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HTR-E / WP5: Tribology in helium environment

DELIVERABLE D40

"Proposal of elementary tests"

MOTS CLES

Tribology
Temperature - Pressure load
Sliding – fretting
Gas environment– helium
HTGR component - GTMHR
PBMR
Materials - Coatings

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Content

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(1) European contract: “High temperature reactor components and systems” – Project FIKI – CT-2001-20177 “HTR-E” – August 2001 – Annex 1

(2) WP5 Work Plan Report for : " Tribology in Helium Environment" - Document N°: HTR-E- 02/03 – D – 5- 0 – 1 – deliverable D36

(3) Deliverable D37 – HTR-E- 02/12 – D – 5 – 1 - 1– Review and identification of tribological problems in former HTR or FBRs

(4) Deliverable D38 – HTR-E 02/12-D-5-1-2 –rev B - Review and identification of typical HTR tribology conditions of components – 11th/08/2003

(5) Deliverable D39 - HTR-E 03/12-D-5-1-3 –rev A –"Review of existing materials and coatings" – 30th January 2004

(6) Contribution from NNC to Deliverable D40 – August 2003 - B. RILEY (NNC)

(7) Contribution from CEA to Deliverable D40 - NT – STR/LCET – 03/038 – dated 21st /11/2003

(8) Contribution from FANP to Deliverable D40 – TFCM R03.1059 – C. FALCAND – 18th February 2004

(9) Contribution to Deliverable D37 – FANP GmbH – E. Ebert, W. Wild – ref NGES3/2002/0026 – June 2002

SUMMARY - CONCLUSIONS

A number of materials including 316 Stainless Steel, other austenitic steels type 347, alloy 800, carbon steel, 9Cr steel, or nickel alloys and graphite, are envisaged in PBMR and GTMHR for several main components such as control rod drive mechanisms, hot gas duct, stators seals, internals...

The type of tribological solicitations per component are described for PBMR and GTMHR (sliding, fretting, adhesion, …). The possible coatings to be used in order to protect the base material, are listed per operating temperature field (ZrO_2, SiC, Cr_3C_2, TiC, WC/NiCr,..). A test protocol common to FANP and CEA and a description of available tribometers are given. Selected experiments to be performed in 2004-2005 by Framatome-ANP and CEA in "pure" Helium and Helium + impurities environment, are listed.

Notas :

(1) Niveau de protection (rayer les 2 mentions inutiles)

NORM	Diffusion sans restriction
FILT	Diffusion restreinte, avec accord du rédacteur et du client
CONF	Aucune diffusion autre que celle demandée par le client

(2) Nature document (indiquer le code correspondant)

APPRO	Spécification d'appro
CON	Spécification de contrôle
CR	Compte rendu
DF	Document fournisseur
EQUIP	Spécification d'équipement
FMO	Fiche de mode opératoire
NT	Note technique
PROC	Procédure
QMO	Qualification de mode opératoire
RECETTE	Spécification de recette
RES	Rapport d'essais
RET	Rapport d'étude
RT	Rapport technique
STAGE	Rapport de stage

HTR-E / WP5: DELIVERABLE D40
PROPOSAL OF ELEMENTARY TESTS

INTRODUCTION

This document reports on elementary tribological tests to be carried out in support of the HTR programme. The report contributes to deliverable D40 of the HTR-E Project (1)(2). Information relevant to test conditions and detailed recommendations are made for the conditions to be applied during the elementary tribological tests.

Tribological problems identified by previous studies were reviewed in D37 (3). In D38 (4), tribological concerns were identified for the GTMHR (Gas Turbine Modular Helium Reactor), and PBMR (Pebble Bed Modular Reactor). Materials and coatings were reviewed in D39 (5). A synthesis of these documents was done. This synthesis leads to the present report which contains a list of elementary tests and the associated tribological conditions needed to describe all the listed configurations.
A selection of experiments to be performed in the frame of D41 "Realisation of tribological tests", will be given from this list of elementary tests.

1. Definition of the tests

1.1. Tribological solicitations

To define the tests, the frame of the possible tribological solicitations, will be the following:

- Sliding: it is induced by 2 kinds of processes :
    - Motion of mechanism, i.e. valve, CRDM, bearing
    - Thermal dilatation of a normally static contact, i.e. seals, liner, internals.
- Fretting: it occurs nearly everywhere the contacts are submitted to sliding, because of the vibrations induced by blowers, or turbine and also because of helium circulation. So the level of temperature or contact pressure are similar than those found in sliding solicitation.
- Bearing: fluctuation of contact pressure on the surface (gears)
- impact /sliding: it corresponds to sliding preceded by an impact (bearings, CRDM on fuel entrance side)

1.2. Other parameters

The other parameters necessary to define the tests, are:

- The temperature range: different according the concerned components, and till 850°C for GTMHR design, till 900°C for the PBMR design.
- The load pressure applied on the component (MPa)
- The displacement amplitude, and the frequency for fretting, or velocity for sliding
- Duration of tests or number of cycles

- Gas pressure: impurity content and nature in the environment

- The "GCR atmosphere" (He + impurities), will be defined as the global atmosphere which can be encountered in GCR during operations, without any regards to the evolution of this gas mixture as function of the location of the components.

2. NNC test proposal in the frame of PBMR (NNC) (6)

UK experience in helium tribology comes largely from the Dragon Project and test programmes in support of a Mk III gas-cooled reactor. Extensive experience of tribology in gaseous environments was also gained from the operation of the Magnox and AGR reactors (CO_2 environment), and from the test programmes supporting them.

The effects of different parameters were assessed.
They concerned:

- **Sliding: friction and wear testing**, with effect of:

  Gas pressure,

  Contact pressure,

  Helium purity (presence of H_2, CO or water) with effect of moisture (seizing when water vapour concentration (initially 100vpm) was reduced below 20 vpm at 350°C)

  Dwell at elevated temperature (associated to components or structures which move only during temperature cycles or are inserted or withdrawn occasionally from the reactor)

- **Static adhesion** (essentially concerns high temperatures ≥ 600°C)
- **Fretting** (long term (~10^3hours) fretting tests are essential)

2.1. Potential problems

Sliding contacts arise during the insertion and withdrawal of components within the reactor and as a consequence of expansion and contraction upon thermal and load cycling. During periods in which no relative motion occurs, especially at small area contacts, static adhesion may follow: fatigue or component seizure may then result. The galling of fasteners during protracted exposure to an inert atmosphere at elevated temperature was another area identified for concern. Fretting may arise between contacting parts in high velocity turbulent gas flow. In the heat exchangers, impact/slide and fretting were the major concerns. The following table gives a summary of the components on which we may have tribological concerns:

***Table 1*: Areas of tribological concern in a PBMR**

Component	Area	Temperature	Type of Motion	Possible Materials	Potential Problems
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 (electromagnetic. 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 motion	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

2.2. Possible materials

The envisaged materials and coatings are the following one:

Materials: component alloys, e.g. nickel-based alloys and stainless steels
Graphite (vs graphite; vs steel)

Hard coatings: ***tables 2a and 2b*: *types of coatings according to the operating temperature***

Temperature	$T \leq 350°C$	$T \leq 700°C$	$T \leq 850°C$	$T \leq 950°C$
Coating	D-GunWC/Ni/Mixed W/Cr carbides (LW5 type)	D-Gun Cr_3C_2/Ni-Cr (LC1B type); Plasma sprayed Cr_3C_2/Ni-Cr (LC2 type)	$Cr_{23}C_6$-$Cr_{23}C_6$/Ni-Cr duplex	Plasma sprayed Y stabilised ZrO_2 on NiCrAlY

Coating (cermet)	*Deposition technique**	*Composition (%)*
LC-1B	*D-Gun*	*80 vol Cr_2C_3, 20 vol NiCr*
LC-2	*Plasma Gun*	*75 vol Cr_2C_3, 25 vol NiCr*
LW-5	*D-Gun*	*25 WC, 70 mixed WC_3/Cr_2C_3, 5 Ni*

** [Manufacturer: Union Carbide (now Praxair)]*

Lubricating coatings: MoS_2; different formulations to be assessed at all temperatures in friction and wear tests - Graphite; to be assessed at all temperatures in friction and wear tests

2.3. Helium gas environment according to NNC

***Table 3**: NNC gas composition*

	Helium	H_2O (vpm)	CO (vpm)	H_2 (vpm)	CH_4 (vpm)
"Pure" gas	balance	0.1	2	20	0
Impure gas	balance	2	20	20	2

Gas flow: Circulating gas, continuously purified if feasible
Pressure: ≈ 70 bar or, if lower, as high as practicable
Continuous gas monitoring recommended
Effect of small quantities of oxygen on the tribological system will need to be considered at some stage.

2.4. Tests

2.4.1. Test recommendations

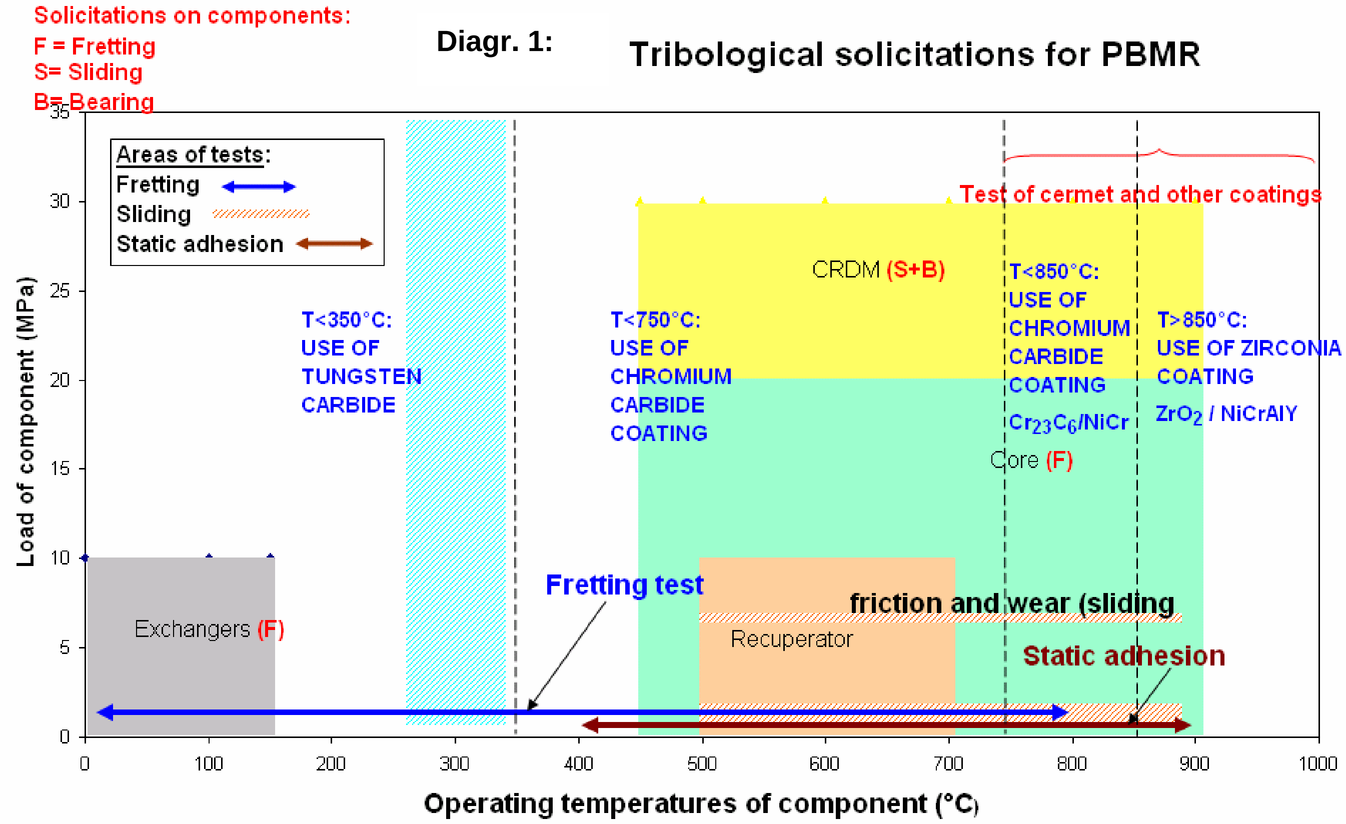
Sliding, fretting and static adhesion tests will be required. To cover the range of potential impurity levels, tests will be required in gases of different composition, in particular different moisture content. Different test pressures will also be required; for preliminary tests: the highest practicable pressure should be employed. Temperature dwells should be incorporated into tests involving parts in relative motion.

2.4.2. Tests

***Table 4:** tests suggested by NNC*

Type of test	**Stroke (mm)**	**Frequency (Hz)**	**Number of cycles**	**Duration**	**Contact pressure (MPa)**	**Temperature range (°C)**	**Measurements**
Sliding	10	1	10^3-10^4 with dwell inserted	10^3 meters	▪ 0,2 - 1 MPa. ▪ 5 – 10 MPa	20 – 800 or more	▪ Dynamic friction coeff. ▪ Static friction ▪ Weight change ▪ Wear depth
Sliding	Same, but with pre-exposure of coatings to reactor gas						
Static adhesion	-	-	-	10^2-10^3 hours	0,2 – 0,5 MPa initially	400-900	Parting load
Fretting	0.2mm	50-150	10^7-10^9 with impact slide if available	-	0,1 – 0,5 MPa	20 – 800 or more	▪ Weight loss ▪ Wear depth ▪ Metallography of cross section

They are summarised in the next diagram, together with the concerned PBMR components, and suggested materials (cf D39):



3. Test proposal in the frame of GTMHR (CEA and FANP) (7)-(8)

The tests will be related to the main following components and solicitations, which are :

- ***Valves*** : the temperature never goes up to 400°C. The maximum contact pressure of a such component is about 20 to 30 MPa. For GCR concepts, valves are required to cut off the hot gas flow. Usually, according to their design, rubbing is not waited for.

- ***Blower*** : for bearings or catcher bearings. Same requirements (Tmax 400°C, load pressure 20-30MPa) with sliding and fretting solicitations.

- ***Seals*** : several seals are located to the tightness of the different stage of the stator (T till 500°C, load pressure 0.5-5MPa). Seal is needed too, for the thermal expansion unit of the hot duct. They are subjected to sliding and fretting motion.

- ***Control Rod Drive Mechanism (CRDM)*** for several parts : first the guidance of the rack between gears, and second, the fuel entrance.
  - o Guidance of the rack: requirements: T till 500°C, load pressure till 50MPa
  - o CRDM (fuel entrance): operating temperatures between 500 and 850°C, lower load pressure (less than 5MPa)
  - o Both are working under sliding and fretting solicitations.

- o At the level of gears, the load pressure is 1000MPa, with Tmax close to 500°C. The motion is described as bearing solicitation.

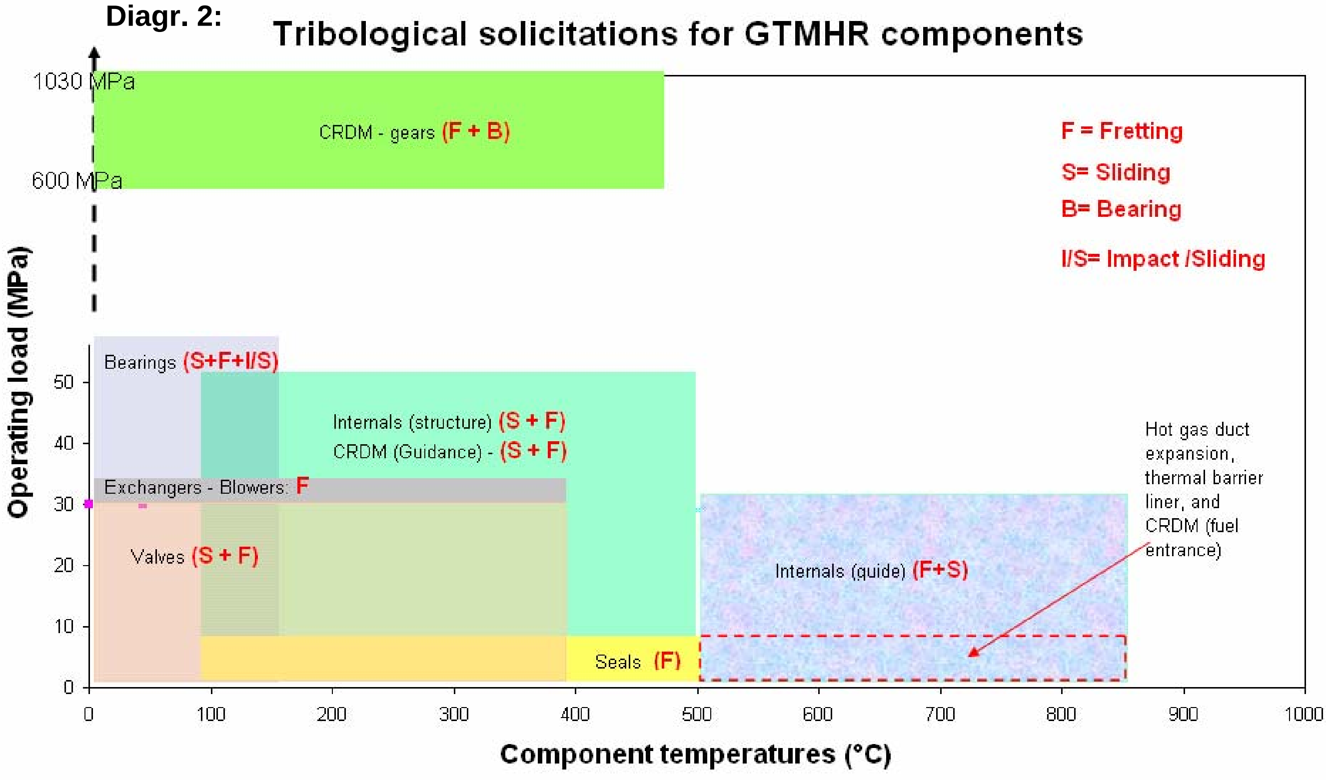
- ***Internals*** : two parts are distinguished. The contacts between internals and the structure which are metal / graphite contacts (Tmax 500°C, max. load pressure 50MPa), and the contacts between internals themselves, which are graphite / graphite contacts (500 ≤ T ≤ 850°C - max. load pressure 30MPa). Both are concerned by sliding and fretting, with possibility of impact / sliding solicitations for fuel entrance part.

- ***Bearings***: several kinds of solicitations can be found (sliding, fretting, impact/sliding) on these components which have to operate at less than 150°C on GTMHR, with load pressure up to 60MPa.

- ***Heat exchangers***: they are concerned by fretting at low load pressure (10MPa max) and low temperatures (150-400°C max)

The next graph summarises the main fields to be tested:

Diagr. 2:



These fields are described in the following paragraphs by a list of experiments potentially needed to have a good view of component metallic material behaviour, with or without coating. At the end of this presentation, the document is completed by a choice of the experiments which will be really performed in task 3.1 of this WP5 work (Deliverable D41).

3.1. *Tests for the CRDM (guidance)*

- ***The base material***

If considering the GTMHR data for this component, the base material could be 38CD4 tempered at higher temperature than operating temperature, to be used till 500°C. Other materials are under study.

- ***The coatings***

Surface treatment may be envisaged to enhance surface properties, or coatings. Coatings could be Tungsten carbide (WC/NiCr), Titanium carbide (TiC)… If the base material is not completely defined, the tribology work can be done on the coatings, assuming an adequate gradient between the base material and the coating, to prevent from thermal expansion problems.

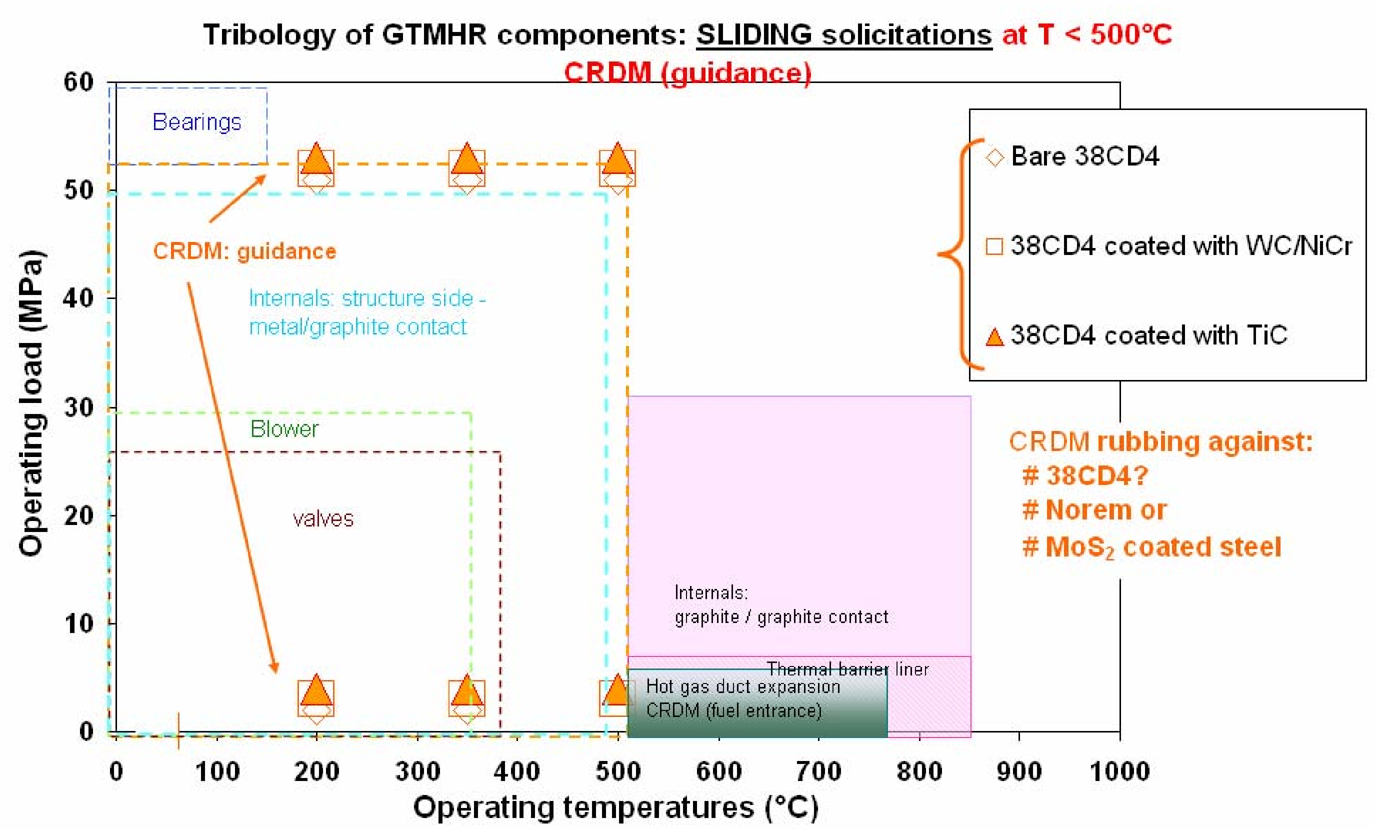
- ***The antagonistic material***

It could be base material, or coated base material. Not yet defined

- ***The tests***

The material data are not completely available to define correctly the tests, which are shown in orange pictograms on the next diagram for sliding, till 500°C and 50MPa, as maximum values for temperature and load pressure.
Sliding and fretting tests are needed.

Diagr. 3:



3.2. Tests for the internals (structure side)

- ***The base material***

If considering the GTMHR data for this component, the base material could be Ni alloys or more probably 9%Cr 1Mo Mod.

- ***The coatings***

The suggested coatings are Tungsten carbide (WC/NiCr), Titanium carbide (TiC), Titanium nitride TiN, and Silicium carbide (SiC)…

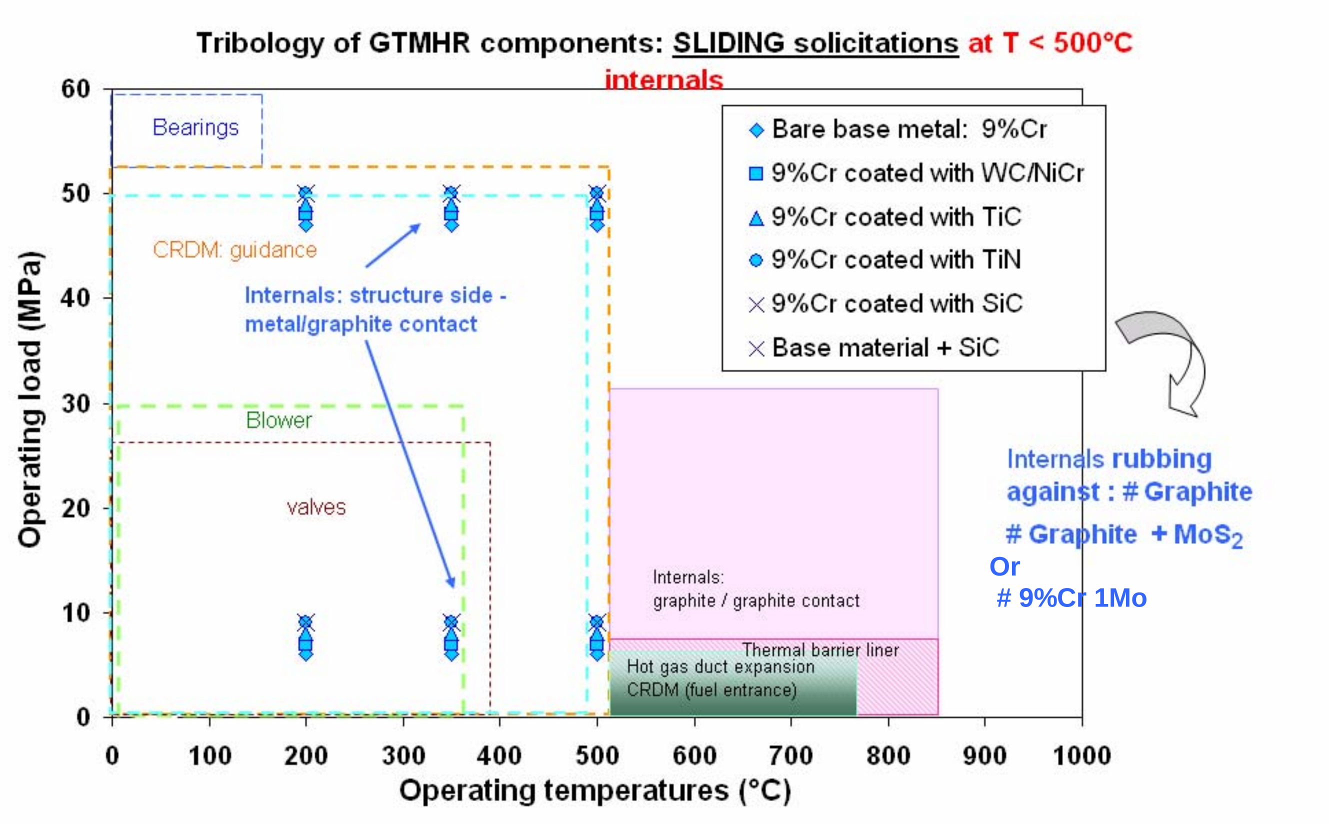
- ***The antagonistic material***

The antagonistic material could be graphite blocks (the grade is not defined), or block support, or vessel itself. Concerning graphite, a lubricating compound such as MoS_2 or other, could be used to impregnate the graphite surface and make rubbing easier. Concerning vessel or block support, the antagonistic material could be 9%Cr 1Mo Mod.

- ***The tests***

They would be performed till 500°C and 50MPa. Sliding and fretting solicitations are required. Hereafter is the recapitulative diagram for sliding. Same type has to be foreseen for fretting.

Diagr. 4:

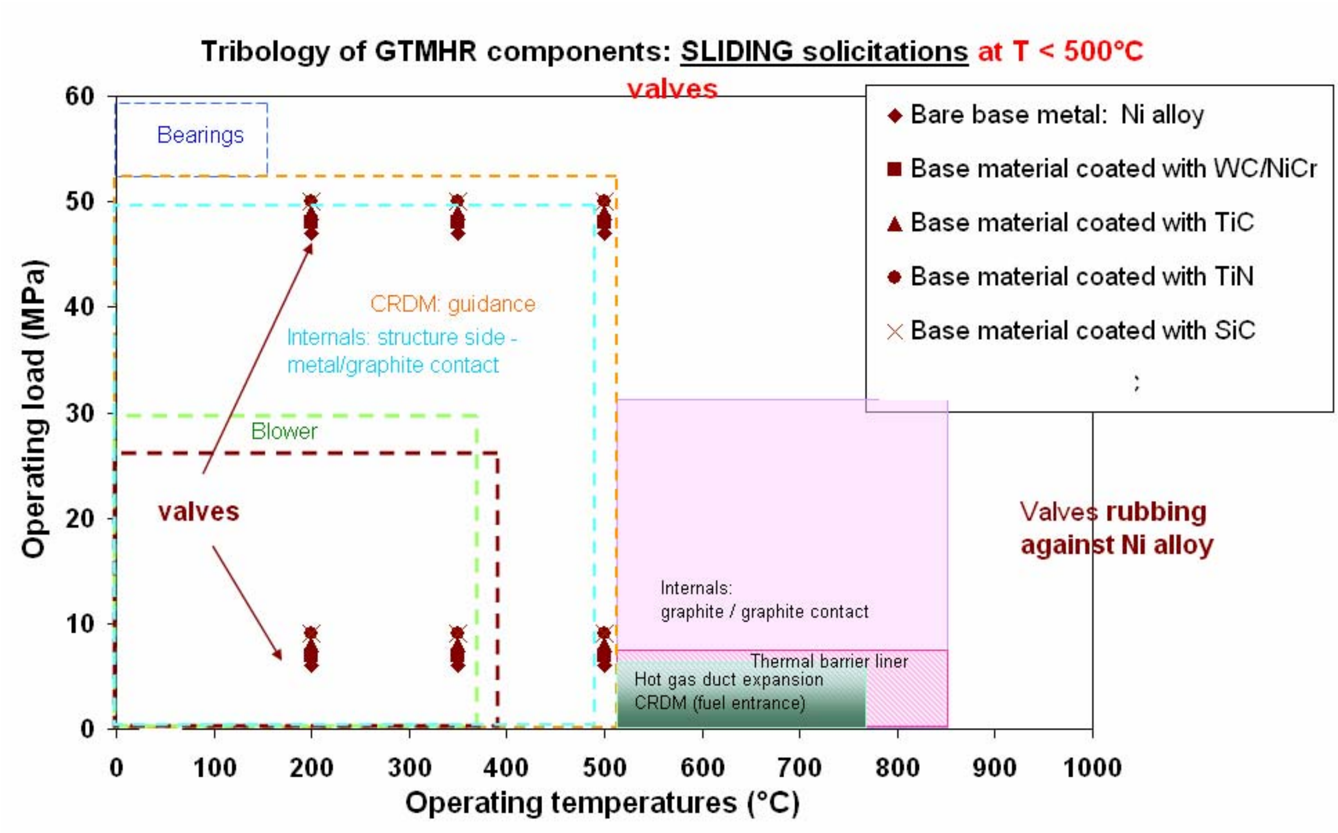


3.3. Valves

At temperatures less than 500°C, no real tribological problems are expected on that type of component, but no data are really available in helium environment. The risk is to "weld" the surfaces in contact.

The samples could be Ni base alloy coated with WC/NiCr, TiC, TiN, SiC, rubbing against Ni alloy at temperatures till 400°C and load pressure till 30MPa, with sliding solicitations. As adhesion risk exists, dwell tests could be associated. See next diagram for the parameter values.

Diagr. 5:



3.4. Tests for hot gas duct liner

- ***The base material***

If considering the GTMHR data for this component, the base material could be a Ni alloy (617 type) or alloy 800H.

- ***The coating***

At these high temperature operating conditions (till 850°C), a Zirconia coating (ZrO_2) is well adapted. Other possibilities are silicium carbide SiC, or alumina Al_2O_3, with oxide lubricant (such as CaO, ..). The binders such as CaO, NiO, Y_2O_3 (with NiCrAlY sub-layer), … have to be investigated since they have an effect on the friction coefficient and on the wear.

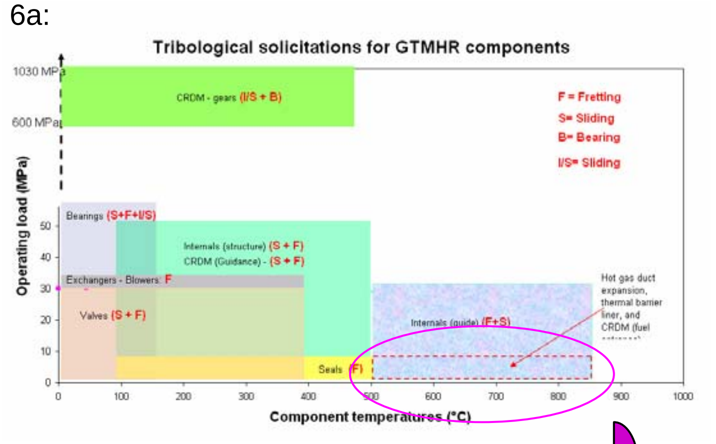
- ***The antagonistic material***

The antagonistic is the liner itself.

- ***The test***

A ZrO_2 / ZrO_2 sliding contact has to be tested at 850°C, for 1 and 5 MPa load pressure. SiC is also recommended.

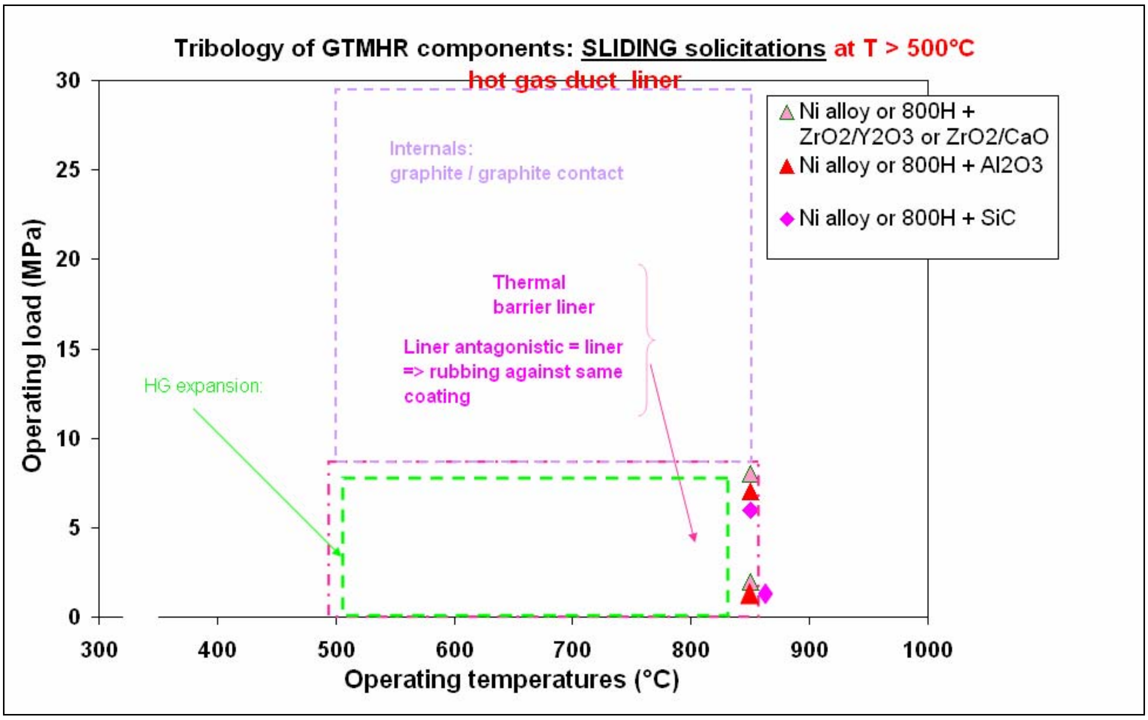
6a:



Diagrams 6a and 6b:

ZOOM of the 500-850°C area for the hot gas duct

6b:



3.5. Tests for hot gas duct expansion

- ***The base material***

If considering the GTMHR data for this component, the base material could be a high temperature Ni alloy (617) .

- ***The coating***

At 500°C, the chromium carbide Cr_3C_2 could be adapted, but it has to work till 850°C. In high temperatures areas (700-850°C), ZrO_2 coating is announced as better [9].

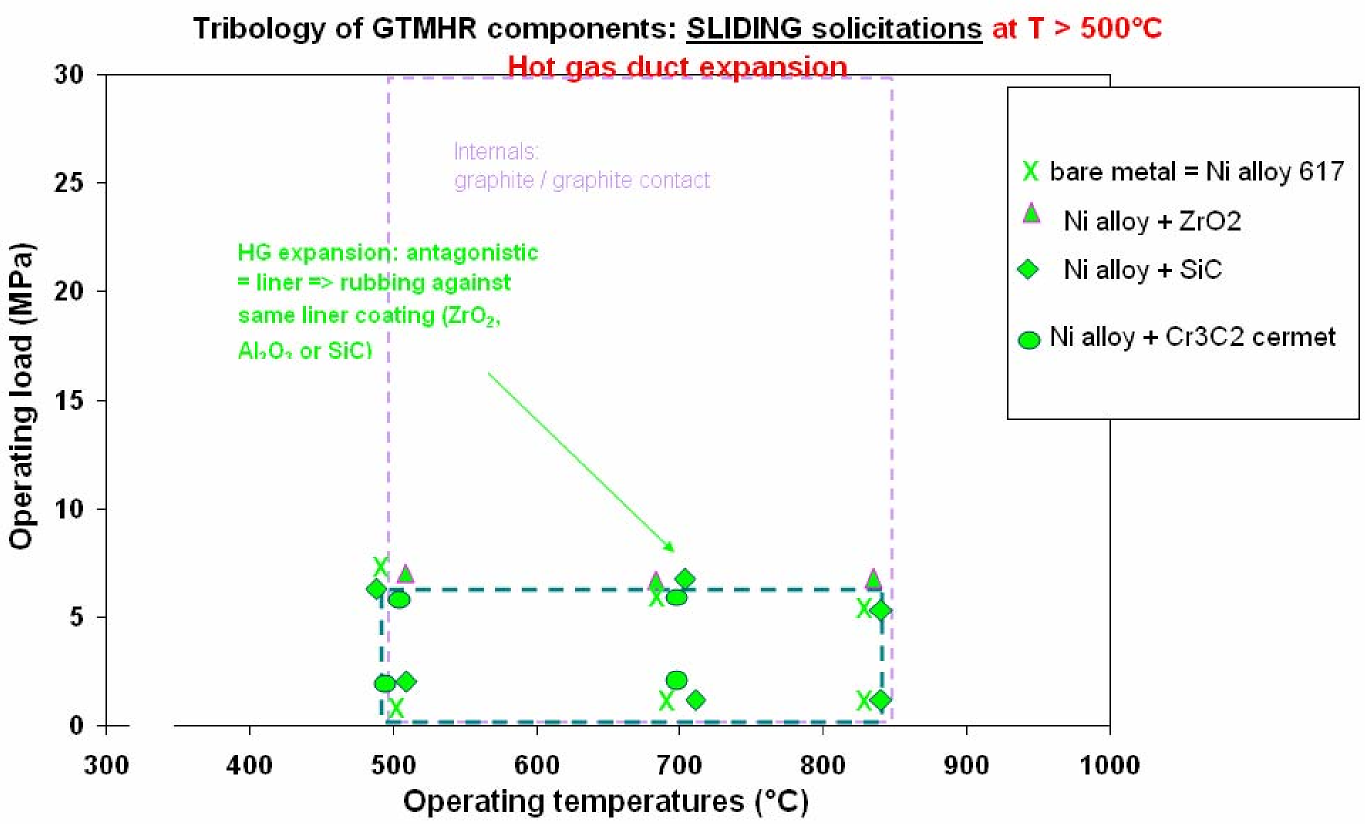
- ***The antagonistic material***

Our GTMHR available data showed that the antagonistic material is the liner material or ZrO_2 if coated.

- ***The test***

A ZrO_2 / ZrO_2 sliding contact would be tested at 500, 700 and 850°C, for 1 and 5 MPa load pressure. The evolution of Cr_3C_2 cermet behaviour is tested till 750°C. The choice of Ni, or NiCr binder will have a role in this behaviour. SiC can be used on the whole range of temperatures. Rubbing of ZrO_2 against ZrO_2, ZrO_2 against SiC or SiC /SiC contact would have to be tested, compared to bare material results.

Diagr. 7:



3.6. Tests for CRDM (gears)

No definitive data are known about gear material and antagonistic material. The load pressure is very high, from 600 to 1030MPa. It's applied during a bearing motion, i.e. a rolling sliding motion. It's not really a pure sliding solicitation so that no experiment could be representative with the available equipment.

3.7. Tests for CRDM (fuel entrance)

- ***The base material***

No definitive data is available. High temperature Nickel alloys as well as graphite base materials could be adapted.

- ***The coating***

At 500°C, the chromium carbide Cr_3C_2 could be adapted, but it has to work till 850°C. In high temperatures areas (700-850°C), ZrO_2 coating is announced as better.

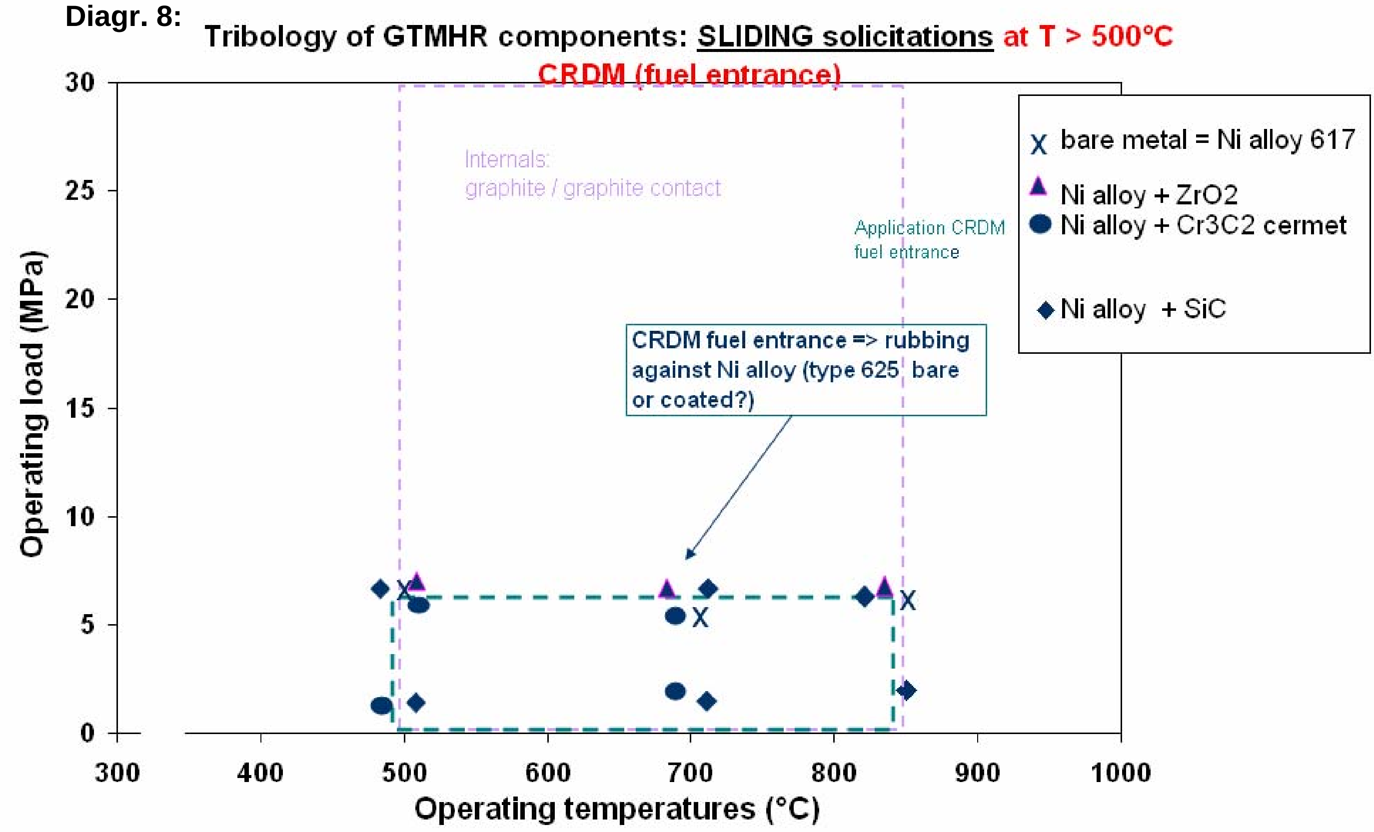
- ***The antagonistic material***

Our GTMHR available data showed that the antagonistic material is an Ni alloy. Is a coated Ni alloy possible as the antagonistic rubbing material?

- ***The tests***

This component will undergo sliding, fretting and impact/sliding solicitations at high temperatures, till 850°C. A ZrO_2 / Ni alloy sliding contact would be tested at 500, 700 and 850°C, for 1 and 5 MPa load pressure. Cr_3C_2 cermet is recommended only for temperatures under 750°C (role of Ni, or NiCr binder) [6]. The antagonistic material has to be defined: 625 alloy coated or not. Silicium carbide SiC is also recommended in that range of temperatures.

Diagr. 8:



4. Test proposal summarised for GTMHR and PBMR

An impressive amount of experiments was listed in paragraph 3. The objective of this deliverable D40 is to select a list of experiments which will be effectively performed in Helium environment. The selection was realised on the following criteria:

- Component materials well defined
- Same reference experiment on both CEA and FANP tribometers
- Obtain more data at high temperatures in Helium environment
- Obtain data for highest load pressures in Helium environment
- Usefulness for both PBMR and GTMHR designs
- Continuous tests : no dwelling (dwelling = sliding (or fretting), stopped motion few hours, sliding or (fretting))
- Test repartition according to the characteristics of each tribometer (see § 4-1)

4.1. Presentation of CEA and FANP tribometers (7)(8)

4.1.1. CEA tribometer (fig1a, 1b and 2)

"He tribometer" is a "pins on rail alternative sliding" tribometer. This apparatus is divided in two parts :

- The mechanism which operates the load and the motion of the samples (2 pins and 1 rail),
- The furnace which operates the temperature and the pressure of the running atmosphere.

With a normal quasi-static load (F_N) applied to the pins, a tangential load (F_T) is needed to move the rail. The coefficient of friction, μ, is calculated from F_N and F_T as following :

$$\mu = \frac{|F_T|}{2 \cdot F_N}$$

The tangential load (F_T) is applied by a Jack via the sliding shaft. The normal quasi-static load (F_N) is applied with a weighting device (lever arm and weight).

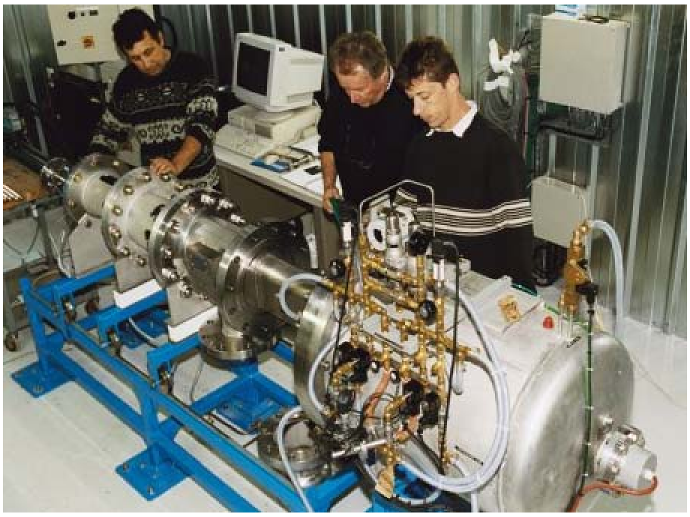


Figure 1a: View of CEA He tribometer

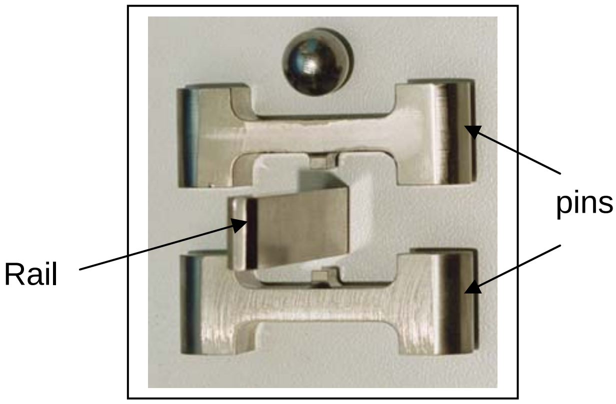


Figure 1b: View of samples

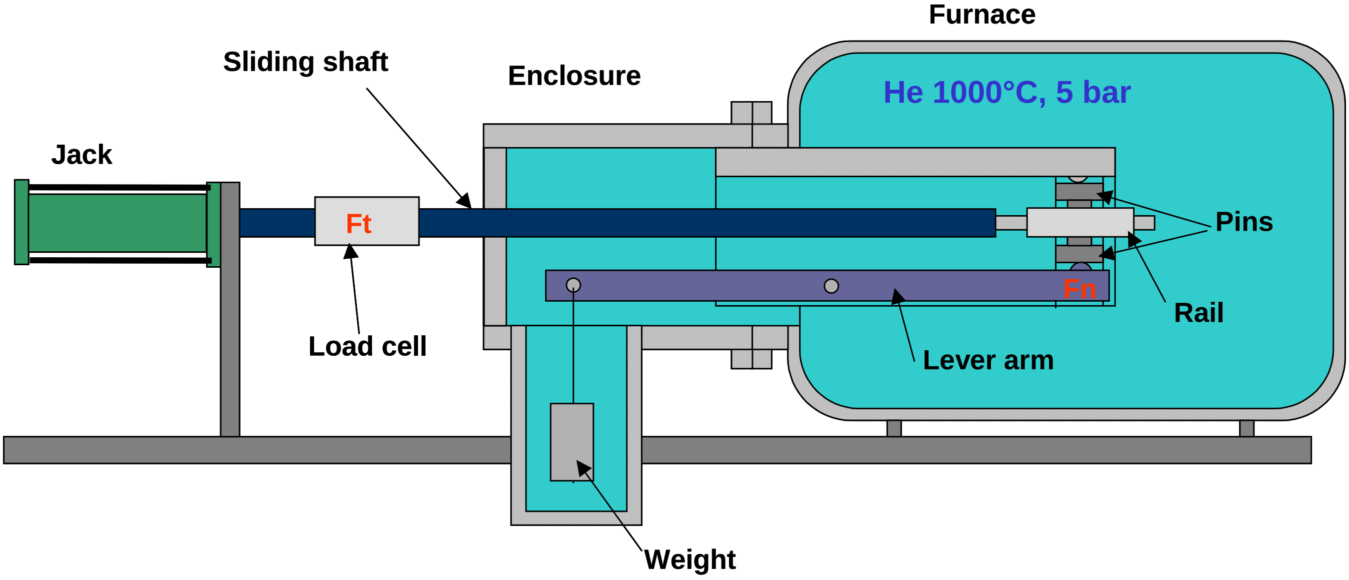


Figure 2: Schematic diagram of CEA He tribometer.

The major characteristics of this He tribometer are :

- Plane/plane contact (0,5 cm²),
- Alternative motion,
- load : 0 – 20 MPa,
- Amplitude : up to 20 mm,
- Frequency : up to 6 Hz.
- Environment
    - Temperature : up to 1000°C,
    - Helium + steam, impurities.

4.1.2. <u>FANP pin-on-disk tribometer (fig. 3)</u>

The “pin on disc” tribometer is devoted to material characterization to evaluate the friction coefficient and wear evolution. The wear resistance of coatings (or of bulk materials) is used to be analysed according to the features of the friction coefficient, the evolution of penetration of pin into disk and surfaces analysis.

General features:

- Fixed pin and rotating disk
- Thermal housing around the disk
- Normal load generated by free mass or spring
- Little capacity for test in humid or lubricated environment
- Contact forces (normal and tangential) measured by strain gauge sensors

Performances:

- Normal load up to 2,5 daN (estimated contact pressure: from 2 MPa to 300 MPa)
- Sliding speed: 1 to 250 mm/s
- Temperature up to 600°C
- Working environment: liquid (at low temperature) or gas
- Nature of contact: typical sphere on plate or piece of real components
- Measurements of temperature, displacement (wear evolution), normal and tangential forces, distance covered with personal computer during tests.

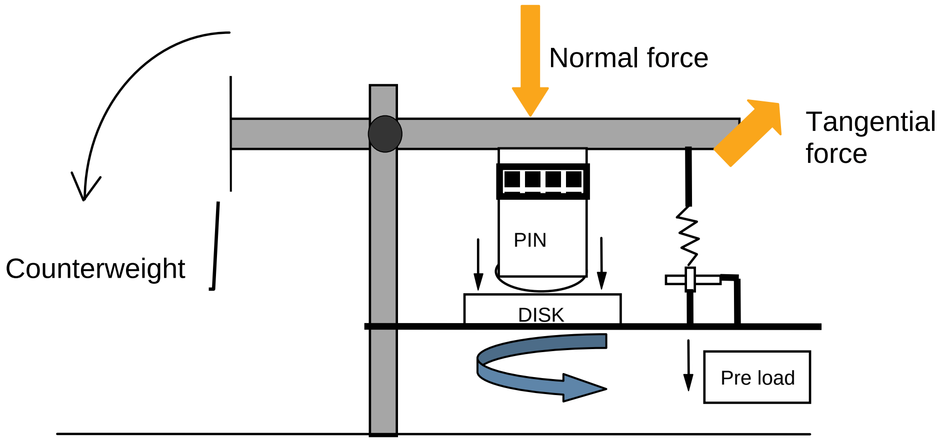


Figure 3 : scheme of FRAMATOME pin-on-disc tribometer

4.1.3. <u>FANP fretting tribometer device (fig. 4)</u>

This device will be available in the beginning of 2005. It allows the study of components subject to fretting solicitations. A particular attention was paid to the hot surfaces of the tribometer which were chosen as not reactive with the HTR typical environment, so that Helium impurities will only react with the sample surface.

The main performances are the following one :

- Temperature up to 1200°C
- Pressure: atmosphere + ε
- Helium + impurities environment
- Alternative movement or fretting: amplitude from ±10 to ±200 µm, frequency up to 50 Hz
- Contact pressure from 0.5 to 1000 MPa (plane on plane or pin on disk)
- Measurements: normal force, tangential force, wear, temperature

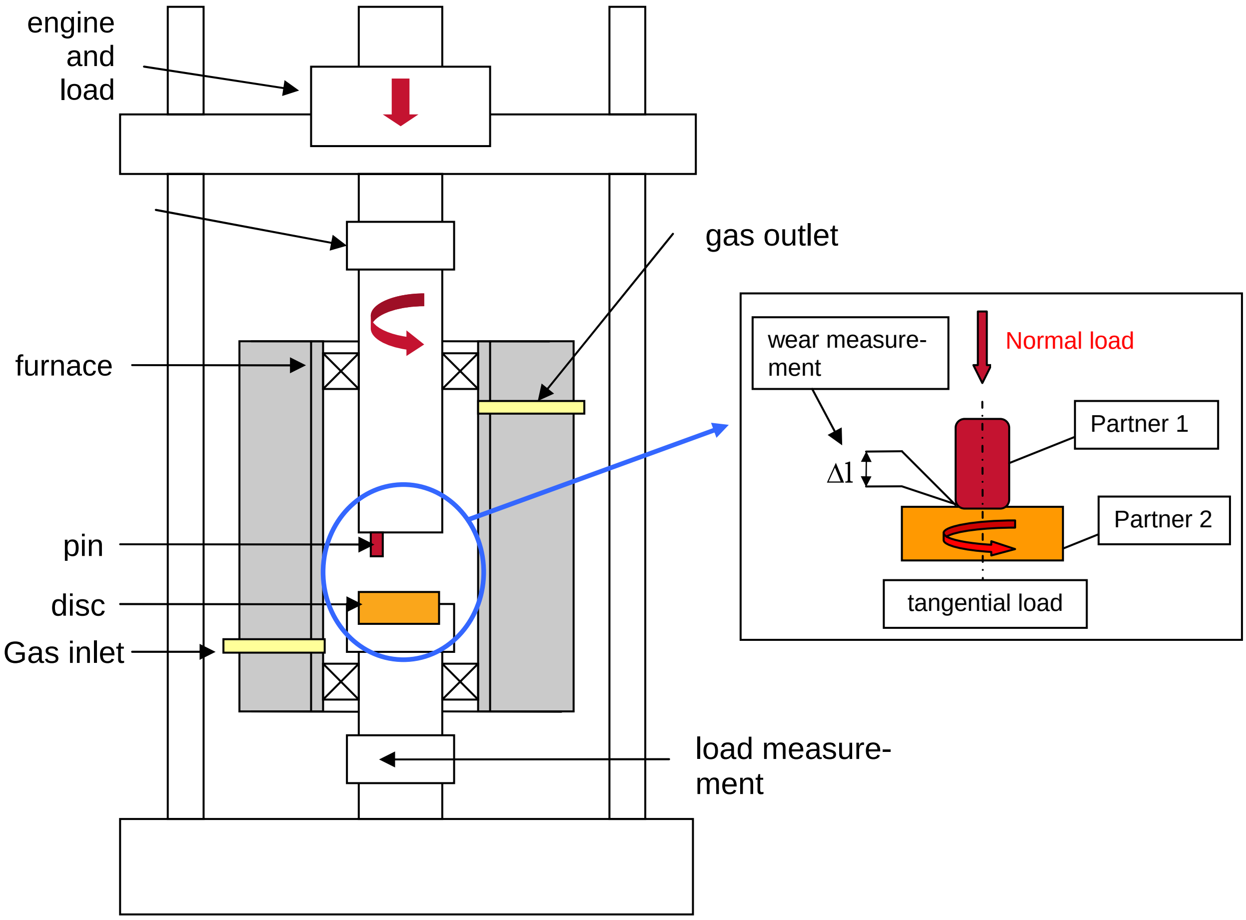


Figure 4 : scheme of FRAMATOME fretting tribometer

4.2. *Proposition of a common test protocol (8)*

A common test protocol has been defined together with FANP and CEA, to make easier the comparison of results whatever the used tribometer or the type of test.

4.2.1. Sample preparation

Substrate: material report to have the chemical composition, mechanical and hardness characteristics.

Coating: Define a common procedure (type, coating process, nature of the layers, thickness) and have the same supplier. For each coating, a test sample will be qualified by the supplier to validate the coating process.

Surface finish: to be define (CEA: Ra<0.4 for metallic materials and 0.4<Ra<0.8 for ceramic or Cermet).

Cleanliness: Alcohol + ultrasonic cleaning for metallic samples;
Thermal housing 200°C, 15 mn for ceramic samples.

Sampling and analysis of a reference sample (hardness, SEM, micrographic examination, …)

4.2.2. Sample assessment

Visual examination:

- Identification of the rubbing surface
- Sample colour
- Picture of the entire sample before cleaning
- Sample of the debris (morphology)
- Cleaning: dry air + paintbrush
- Picture after cleaning

Weight loss measurement

Options:

- Measurements of the surface profile;
- SEM and EDS analysis;
- Hardness and micro-hardness on cross section.

4.2.3. Common reference test

For the same reason aiming at an easier comparison of results, an identical reference test was defined before starting the other tests on tribometers.

It is described as follows:

Material 1:	HR230 (bare)
Material 2 (antagonistic):	HR230 (bare)
Environment:	Pure Helium
Temperature:	500°C
Load:	20MPa
Displacement:	20mm
Velocity:	1cm/s
Number of cycles:	5000 cycles

4.3. List of elementary tests for D41

4.3.1. Helium environment

The first tests will be realized in "pure" (99,9999%) Helium (for example laboratory Helium 6.0). An inspection by sampling & chromatography, of Helium content is needed from the bottle and from the test area.

In a second step, the same experiments will be made in Helium containing impurities, as close as possible to PNP helium for tests representing GTMHR design (operating temperature up to 850°C), and Helium at 900°C for tests representing PBMR design (operating temperature up to 900°C)

Finally, in order to compare results and to obtain data at higher temperatures, it could be useful to work with the Helium composition aimed at high temperatures:

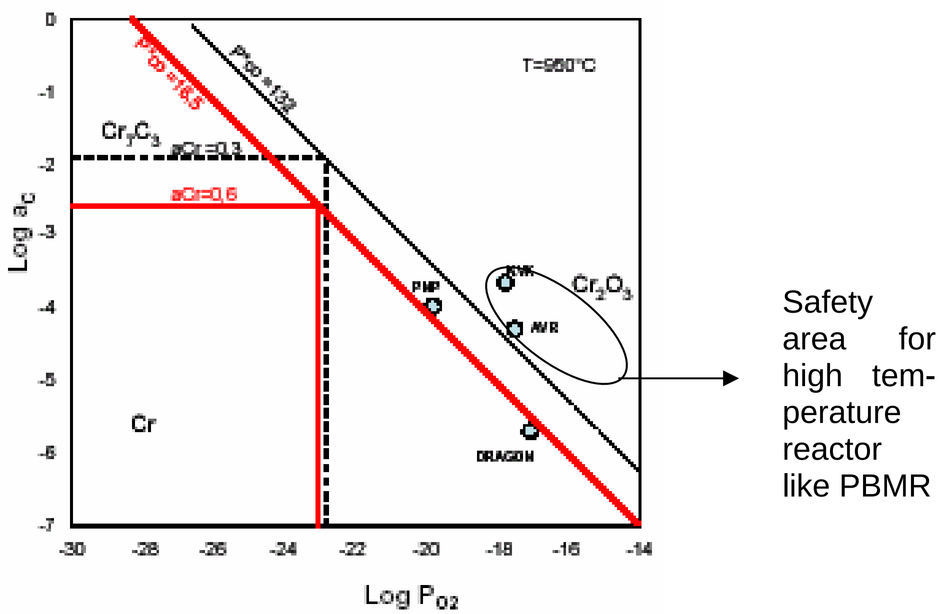
4-3-1-1 Helium environment from WP6 results

Experiments have to be realised in the frame of GTMHR and PBMR designs.

It can be shown from the following diagram, that the PBMR environment, operating at higher temperature, ought to be more oxidising, than the GTMHR one (PNP Helium): see the diagram from WP6 results, here after.

The safe area is on the down - right part of the diagram. PNP Helium is not enough oxidising at 900-950°C (left of the black line).

Diagr. 9: Calculated stability diagram of chromium at 950°C. Effect of the chromium activity and location of former HTR helium atmospheres



(From FANP report: PVEK DC 04 0084 ELR)

Gas compositions for PNP Helium, AVR and KVK which can be localised on the diagram, are given in the next table, in µbar:

***Table 5**: Gas compositions for PNP Helium, AVR and KVK*

Helium environment (µbar)	O_2	H_2O	CO	CO_2	CH_4	H_2	N_2
PNP Standard (1981) – 850°C	-	1,5±1	15±5		20±5	500±50	<5
AVR	-	1	2000		2	500	-
KVK	-	6	-	240	-	200	300

Generally speaking, the helium gas composition corresponding to the safe area can be summarised with the following specifications:

***Table 6**: Gas composition for PBMR and HT reactors operating at 900-950°C (FANP)*

Helium environment He 70 bar	P_{O2}	p_{H2O} / p_{H2}	CO (µbar)	CO +CO_2	P_{CH4} / p_{H2O}	-	-
Recommended Helium high temperature – T=900-950°C (FANP)	$>2.10^{-23}$	> few 10^{-4}	> 150	-	$< 10^{-2}$	-	-

Specifications exist also given in vpm by FANP GmbH. [NGPS3/2003/en/0037]:
From the german operational experience of "high temperature reactors source terms for important types of impurities can be defined. In reference to established purification constants expected values for Helium impurity concentrations for normal operation of a high temperature reactor in its primary Helium atmosphere are recommended: "

Table 7: Gas composition for HT reactors (FANP GmbH) – in vpm

Impurity	Concentration (vpm)
H_2O	< 0.1
CO	< 2
N_2	< 1
H_2	< 5
CH_4	< 1

After conversion in µbar for a 70 bar pressure Helium environment, the two environments can be compared: except the recommendation for CO pressure, the others remain compatible.

Helium environment He 70 bar	*P_{O2}*	*p_{H2O} / p_{H2}*	*CO (µbar)*	*CO $+CO_2$*	*P_{CH4} / p_{H2O}*
Recommended Helium high temperature – T=900-950°C (FANP GmbH)	-	< 0.02	< 140	-	< 10

4-3-1-2 Conclusion from WP6 results

A correlation is needed from WP6, between the two FANP (F and GmbH) propositions, since at the moment two specifications differ such as P_{CO} and P_{CH4}/P_{H20} if total pressure assumed to be 70 bar.

4.3.2. List of suggested tests

From the diagrams 3 to 8, a list of experiments was chosen on the basis of available data concerning materials (for instance, no real data concerning CRDM).

The chosen experiments concerned in one hand the liner / liner contact in the thermal barrier of the hot gas duct and in another hand the internal / block or vessel contacts.

From the D39 results (5) and (9), the following coatings were chosen:

- for the liner: ZrO_2/Y_2O_3 and ZrO_2/CaO ceramics
- for the internals: Cr_3C_2, TiC and WC/NiCr

The base materials are HR230 (as Ni base alloy) for a hot gas duct design with sliding systems, and 9%Cr mod. 1Mo for internals. The motion is sliding.

Possible tests were listed at different temperatures, as shown in the following tables 8a and 8b in pure helium as reference tests (8a), and in Helium with impurities (8b):

Table 8a: proposed tests in "pure Helium":

	Continuous tests: no dwelling							
	New samples							
N°	**Component / contact**	**Environment**	**Material 1**	**Material 2**	**Temper. (°C)**	**Load (MPa)**	**Covered length (m)**	**Velocity (cm/s)**
2	**Reference test**	**Pure He**	**HR230**	**HR230**	**500**	**5**	**200**	**1**
4	**Liner / Liner**	**Pure He**	**HR230 + ZrO_2/Y_2O_3**	**HR230 + ZrO_2/Y_2O_3**	**500**	**5**	**200**	**1**
6			**HR230 + ZrO_2/Y_2O_3**	**HR230 + ZrO_2/Y_2O_3**	**900**	**5**	**200**	**1**
8		**Pure He**	**HR230 + ZrO_2/CaO**	**HR230 + ZrO_2/CaO**	**500**	**5**	**200**	**1**
10			**HR230 + ZrO_2/CaO**	**HR230 + ZrO_2/Y_2O_3**	**900**	**5**	**200**	**1**
12	Liner / Liner	Pure He	HR230 + SiC	HR230 + SiC	500	5	200	1
14			**HR230 + SiC**	**HR230 + SiC**	**900**	**5**	**200**	**1**
16		Pure He	HR230 + Cr_3C_2	HR230 + Cr_3C_2	500	5	200	1
18			**HR230 + Cr_3C_2**	**HR230 + Cr_3C_2**	**750**	**5**	**200**	**1**
20	Internals / vessel or Internals / block support	Pure He	9%Cr	9%Cr	250	50	200	1
22			9%Cr	"	500	50	200	1
24		Pure He	9%Cr + TiC	9%Cr	250	50	200	1
26			9%Cr + TiC	"	500	50	200	1
28			9%Cr + WC/NiCr	9%Cr	250	50	200	1

Table 8b: proposed tests in Helium + impurities (gas composition given in § 4-3-1-1):

N°	**Component / contact**	**Environment**	**Material 1**	**Material 2**	**Temper. (°C)**	**Load (MPa)**	**Covered length (m)**	**Velocity (cm/s)**
2	**Reference test**	**He + impurities**	**HR230**	**HR230**	**500**	**5**	**200**	**1**
4	Liner / Liner	He + impurities	HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	500	5	200	1
6			HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	900	5	200	1
8	Liner / Liner	He + impurities *	HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	500	5	200	1
10			HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	900	5	200	1
12	Liner / Liner	**He + impurities**	HR230 + SiC	HR230 + SiC	500	5	200	1
14			**HR230 + SiC**	**HR230 + SiC**	**900**	**5**	**200**	**1**
16	Liner / Liner	**He + impurities**	HR230 + Cr_3C_2	HR230 + Cr_3C_2	500	5	200	1
18			**HR230 + Cr_3C_2**	**HR230 + Cr_3C_2**	**750**	**5**	**200**	**1**
20	**Internals** / vessel or Internals / block support	**He + impurities**	**9%Cr**	**9%Cr**	**250**	**50**	**200**	**1**
22			**9%Cr**	**"**	**500**	**50**	**200**	**1**
24		**He + impurities**	**9%Cr + TiC**	**9%Cr**	**250**	**50**	**200**	**1**
26			**9%Cr + TiC**	**"**	**500**	**50**	**200**	**1**
28			**9%Cr + WC/NiCr**	**9%Cr**	**250**	**50**	**200**	**1**

*****: composition of gas given for high temperature reactor operating till 900-950°C

4.3.3.

List of tests to be performed in D41 task

In the previous lists (tables 8a and 8b) concluding the Deliverable D40, the experiments which will be realised in the frame of D41, are signalised by a color: yellow for FANP, and blue for CEA.

They are the following in pure Helium environment

***Table 9a**: in yellow and blue, tests in "pure" helium to be performed for D41*

Continuous tests: no dwelling
New samples

N°	Component / contact	Environment	Material 1	Material 2	Temper. (°C)	Load (MPa)	Covered length (m)	Velocity (cm/s)	Tribometer FANP	Tribometer CEA
2	**Reference test**	**Pure He**	**HR230**	**HR230**	**500**	**5**	**200**	**1**		
4	**Liner / Liner**	**Pure He**	**HR230 + ZrO_2/Y_2O_3**	**HR230 + ZrO_2/Y_2O_3**	**500**	**5**	**200**	**1**		
6	**Liner / Liner**	**Pure He**	**HR230 + ZrO_2/Y_2O_3**	**HR230 + ZrO_2/Y_2O_3**	**900**	**5**	**200**	**1**		
8	**Liner / Liner**	**Pure He**	**HR230 + ZrO_2/CaO**	**HR230 + ZrO_2/CaO**	**500**	**5**	**200**	**1**		
10	**Liner / Liner**	**Pure He**	**HR230 + ZrO_2/CaO**	**HR230 + ZrO_2/CaO**	**900**	**5**	**200**	**1**		
12	Liner / Liner	Pure He	HR230 + SiC	HR230 + SiC	500	5	200	1		
14	Liner / Liner	Pure He	HR230 + SiC	HR230 + SiC	900	5	200	1		
16	Liner / Liner	Pure He	HR230 + Cr_3C_2	HR230 + Cr_3C_2	500	5	200	1		
18	Liner / Liner	Pure He	HR230 + Cr_3C_2	HR230 + Cr_3C_2	750	5	200	1		
20	Internals / vessel or Internals / block support	Pure He	9%Cr	9%Cr	250	50	200	1		
22	Internals / vessel or Internals / block support	Pure He	9%Cr	"	500	50	200	1		
24	Internals / vessel or Internals / block support	Pure He	9%Cr + TiC	9%Cr	250	50	200	1		
26	Internals / vessel or Internals / block support	Pure He	9%Cr + TiC	"	500	50	200	1		
28	Internals / vessel or Internals / block support	Pure He	9%Cr + WC/NiCr	9%Cr	250	50	200	1		

Here after are the experiments proposed in Helium + impurities environment :

***Table 9b**: in yellow and blue, tests in He + impurities, to be performed for D41*

N°	Component / contact	Environment	Material 1	Material 2	Temper. (°C)	Load (MPa)	Covered length (m)	Velocity (cm/s)	Tribometer FANP	Tribometer CEA
2	**Reference test**	**He + impurities**	**HR230**	**HR230**	**500**	**5**	**200**	**1**		
4	Liner / Liner	He + impurities	HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	500	5	200	1		
6		He + impurities	HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	900	5	200	1		
8	Liner / Liner	He + impurities *	HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	500	5	200	1		
10		He + impurities *	HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	900	5	200	1		
12	Liner / Liner	**He + impurities**	HR230 + SiC	HR230 + SiC	500	5	200	1		
14		**He + impurities**	**HR230 + SiC**	**HR230 + SiC**	**900**	**5**	**200**	**1**		
16	Liner / Liner	**He + impurities**	HR230 + Cr_3C_2	HR230 + Cr_3C_2	500	5	200	1		
18		**He + impurities**	**HR230 + Cr_3C_2**	**HR230 + Cr_3C_2**	**750**	**5**	**200**	**1**		
20	**Internals** / vessel or Internals / block support	**He + impurities**	**9%Cr**	**9%Cr**	**250**	**50**	**200**	**1**		
22	**Internals** / vessel or Internals / block support	**He + impurities**	**9%Cr**	**"**	**500**	**50**	**200**	**1**		
24	**Internals** / vessel or Internals / block support	**He + impurities**	**9%Cr + TiC**	**9%Cr**	**250**	**50**	**200**	**1**		
26	**Internals** / vessel or Internals / block support	**He + impurities**	**9%Cr + TiC**	**"**	**500**	**50**	**200**	**1**		
28	**Internals** / vessel or Internals / block support	**He + impurities**	**9%Cr + WC/NiCr**	**9%Cr**	**250**	**50**	**200**	**1**		

5.

Conclusion

A number of materials including Stainless Steel 316, other austenitic steels type 347, alloy 800, carbon steel, 9Cr steel, or nickel alloys and graphite, were envisaged in PBMR and GTMHR for several main components such as control rod drive mechanisms, hot gas duct, stators seals, internals...

The review of each component concerned the following characteristics:

- The type of tribological solicitations per component were described for PBMR and GTMHR (sliding, fretting, adhesion, …).
- The possible coatings to be used in order to protect the base material, were listed per operating temperature field (ZrO_2, SiC, Cr_3C_2, TiC, WC/NiCr,..).
- A test protocol common to FANP and CEA and a description of available tribometers were given.
- Selected experiments to be performed in 2004-2005 by FANP and CEA in "pure" Helium and Helium + impurities environment, were listed. The experiments which will be realised in the frame of D41, are signalised by a color: yellow for FANP, and blue for CEA.

  - o The chosen experiments concerned in one hand the liner / liner contact in the thermal barrier of the hot gas duct and in another hand the internal / block or vessel contacts.
  - o The base materials are HR230 (as modified 617 alloy) for a hot gas duct design with sliding systems, and 9%Cr mod. 1Mo for internals. The coatings which were chosen, were ZrO_2/Y_2O_3 and ZrO_2/CaO ceramics for the liner, and Cr_3C_2, TiC and WC/NiCr for the internals.
  - o The experiments are listed here after.

Continuous tests: no dwelling
New samples

N°	Component / contact	Environment	Material 1	Material 2	Temper. (°C)	Load (MPa)	Covered length (m)	Velocity (cm/s)	Tribometer FANP	Tribometer CEA
2	Reference test	Pure He	HR230	HR230	500	5	200	1		
4	Liner / Liner	Pure He	HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	500	5	200	1		
6	Liner / Liner	Pure He	HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	900	5	200	1		
8	Liner / Liner	Pure He	HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	500	5	200	1		
10	Liner / Liner	Pure He	HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	900	5	200	1		

N°	Component / contact	Environment	Material 1	Material 2	Temper. (°C)	Load (MPa)	Covered length (m)	Velocity (cm/s)	Tribometer FANP	Tribometer CEA
12	Liner / Liner	He + impurities	HR230 + SiC	HR230 + SiC	500	5	200	1		
14	Liner / Liner	He + impurities	**HR230 + SiC**	**HR230 + SiC**	**900**	**5**	**200**	**1**		
16	Liner / Liner	He + impurities	HR230 + Cr_3C_2	HR230 + Cr_3C_2	500	5	200	1		
18	Liner / Liner	He + impurities	**HR230 + Cr_3C_2**	**HR230 + Cr_3C_2**	**750**	**5**	**200**	**1**		
20	**Internals** / vessel or Internals / block support	He + impurities	9%Cr	9%Cr	250	50	200	1		
22	**Internals** / vessel or Internals / block support	He + impurities	9%Cr	"	500	50	200	1		
24	**Internals** / vessel or Internals / block support	He + impurities	9%Cr + TiC	9%Cr	250	50	200	1		
26	**Internals** / vessel or Internals / block support	He + impurities	9%Cr + TiC	"	500	50	200	1		
28	**Internals** / vessel or Internals / block support	He + impurities	9%Cr + WC/NiCr	9%Cr	250	50	200	1		