact, fretting, dwelling, were shown to be seriously considered during the characterisation test phase.
From the obtained data, it also appeared that for both PBMR and GTMHR components, excepted the graphite internals working till 850-900° C, and generally speaking the hottest parts of the core, other components have lower operating temperatures around 500-700° C, which can be studied on both tribometers proposed by Framatome-ANP (till 600°C – load max 500 MPa) and CEA (till 1000°C – load max 20 MPa).

- FANP Technical Centre presented the pin on disk tribometer bench, whose characteristics are:
  - Temperature up to 600° C
  - Load up to 500 MPa (representative of real loading conditions with specific pressure and adapted shape (pieces of real component))
  - Helium 1 bar

- CEA tribometer bench, whose characteristics are :
  - Temperature up to 1000° C
  - Load up to 20 MPa
  - Helium 6 bar + impurities

During the test phase, the needed parameters shall be: contact pressure, type of contact, temperature, range of displacement, range of frequency, antagonist materials. Data are missing for contact pressure and range of displacement, but they are available for other parameters.

5.2. Feedback from tube support in He heat exchanger [2]

A closed-cycle gas turbine plant for high-temperature gas-cooled reactor application contains a number of heat exchangers for low to medium temperatures (up to 500°C). The tubes of these heat exchangers are held in multiple spacers. Since thermal expansions lead to relative motions between tubes and spacers, a predictable tribological behaviour of this sliding pair is important.

The search for a low-cost treatment to achieve good tribological properties has led to manganese phosphate conversion layers on ferritic steel. Laboratory tests in helium with representative tube/spacer configurations have shown very small wear rates, complete absence of scuffing, and moderate and predictable coefficients of friction.

Mechanical testing of phosphated tube material did not reveal any detrimental influence from the phosphate treatment. This work was performed under the joint German/Swiss development agreement for the helium high-temperature turbine project, HHT.

An important point was to adapt the design to minimise contact loads. With low loads, the manganese phosphate treatment has a good behaviour, and it's not necessary to get hard coatings, more expensive. It is not necessary to treat both pieces.

In conclusion, Phosphate treatments on ferritic spacers and tubes impart excellent tribological properties at the low loads tested and at temperatures of up to at least 530°C. Phosphating the spacer alone is a very economical solution and is sufficient at loads up to 20 N per tube. At higher loads, the tubes ought to be phosphated as well.
Negative clearances, e.g., preload between tube and spacer, can be tolerated for tribological considerations. Untreated tubes and spacers are not recommended because of high friction and the danger of surface deterioration.
It shall be remarked that the information of the long term temperature stability of these coatings has been assessed but, information is not sufficient at present time.
More sophisticated surface treatments, such as plasma-sprayed hard facings or nitriding, give equally good or better results but are not an economical proposition.

5.3. Feedback from J.M. Voisin's thesis [3]

The aim of this thesis was to suggest a method for the study of grid-tube contact damage.
The conclusion of the work is as following:

For a new steam generator design, material choice can’t be issued from used component examination: all damage origin have to be studied so long the working condition knowledge does not allow to exclude them. Concerning contact problems, it is known that 2 major mechanisms are able to lead to the previous interface failure: crack and material loss (wear). For grid-tube contact, it is difficult to determine precisely the *type of contact*, and particularly loading conditions whole contacts (more than 30 000 by steam generator). Thus, it is not possible to cancel a priori one of two possible failure modes, due to the long term reliability. That’s why this study has been conducted in two directions, in order to research the “ideal material” to answer the initial question.

A purely theoretical approach does not allow to define the tribological behaviour of materials from their mechanical and physico-chemical characteristics. The experimental way turns out always essential. Here, this approach was to be double.

On one hand, a test bench has been realized (movements of *shocks and sliding*) to get closer to real conditions of functioning, leading to the material loss of the loaded samples. The loads at the connection level depend on the architecture of the generator and in particular the distance between anti-vibration bars. The influence of the vibratory movement was studied: the oblique impact movement (*shock + sliding*) generated the most consequent wear. Furthermore, we determined that the damages on the tube are more important when the material of *the boring is harder* than that of the tube. The realized tests also emphasized the *geometry of the tube-grid connection*. Indeed, a straight shape of the boring produces, even for a low alignment defect between boring and tube, a geometrical singularity at the contact level. This one generates stronger damages than those obtained with a shape in diabolo.

On the other hand, the study of *sticking* and *cracking* led to develop a test procedure which characterizes the behaviour of various materials in contact loaded in small displacements. So, to decrease the risk of crack initiation, in a given environment, it is important that the sticking does not lead to strong local stresses (case of stainless steel against ferritic steel). It is preferable for the *local loads* to be *low* (case of the sliding varnish), because they create tensile stresses, noted σ_{xx}, in contact edge. The crack creation also depends on the crack initiation material resistance. The tube nature, being imposed, was not able to be modified to decrease the possibilities of sticking and cracking. The nitriding treatments, as well as the sliding varnish, however allowed to improve the behaviour of the ferritic steel regarding the cracking risk.

However, the nitriding treatments do not answer both requirements (good behaviour of the connection in terms of wear and cracking) contrary to the sliding varnish which limits the sticking and the damages in vibratory movements.

An organization chart is proposed below. It shows the various stages to choose a material:

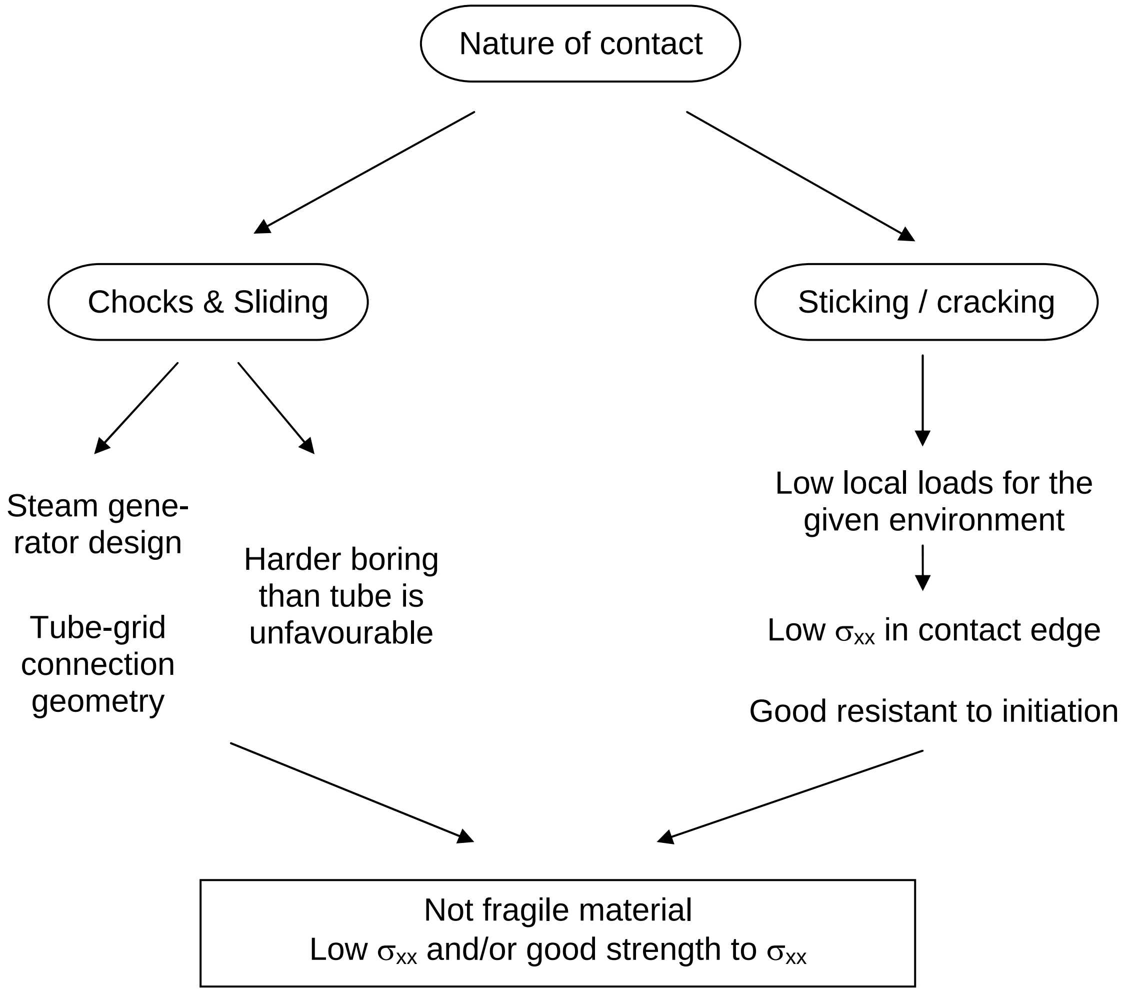

Figure 1: Interaction - Result Organization Scheme

The technical realization and functioning imperatives impose the nature of contact. It was necessary to avoid debris strapping within the contact (often favourable configuration in the problems of contact) not to block the passage of the coolant and risk a connection blocking. Furthermore, the economic criteria ask that the connection is simple of realization.

From this observation, both experimental approaches end in the following conclusions:

- At the level of the vibratory tests close to characteristics of nominal functioning of the steam generator (types of movement, amplitude of shocks, geometry), it is necessary to avoid the geometrical peculiarities of contact. It is thus essentially a question of design. Furthermore, a boring which presents a bigger hardness than that of the tube is harmful to a good behaviour of the connection in term of wear.
- At the level of the simulation of the behaviour in sticking, the used test having a more general character (the conditions of contact are a priori taken away from those of the normal functioning), it allows to highlight the catastrophic risks of

cracking. The behaviour of materials put in contact does not have to lead to strong local stresses otherwise cracks can begin in the contact periphery by a mechanism of fatigue. The reliability of the installation requires that the loads are low because the presence of cracks is not allowable.

5.4. Feedback from General Atomic Company [4]

High temperature gas-cooled reactor wear protection needs:

Key component	*Technical considerations*	*Activities and comments*
Thermal barrier	The major concerns are sliding wear and self-welding of coverplates and attachment fixtures. There is also possible fatigue loading in the attachment fixtures due to chattering (stick-slip sliding at low sliding velocity)	Previous work on full-scale components and experimental specimens under SC HTGR conditions with testing temperatures up to 816 °C (1500 °F) has shown that chromium carbide-Nichrome coatings provide good wear protection. Work under GT HTGR and PH HTGR conditions is in progress.
Control rod drive mechanisms	Wear coatings are needed in high stress flexible joints etc. In addition, neutron irradiation damage of coatings must he considered	Preliminary results of irradiation testing reported by the Hanford Engineering Development Laboratory have shown that detonation-gun-applied chromium carbide-Nichrome coatings are capable of withstanding fluences of 8×10^{22} neutrons cm^{-2} fast-neutron irradiation
Reactor internals	The core lateral restraint and peripheral seal are subject to motions that have the potential to cause wear damage. Another concern is that there are locations where contact occurs between metals and the graphite reflectors, and this requires evaluation of adhesion between graphite and metal.	Previous studies on graphite-metal compatibility indicated that metals are subject to carburization. Additional work on friction and wear between coatings, metals and graphite is required
Heat exchangers	Tube damage caused by interactions between the tubes and tube-support plate is the major concern in recuperator, precooler, core auxiliary heat exchanger and intermediate heat exchanger design. Wear protection devices such as wear shields and ring assemblies are used in some heat exchanger designs. Coating residual stresses which could cause distortion of protection devices with thin cross sections may pose some limitation for coating application. Other solutions under development include applying insert material to the support plate as cushioning or applying a wear coating directly to the tube.	Preliminary studies of the tribological properties of high temperature self-lubricating materials under simulated SC HTGR conditions have shown them to be feasible as insert material. In the application of coatings on tubes, there is concern about the creep and creep-fatigue properties of the tube being degraded. If a coating is to qualify for application to the tube, information will be needed on the effects of coatings on the properties of substrate alloys
Turbomachinery	An in-reactor turbomachine will exhibit some unique features. Preliminary study	Evaluation of chromium-carbide-base and stabilized zirconium-oxide-base

Key component	*Technical considerations*	*Activities and comments*
	indicates that fretting wear at the turbine blade root and self-welding and sliding wear at the turbine inlet volute, rotor, casing and duct will be important and that coatings are called for to provide protection of critical components	coatings and alternative commercial coatings is under way

Table 1: Compilation of Locations Exposed to Wear in a HTGR

This article gives coating selection criteria:

- Elevated temperature structure stability
- Compatibility with substrate alloys
- Compatibility with high temperature gas-cooled reactor helium
- Friction and wear behaviour

Techniques for metallurgical characterization:

- Microstructural analysis (X-ray diffraction, SEM, EDAX, TEM)
- Coating substrate bond strength measurement (difficult to get a right value)
- Residual stress measurement
- Hardness and density measurements
- Compatibility study of coatings with substrate alloy and high temperature gas-cooled reactor helium environment
- Friction, wear and self-welding studies

5.5. Helium impurity level

The levels of impurities defined in HTR-E WP6 are as following:

Impurity	**Concentration in vpm**	**Partial pressure for 70 bar in** μbar
H_2O	< 0.1	< 7
CO	< 2	< 140
N_2	< 1	< 70
H_2	< 5	< 350
CH_4	< 1	< 70

Table 2: Impurity Level in a VHTR

Remark: the numbers given here do not necessarily represent the maximum permitted impurity level but, have to be set and adjusted to a selected level in order to provide “benign” VHTR environment

5.6. Localisation of Problems VHTR // ANTARES

Since the plant’s design is not finalized yet, assessment to possible localizations of wear are based on existing designs and general expertise in equipment design.

A recapitulative table of components with potential problems, type of motion and temperature, is provided with Table 5.

Table 3:
Deliverable D-CT3.1

Title	"Review of tribology and corrosion conditions of components for HTR and VHTR"
Schedule	***May 2005 – October 2006***
Responsible	***Framatome ANP France (1)***
Partners	***Framatome ANP Germany (11)***

DOCUMENT ORGANISATION

INDEX	**RESPONSIBLE**	**INPUT NEEDED**	**DATE REFERENCE**
General principles			
Document listing the information required in the text, will concern the following types of reactors: • VHTR (ANTARES) • HTR-E	**FANP-F and FANP-D**		Draft : Aug 2006 for partner comments RAPHAEL06/08-D-CT3.1 Final : Oct 2006

Component	Area	Tempera-ture	Type of Motion	Possible Materials	Potential Prob-lems
Helium Inventory Control System	valves compressors				static adhesion wear and leakage
Heat Exchangers	pre-cooler inter-cooler	<150°C	thermal movement vibration	carbon steel	fretting adhesive wear rubbing
Power Turbine	magnetic bearings braking system	700°C			
Recuperator	plate supports	500- 700°C		austenitic steel (type 347)	
Turbo Units (LP & HP)	bearings (elec-tromagnetic. axial, capture)		sliding		high speed, long life fretting erosion due to dust
Reserve Shut Down System	storage container valve		sliding		static adhesion wear and leakage
Reactivity Control System (Control Rod)	drive mechanism	450 - 900°C	sliding mo-tion	alloy 800 or similar	wear gear wear chain drive wear contact adhesion
Core	pebbles blocks bricks keys supports steel barrel	450 - 900°C	thermal movement sliding	graphite type 316 stainless steel	brick restraint brick movements thermal cycle wear cracking from keyed slots
Core Conditioning System	valves blowers service hatch heat exchanger	~150°C	sliding		static adhesion wear and leakage

Table 4: Potential problem - PBMR

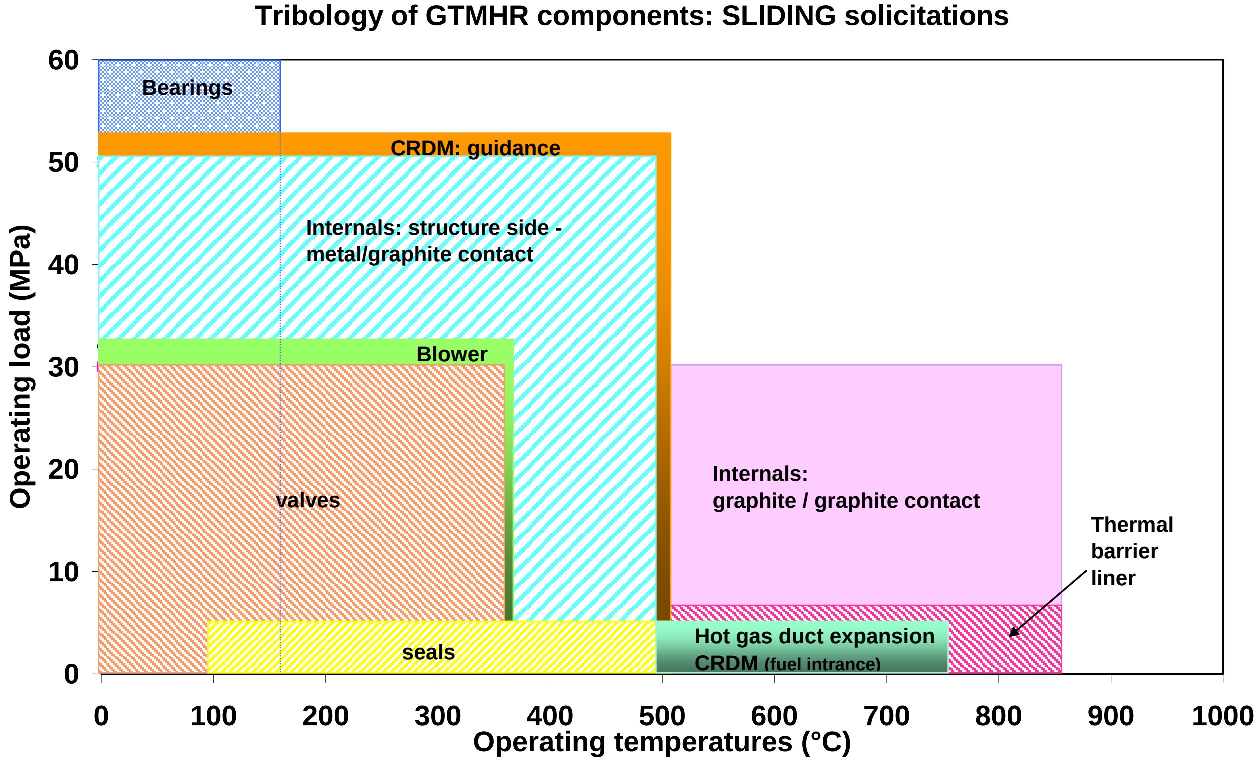

Figure 2: Sliding solicitation

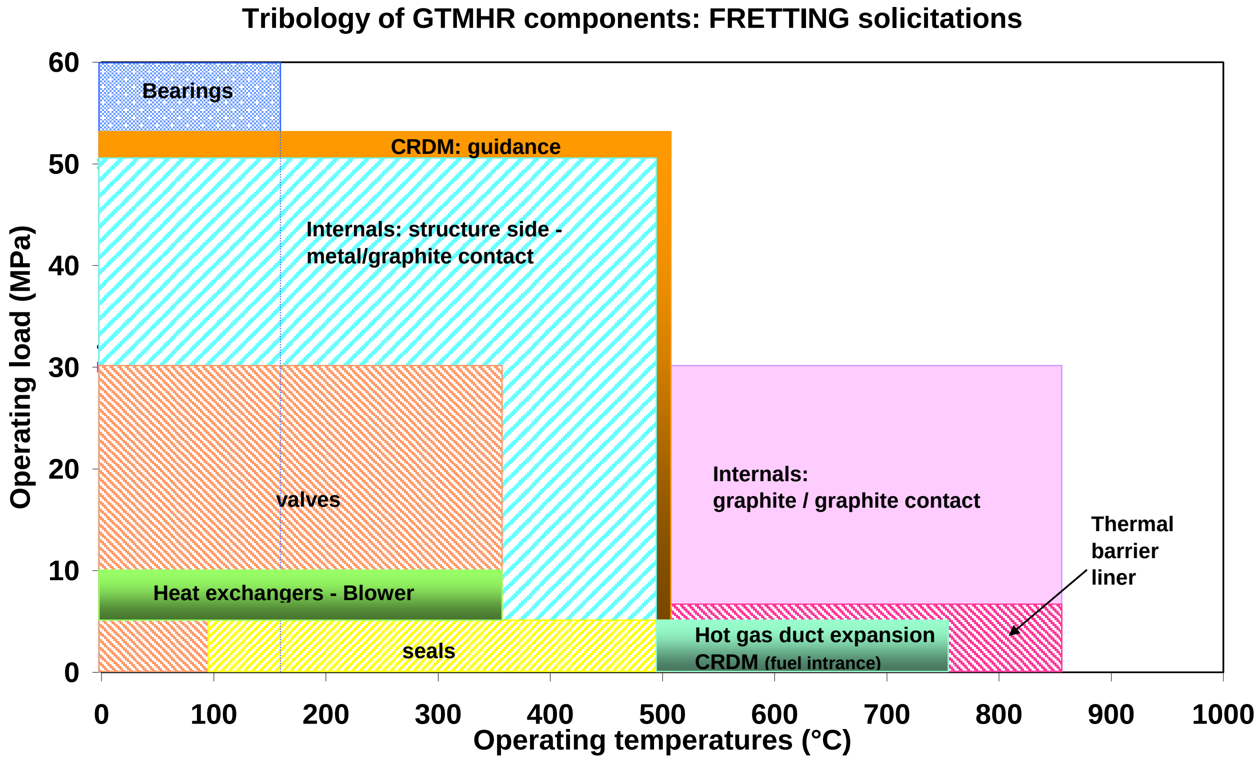

Figure 3: Fretting solicitation

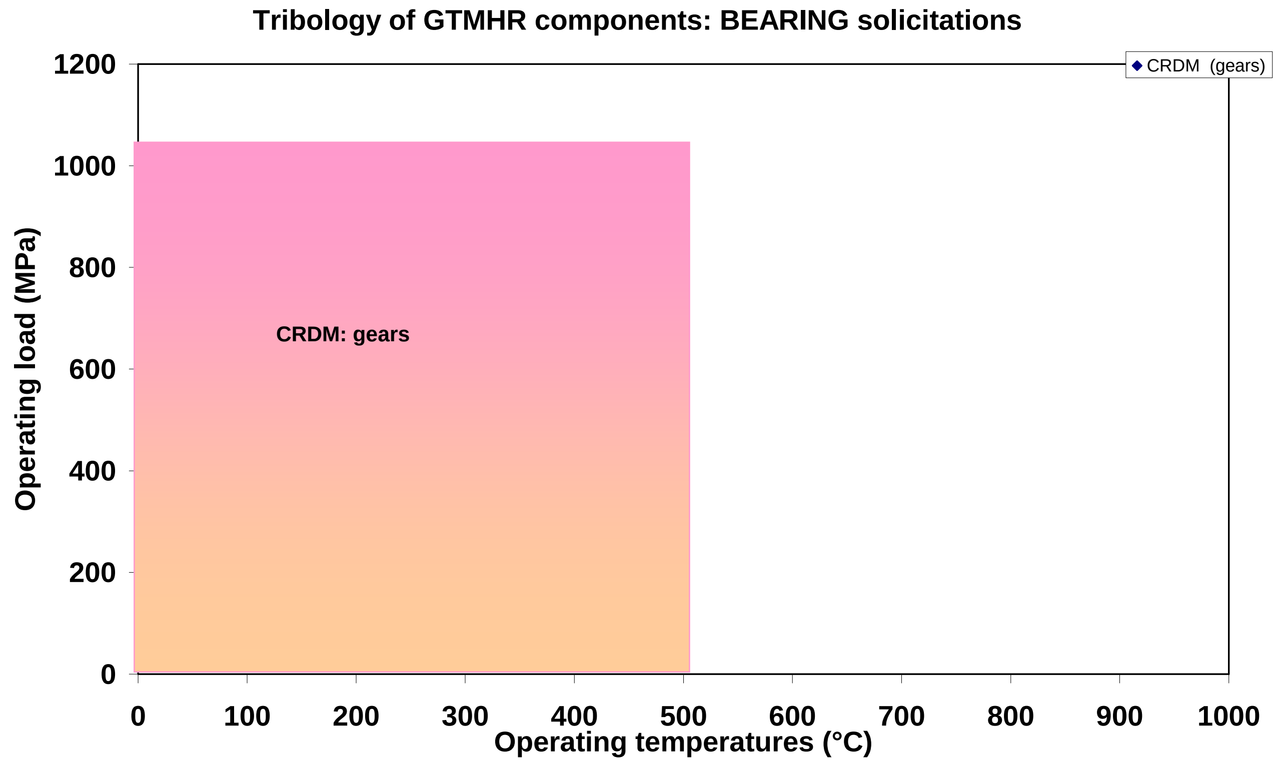

Figure 4: Bearing solicitation

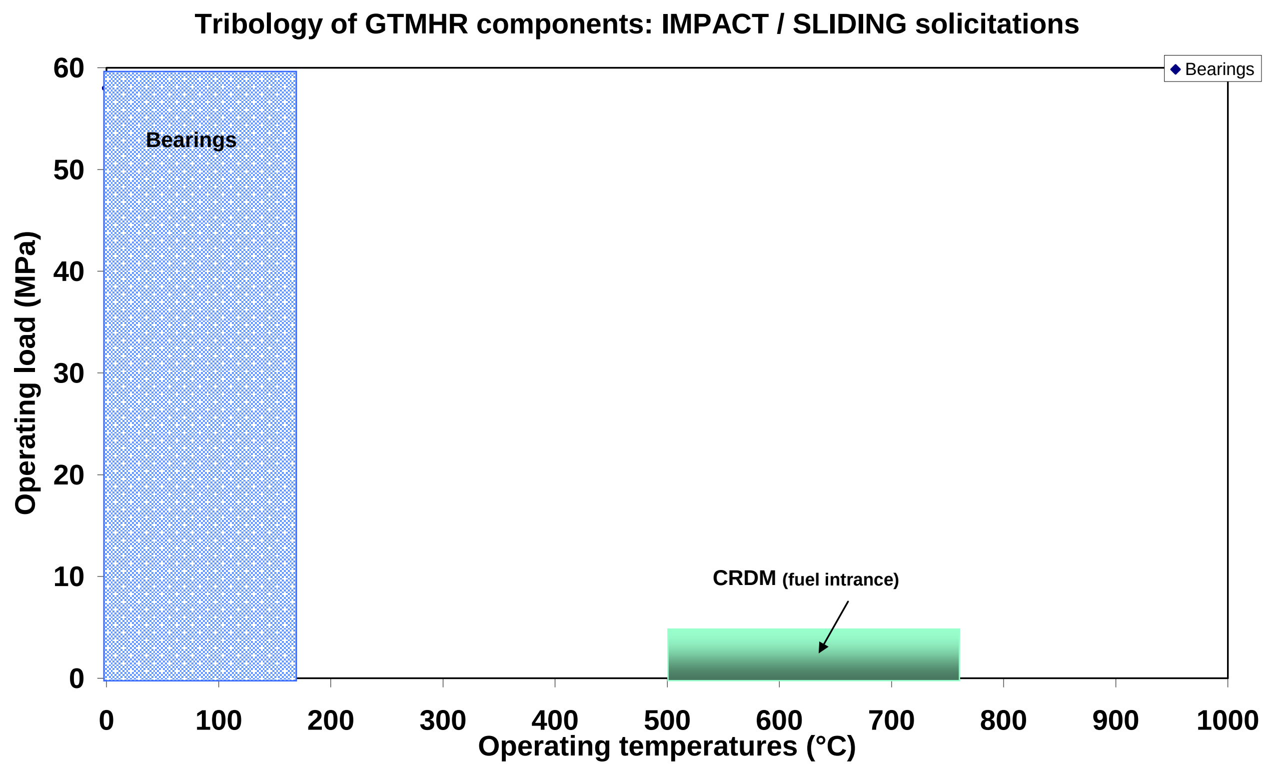

Figure 5: Impact / Sliding solicitation

Component	Area	Temperature	Type of Motion	Possible Materials	Potential Problems
Primary Hot Gas Duct	Liner	850 - 950°C	Thermal Movement Vibration	Alloy 800 or Alloy 617	Static adhesion/Sticking Fretting Long life
Heat Exchanger Plate Type	Plate supports	500 - 700°C	Thermal Movement Vibration	Alloy 800 or Alloy 617 or Alloy 230	Static adhesion/Sticking Fretting Long life
Heat Exchanger Tubular Type	Tube spacers	850 - 950°C	Thermal Movement Vibration	Alloy 800 or Alloy 617 or Alloy 230	Static adhesion/Sticking Fretting Fatigue Long life
Primary Blower	Bearings (electromagentic. axial, capture)	500 - 700°C	Sliding		High speed Long life Fretting Erosion due to dust
Small Primary Valves	Sealing systems Guiding system Drive mechanism	250 - 450°C	Sliding		High speed Long life Fretting Fatigue Gas tightness
Control Rods	Drive mechanism	250 - 450°C	Sliding		Low speed Long life Fretting Fatigue
Core	Blocks Bricks Keys Supports Core barrel	450 - 900°C	Thermal movement Sliding	Graphite Type 316 stainless steel	Brick restraint Brick movement Thermal cycle wear Cracking from keyed slots
Secondary Hot Gas Duct	Liner	800 - 900°C	Thermal movement Vibration	Alloy 800 or Alloy 617	Static adhesion/Sticking Fretting Long life
Secondary Separation Valves	Sealing system Guiding system	350 - 900°C	Sliding		High speed Fretting

Component	Area	Tempera-ture	Type of Motion	Possible Materials	Potential Prob-lems
	Drive mechanism				Fatigue Long life Gas tightness
Reverse Shutdown System - Storage Container Valves	Sealing system Guiding system Drive mechanism	250 - 450°C	Sliding		High speed Long life Fretting Fatigue Gas tightness
Shutdown Cooling System - Valves Blowers Heat Exchangers	Sealing system Guiding system Drive mechanism Bearings Supports	100 - 950°C	Sliding Thermal movement Vibration		High speed Long life Fretting Fatigue Gas tightness Static adhe-sion/Sticking Erosion

Table 5: Potential Problems - VHTR//ANTARES