EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-E

High-Temperature Reactor Components and Systems

CONTRACT N°
FIKI-CT-2001-00177

HTR-E WP5 Tribology
Review and identification of typical HTR tribology conditions of components

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Dissemination level : RE
Document N° : HTR-E-02/12-D-5-1-2
Status : Preliminary

Deliverable N°: 38

Framatome ANP identification N° : TFCW-R03.887 A

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N° TFCW R 03. 887 A

MODIFICATIONS	
INDEX	DATE
A	24/01/2003

DISTRIBUTION

Protection level :

~~NORM (normal)~~

~~FILT (filtered)~~

CONF (confidential)

KEY - WORDS

HTR – GTMHR - PBMR

tribology conditions
Helium environment
control rods - CRDM
internals - compressor
blower - bearings
stator seals

HTR-E / WP5

Deliverable D38

Review and identification of typical HTR tribology conditions of components

Customer : DT
Reference : 72H. AFW0021-2

Type of Document : R

DISTRIBUTION	FUNCTION	NAME	VISA	DATE
NOVATOME (E. Breuil)	writer	I. BOBIN VASTRA		23/01/03
Diffusion on SINTER Network	verifier	JPh. VERNOT		24/01/03
All partners +	approver	G. BERTHOLLON		24/01/2003
TFCM: JPh. Vernot – C. Falcand – G. Berthollon				
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Modifications

Revision	Date	Modifications
A	24th January 2003	First issue

Contents

List of tables

List of references

(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) Contribution to Deliverable D38 – NNC – D. E. Buckthorpe – ref C6940/TR/002 – August 2002

(4) Contribution to Deliverable D38 – FANP – C. Falcand – JPh. Vernot – ref TFCM – R02.1054 – December 2002

(5) Contribution to Deliverable D38 – CEA – L. Cachon – ref NT-STR/LCET – 02/ 037

HTR-E / WP5 - *Deliverable D38*

Review and identification of typical HTR tribology conditions of components

1. Introduction

The objective of WP 5 of HTR-E is to firstly 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 D38 is to make a point on the different tribological conditions which can be met by GTMHR and PBMR components in operating conditions.

2. Description of D38 [2]

The title of the document is "Review and identification of typical HTR tribology conditions of components".
Based on available information concerning the present design for GTMHR or PBMR, this review will point out the tribological operating conditions of main components presenting tribological problems such as control rods, turbine, rotating seals, internal seals, hot gas duct, …….

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

3. Organisation of D38 [2]

The organisation of the document can be found in **Table 1**. The involved partners were CEA, FANP (F) and NNC. All contributions were received and are available on SINTER network.

4. Results of D38

The main results of the work were the following:

4.1. PBMR type Reactor [3]

4.1.1. 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 central column of graphite spheres. 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^{o}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. **Figure 1** shows a schematic cross section through the reactor and PCU components.

4.1.2. Localisation of problems

The published information on this reactor design is very 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 2**.

4.2. GTMHR type Reactor [4-5]

4.2.1. Description

The GTMHR is an Helium cooled graphite moderated reactor core coupled to a power conversion unit using a gas turbine driven by the reactor coolant gas (see figure 2). 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 70b), with a 490°C inlet temperature.
The characteristics of the GTMHR is given by:
- the same shaft for the turbine, alternator and compressors
- heat exchangers Helium / water
- a recuperator which enhances the thermal efficiency.

4.2.2. Localisation of problems

- FANP focused his study on control rods drive mechanism and tubes or structures subject to vibration.[4]
- CEA focused his 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 filling cards summarising all the known operating conditions per component (see **Tables 3 to 11**). It gives general information on the component, parts which are in contact with their dimensions, tribological and environmental conditions.

5. Conclusions of D38

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 500MPa) and CEA (till 1000°C – load max 20MPa).

- 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 + impurities

- 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.

Table 1

Deliverable D38: organisation [2]

DELIVERABLE D38
Title "Review and identification of typical HTR tribology conditions of components"
Schedule ***January 2002 –November 2002***
Responsible ***Framatome ANP S.A.S (1)***
Partners ***CEA (2), NNC (7)***
DOCUMENT ORGANISATION

INDEX	**RESPONSIBLE**	**INPUT NEEDED**	**DATE**
General principles			
Document listing the information required in the text, will concern the following types of reactors: • GTMHR • PBMR			
PBMR	**NNC**		Document available in June 2002
GTMHR • Internals • Hot gas duct • …	**CEA**		Document available in June 2002
GTMHR • Stator seals • Control rods • …	**Framatome-ANP**		Document available in June 2002
Conclusion: synthesis of documents	**Framatome-ANP**		Draft : Sep 2002 for partner comments Final : Nov 2002

Figure 1 : Schematic of PBMR Power System [3]

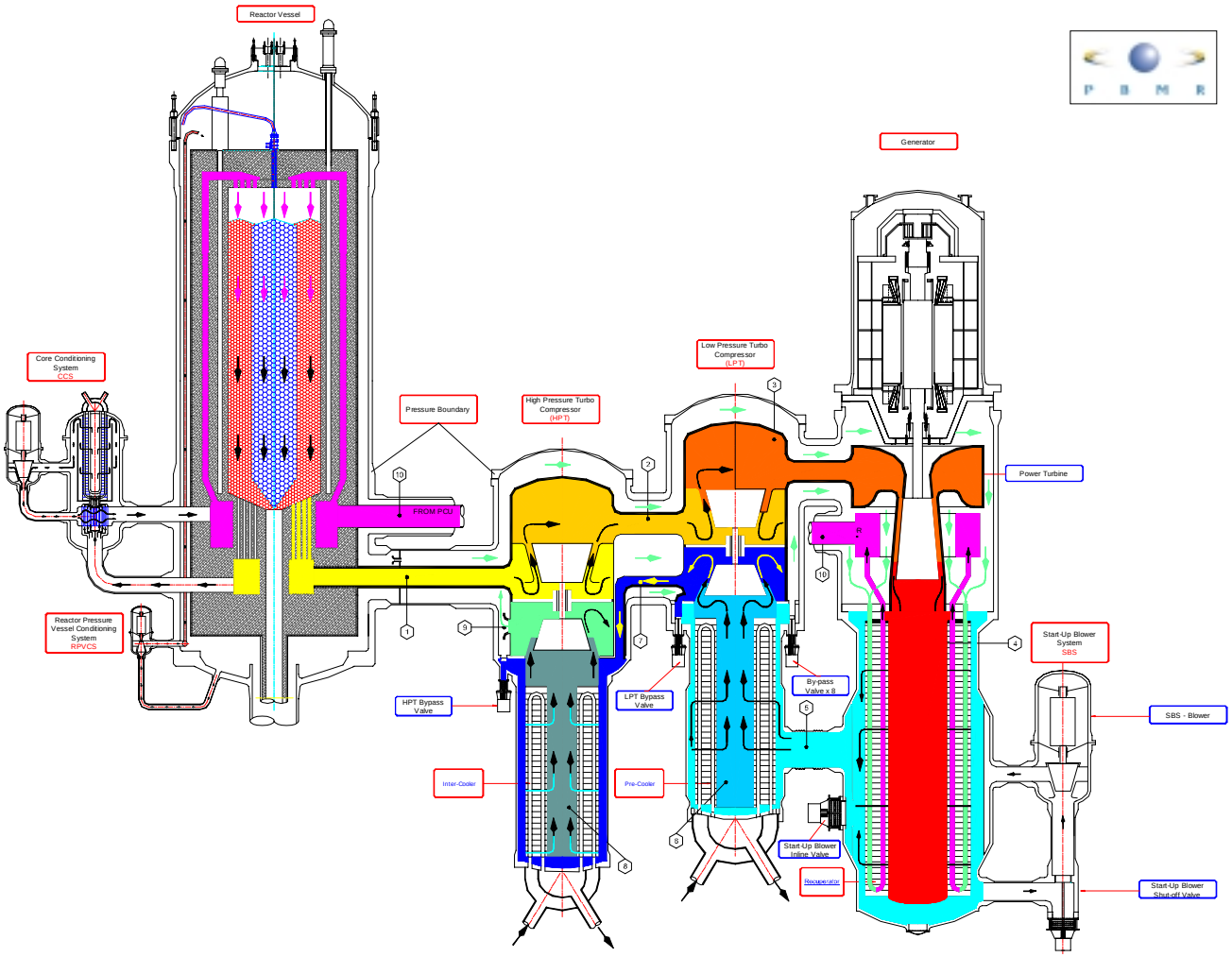


Table 2 Potential Problems [3]

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

Figure 2: general arrangement of GT-MHR Module

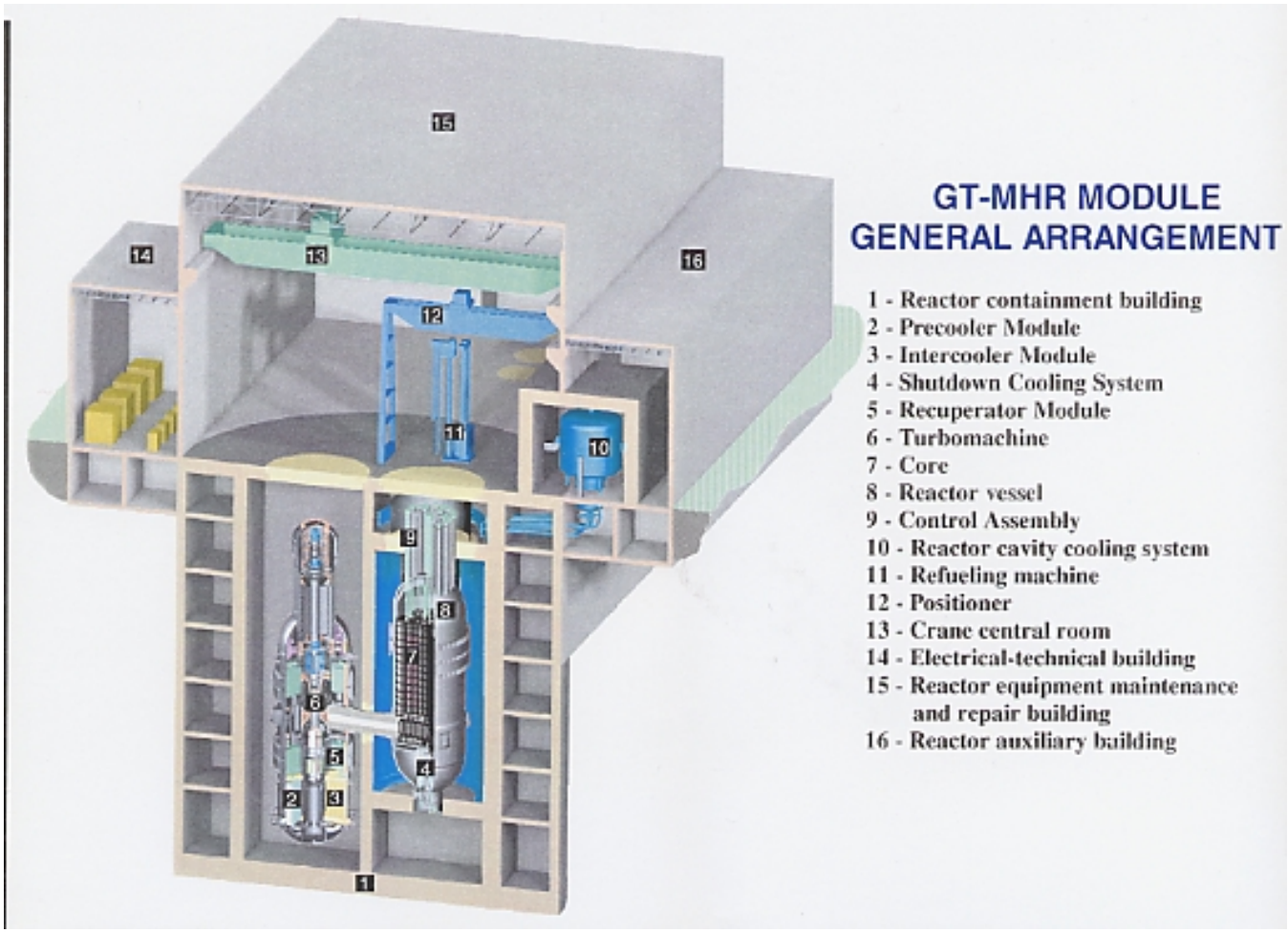
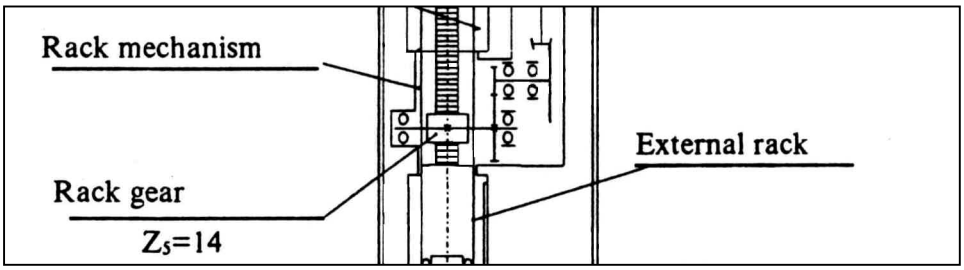
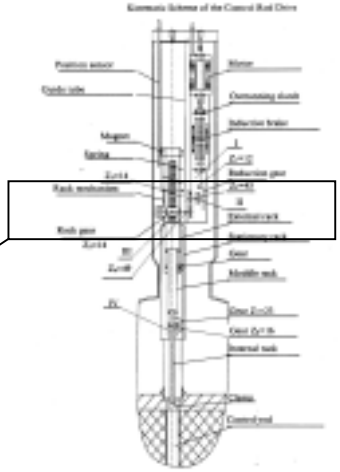


Table 3 : NAME OF THE EQUIPMENT: Control rod drive mechanisms (CRDM) – Rack gear / External rack [4]





1. GENERAL INFORMATION

- Short description of the equipment :
- Usual characterisation : cm² (cm² / mm² / µm² / Other):
- Surface of studied friction zone :
- Lifetime : Nb of control rod rack insertions into the reactor core by emergency protection signals is 400 times during the service life

2. PARTS IN CONTACT DIMENSIONS

- Part 1 - (Rack gear) Shape: gear Dim: (Pitch circle diameter) 56 mm ☐fixed / ☒moving Material: Shaft speed: 0.11 to 0.22 rad/s
- Part 2 – (External rack) Shape: rack Dim: - ☐fixed / ☒moving Material: Gear / rack; Gearing module m= 4 mm
- Representative of a particular setting?

3. TRIBOLOGICAL CONDITIONS

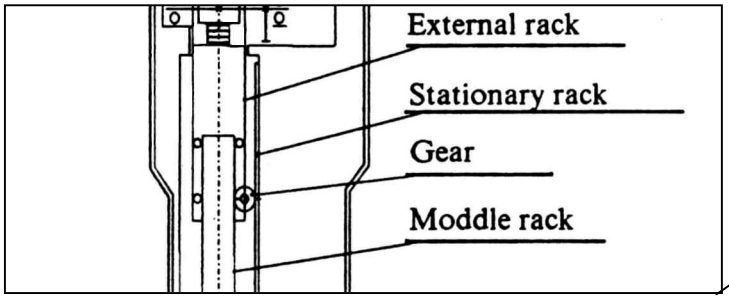
- Load or torque :
- Sliding speed :
- Shift range :
- Frequency :
- Nature of the studied contact : ☐pure sliding / ☒pure bearing / ☒sliding + bearing / ☐impact + sliding (fretting) / ☐Other:
- Displacement kinetics
  - Constant speed ☒YES / ☐NO, value 0.294 m/s (external rack's movement in self-movement mode)
  - Constant acceleration ☐YES / ☐NO, value
  - Sinusoidal speed ☐YES / ☒NO, value
  - Tangential acceleration ☐YES / ☐NO, value
  - Other :

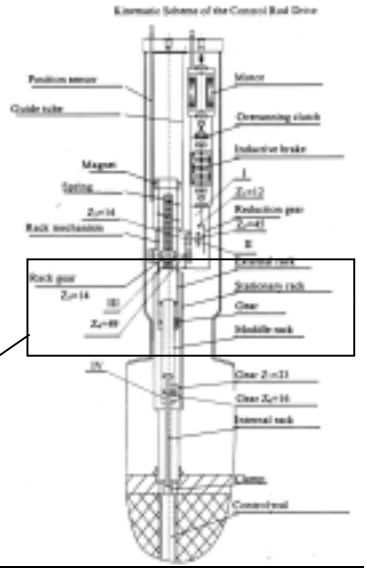
4. ENVIRONMENT CONDITIONS

- Working environment :
- Temperature range : Between 45 and
- Pressure range :
- Particular conditions (magnetism, ...) :

5. OBSERVATIONS

Table 4 : NAME OF THE EQUIPMENT: Control rod drive mechanisms (CRDM) – Gear / Middle rack [4]





1. GENERAL INFORMATION

- Short description of the equipment :
- :
- Usual characterisation : cm² (cm² / mm² / µm² / Other):
- Surface of studied friction zone : Nb of control rod rack insertions into the reactor core by emergency protection signals is 400 times during the service life
- Lifetime

2. PARTS IN CONTACT DIMENSIONS

- Part 1 - (gear) Shape: gear Dim: - ☐fixed / ☒moving Material:
- Part 2 –middle rack Shape: rack Dim: - ☐fixed / ☒moving Material:
- Representative of a particular setting? Gear / rack

3. TRIBOLOGICAL CONDITIONS

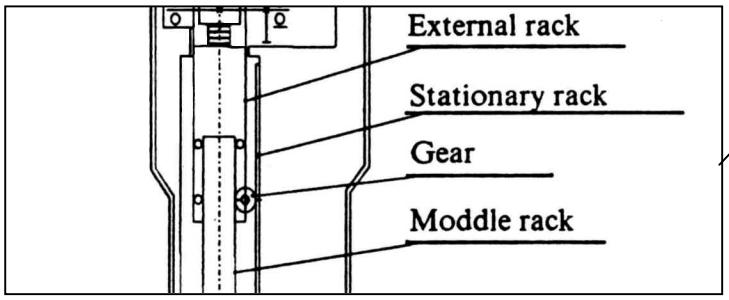
- Load or torque :
- Sliding speed :
- Shift range :
- Frequency :
- Nature of the studied contact : ☐pure sliding / ☒pure bearing / ☒sliding + bearing / ☐impact + sliding (fretting) / ☐Other:
- Displacement kinetics
  - Constant speed ☒YES / ☐NO, value
  - Constant acceleration ☐YES / ☐NO, value
  - Sinusoidal speed ☐YES / ☒NO, value
  - Tangential acceleration ☐YES / ☐NO, value
  - Other :

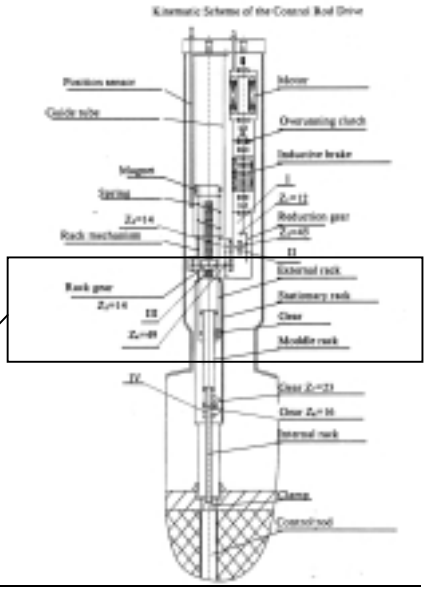
4. ENVIRONMENT CONDITIONS

- Working environment :
- Temperature range : Between 45 and
- Pressure range :
- Particular conditions (magnetism, ...) :

5. OBSERVATIONS

Table 5 : NAME OF THE EQUIPMENT: Control rod drive mechanisms (CRDM) – Gear / Stationary rack [4]





1. GENERAL INFORMATION

- Short description of the equipment :
- :
- Usual characterisation : cm² (cm² / mm² / µm² / Other):
- Surface of studied friction zone : Nb of control rod rack insertions into the reactor core by emergency protection signals is 400 times during the service life
- Lifetime

2. PARTS IN CONTACT DIMENSIONS

- Part 1 - (gear) Shape: gear Dim: - ☐fixed / ☒moving Material:
- Part 2 – stationary rack Shape: rack Dim: - ☒fixed / ☐moving Material:
- Representative of a particular setting? Gear / rack

3. TRIBOLOGICAL CONDITIONS

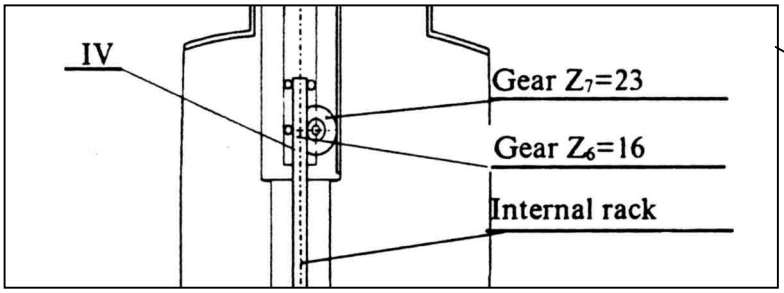
- Load or torque :
- Sliding speed :
- Shift range :
- Frequency :
- Nature of the studied contact : ☐pure sliding / ☒pure bearing / ☒sliding + bearing / ☐impact + sliding (fretting) / ☐Other:
- Displacement kinetics
  - Constant speed ☒YES / ☐NO, value
  - Constant acceleration ☐YES / ☐NO, value
  - Sinusoidal speed ☐YES / ☒NO, value
  - Tangential acceleration ☐YES / ☐NO, value
  - Other :

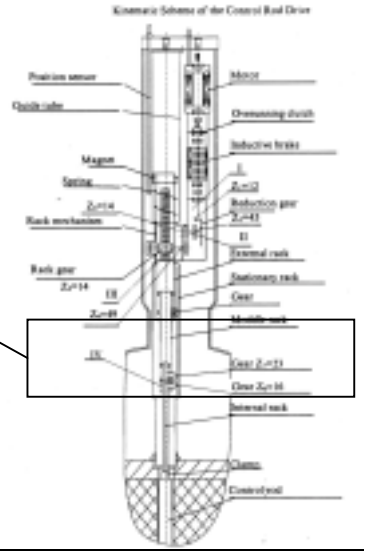
4. ENVIRONMENT CONDITIONS

- Working environment :
- Temperature range : Between 45 and
- Pressure range :
- Particular conditions (magnetism, ...) :

5. OBSERVATIONS

Table 6: NAME OF THE EQUIPMENT:





1. GENERAL INFORMATION

- Short description of the equipment :
  :
- Usual characterisation : cm² (cm² / mm² / µm² / Other):
- Surface of studied friction zone : Nb of control rod rack insertions into the reactor core by emergency protection signals is 400 times during the service life
- Lifetime

2. PARTS IN CONTACT DIMENSIONS

- Part 1 - (Gear Z_6) Shape: gear Dim: (Pitch circle diameter) 48 mm ☐fixed / ☒moving Material:
  Shaft speed: 0.37 to 0.74 rad/s
- Part 2 – internal rack Shape: rack Dim: - ☐fixed / ☒moving Material:
  Gear / rack; Gearing module m= 3 mm
- Representative of a particular setting?

3. TRIBOLOGICAL CONDITIONS

- Load or torque :
- Sliding speed :
- Shift range :
- Frequency :
- Nature of the studied contact : ☐pure sliding / ☒pure bearing / ☒sliding + bearing / ☐impact + sliding (fretting) / ☐Other:
- Displacement kinetics
  - Constant speed ☒YES / ☐NO, value
  - Constant acceleration ☐YES / ☐NO, value
  - Sinusoidal speed ☐YES / ☐NO, value
  - Tangential acceleration ☐YES / ☐NO, value
  - Other :

4. ENVIRONMENT CONDITIONS

- Working environment :
- Temperature range : Between 45 and
- Pressure range :
- Particular conditions (magnetism, ...) :

5. OBSERVATIONS

Table 7: NAME OF THE EQUIPMENT: HOT GAS DUCT – Thermal expansion unit 1- contact between the load bearing tube and the divided sealing strips [5]

GENERAL INFORMATION

- Short description of the equipment: The hot duct is designed to remove the primary coolant headed in the reactor system to PCS with minimum thermal losses due to hot-to-cold helium recuperation effect. The hot duct is located within the cross vessel and is made of a load bearing metallic tube, a thermal insulation, an expansion joint and supports. One end of the load bearing tube is welded tightly to the core metallic support. The other end of the hot duct is connected to the PCS inlet nozzle through an expansion joint.
- Usual characterisation :
- Surface of studied friction zone : cm² (cm^2 / mm^2 / μm^2 / Other):
- Lifetime :

PARTS IN CONTACT DIMENSIONS

- Part 1: Shape: Dim: - ☐fixed / ☒moving
  Material:
- Part 2: Shape: Dim: - ☒fixed / ☐moving
  Material:
  cylinder into a cylinder
- Representative of a particular setting?

TRIBOLOGICAL CONDITIONS

- Load or torque :
- Sliding speed :
- Shift range :
- Frequency :
- Nature of the studied contact : ☒pure sliding / ☐pure bearing / ☐sliding + bearing / ☒impact + sliding (fretting) / ☐Other:
- Displacement kinetics
  - Constant speed ☒YES / ☐NO, value
  - Constant acceleration ☐YES / ☐NO, value
  - Sinusoidal speed ☒YES / ☐NO, value
  - Tangential acceleration ☐YES / ☐NO, value
  - Other :

ENVIRONMENT CONDITIONS

- Working environment :
- Temperature range :
- Pressure range :
- Particular conditions (magnetism, ...) :

OBSERVATIONS

Table 8: NAME OF THE EQUIPMENT: HOT GAS DUCT – Thermal expansion unit 2- contact between the divided sealing strips and the divided sealing strips or the housing ring [5]

GENERAL INFORMATION	
• Short description of the equipment	The hot duct is designed to remove the primary coolant headed in the reactor system to PCS with minimum thermal losses due to hot-to-cold helium recuperation effect. The hot duct is located within the cross vessel and is made of a load bearing metallic tube, a thermal insulation, an expansion joint and supports. One end of the load bearing tube is welded tightly to the core metallic support. The other end of the hot duct is connected to the PCS inlet nozzle through an expansion joint.
• Usual characterisation	:
• Surface of studied friction zone	: cm² (cm^2 / mm^2 / μm^2 / Other):
• Lifetime	:

PARTS IN CONTACT DIMENSIONS			
• Part 1	Shape: Material:	Dim:	- ☒fixed / ☐moving
• Part 2	Shape: Material: plane / plane	Dim:	- ☐fixed / ☒moving
•			
• Representative of a particular setting?			

TRIBOLOGICAL CONDITIONS

- Load or torque :
- Sliding speed :
- Shift range :
- Frequency :
- Nature of the studied contact : ☐pure sliding / ☐pure bearing / ☐sliding + bearing / ☒impact + sliding (fretting) / ☐Other:
- Displacement kinetics
  - Constant speed ☒YES / ☐NO, value
  - Constant acceleration ☐YES / ☐NO, value
  - Sinusoidal speed ☒YES / ☐NO, value
  - Tangential acceleration ☐YES / ☐NO, value
  - Other :

ENVIRONMENT CONDITIONS

- Working environment :
- Temperature range :
- Pressure range :
- Particular conditions (magnetism, ...) :

OBSERVATIONS

Table 9: NAME OF THE EQUIPMENT: Stators seals [5]

GENERAL INFORMATION	
• Short description of the equipment	The turbocompressor design provides multistage seals for a stator in order to minimize coolant by-pass leaks. Each stage of the stator seal consists of two rings which are multisegment elements enclosed in casings. The stator seals limit helium by-pass leaks between places of the turbocompressor interfacing and the other PCS components. Meanwhile, the stator seals act as radial friction supports for the turbocompressor
• Usual characterisation	:
• Surface of studied friction zone	: cm² (cm^2 / mm^2 / μm^2 / Other):
• Lifetime	:
PARTS IN CONTACT DIMENSIONS	
• Part 1	Shape: Dim: - ☒fixed / ☐moving Material:
• Part 2	Shape: Dim: - ☐fixed / ☒moving Material: unknow
• Representative of a particular setting?	cylinder into a cylinder
TRIBOLOGICAL CONDITIONS	
• Load or torque	:
• Sliding speed	:
• Shift range	:
• Frequency	:
• Nature of the studied contact :	☐pure sliding / ☐pure bearing / ☐sliding + bearing / ☒impact + sliding (fretting) / ☐Other:
• Displacement kinetics	
- Constant speed ☒YES / ☐NO, value	- Sinusoidal speed ☒YES / ☐NO, value
- Constant acceleration ☐YES / ☐NO, value	- Tangential acceleration ☐YES / ☐NO, value
	- Other :
ENVIRONMENT CONDITIONS	
• Working environment	:
• Temperature range	: 100 °C to 500 °C
• Pressure range	: DP 1 to 45 bar
• Particular conditions (magnetism, ...)	:
OBSERVATIONS	

Table 10: NAME OF THE EQUIPMENT: Internals 1 - Graphite / graphite contact [5]

GENERAL INFORMATION

- Short description of the equipment: The reactor internals are intended to dispose and put the core into the required configuration, as well as to organize the coolant circulation The reactor internals consist of a permanent site reflector, a core graphite support structure, a metallic support structure, a top collector plenum, a upper core restraint and the hot duct. The reactor internals are located within the reactor vessel. Contacts are graphite/graphite or graphite / metal.
- Usual characterisation
- Surface of studied friction zone : cm² (cm^2 / mm^2 / μm^2 / Other):
- Lifetime :

PARTS IN CONTACT DIMENSIONS

- Part 1: Shape: Dim: - ☒fixed / ☐moving
  Material:
- Part 2: Shape: Dim: - ☐fixed / ☒moving
  Material:
  plane/plane
- Representative of a particular setting?

TRIBOLOGICAL CONDITIONS

- Load or torque :
- Sliding speed :
- Shift range :
- Frequency :
- Nature of the studied contact : ☐pure sliding / ☐pure bearing / ☐sliding + bearing / ☒impact + sliding (fretting) / ☐Other:
- Displacement kinetics
  - Constant speed ☒YES / ☐NO, value
  - Constant acceleration ☐YES / ☐NO, value
  - Sinusoidal speed ☒YES / ☐NO, value
  - Tangential acceleration ☐YES / ☐ NO, value
  - Other :

ENVIRONMENT CONDITIONS

- Working environment :
- Temperature range :
- Pressure range :
- Particular conditions (magnetism, ...) :

OBSERVATIONS

Table 11: NAME OF THE EQUIPMENT: Internals_2 - Graphite / metal contact [5]

GENERAL INFORMATION	
• Short description of the equipment	The reactor internals are intended to dispose and put the core into the required configuration, as well as to organize the coolant circulation The reactor internals consist of a permanent site reflector, a core graphite support structure, a metallic support structure, a top collector plenum, a upper core restraint and the hot duct. The reactor internals are located within the reactor vessel. Contacts are graphite/graphite or graphite / metal.
• Usual characterisation	
• Surface of studied friction zone	: cm² (cm^2 / mm^2 / μm^2 / Other):
• Lifetime	:
PARTS IN CONTACT DIMENSIONS	
• Part 1	Shape: Dim: - ☐fixed / ☒moving Material:
• Part 2	Shape: Dim: - ☒fixed / ☐moving Material: Ex: plane / plane and cylinder into a cylinder
• Representative of a particular setting?	
TRIBOLOGICAL CONDITIONS	
• Load or torque	:
• Sliding speed	:
• Shift range	:
• Frequency	:
• Nature of the studied contact :	☐pure sliding / ☐pure bearing / ☐sliding + bearing / ☒impact + sliding (fretting) / ☐Other:
• Displacement kinetics	
- Constant speed ☒YES / ☐NO, value	- Sinusoidal speed ☒YES / ☐NO, value
- Constant acceleration ☐YES / ☐NO, value	- Tangential acceleration ☐YES / ☐NO, value
	- Other :
ENVIRONMENT CONDITIONS	
• Working environment	:
• Temperature range	:
• Pressure range	:
• Particular conditions (magnetism, ...)	:
OBSERVATIONS	