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 General synthesis

Project coordinator:

FRAMATOME ANP SAS, F (coordinator)

Contractors:

Commissariat à l'Energie Atomique, F
University of Applied Sciences Zittau/Goerlitz, D
Nuclear Research and Consultancy Group, NL
Forschungszentrum Juelich GmbH, D
Empresarios Agrupados Internacional, S.A., E
National Nuclear Corporation Limited, UK
Jeumont Industrie, F
Société de mécanique magnétique, F
ANSALDO ENERGIA S.p.A., I
Von Karmann Institute, B
Heatric, UK
FRAMATOME ANP GmbH, D

Sub Contractors:

Aubert et Duval, F
Energie Versorgung Oberhausen, D

Dissemination level : PU
Document N°: HTR-E-05/12-D-0-0-13
Status : Final

CONTENTS

1 Executive summary

The European Project for the Development of HTR Technology proposed for the 5th Framework Programme concentrates on HTR-related key technologies and innovation potentials that can improve the chances of European industry when HTRs come out in the market. It clearly appears that technical developments are particularly needed for the components and systems of a modern HTR with a direct cycle as this new concept, by comparison with a steam cycle of the former HTRs, considers innovative technologies for the components. It must be noted that the competitiveness, safety and acceptability of such reactors are based on the performances of these technologies.
For the HTR-E project, the critical and innovative components and systems have been selected by reference to the actual projects (GT-MHR, PB-MR):

- the helium turbine, the recuperator heat exchanger, the magnetic bearings and the helium leak-tightness rotating seal.

- the tribology. Sliding innovative components (stator seals, hot gas duct seal,..) in helium environment are particularly concerned.

- the helium purification system. The recommendations concerning the helium impurities contents have provided in accordance with the different materials proposed for the innovative components.

The main outcomes from the HTR-E project are the design recommendations and identification of further R&D needs for these components. These recommendations are based on:

- experience feedback from European past helium test loops and reactors (EVO, HHV, KVK, Dragon, AVR and THTR) but also from outside Europe reactors (Peach bottom, FSV, HTTR, HTR-10), and also from other projects and industries (FBR, AVR, PNP plant,…),

- design studies, CFD and FEM analyses (DACAT, BLADES, CAST3M, Fluent, STAR CD, ANSYS, NASTRAN, MLDyn codes),

- and experimental tests facilities (CLAIRE high temperature heat exchangers test facility from ESTHER platform, FLP 500 test facility for AMBs, tribological test facilities).

The work has been carried out over a period of four years split into two main phases of two years. The first phase concerns the experience feedback, the specifications and design studies and the second one the validation, the tests, the identification of further R&D needs and recommendations for the main components and systems of a modern HTR with a direct cycle.

2 Objectives and Strategic Aspects

The main objective of the work performed for HTR-E was to develop innovative technologies which are needed for the components and systems of a modern HTR with a direct cycle and then contribute to the competitiveness, safety and acceptability of such reactors. The competitiveness of such reactors is based on the use of these technologies for each high efficiency component and system which allow, at the end, to reach a net plant efficiency of around 50 %. Similarly, high performances components and systems in terms of thermo-mechanical resistance, lifetime, maintenance, behaviour in case of failure,… are required to demonstrate the safety and to contribute to the acceptability of such reactors.

The critical and innovative components and systems have been selected by reference to the present projects with a direct cycle concept (GT-MHR, PBMR). These two projects consider indeed design options which lead to select the most innovative technologies for the components to achieve the required performances (turbine material resistance, turbo-machine support by AMBs, recuperator performances).
Consequently a steam generator (helium/water) or a primary helium/secondary fluid heat exchanger which are also important components for HTR technology and which can be considered as critical components are not innovative components relative to the direct cycle. So they have not been addressed in this project. Similarly a component like the compressor is well innovative and relative to the direct cycle but as it is considered less critical it has not been addressed in this project.

The components and systems, selected for HTR-E, are really innovative as there is no fully representative feedback experience from former HTRs and also from other industries. In addition the present technologies cannot be easily transferred to a modern HTR considering the specificity of the operating conditions. That is why some components and systems were considered as critical from a feasibility point of view. An important effort has been required to study these technological key issues and the 5th European Framework Program is a very good opportunity to bring together the capabilities of European R&D laboratories and interested industries in order to give fruitful indications of the feasibility of these components.

The key components and systems selected for HTR-E are:

- the helium turbine, WP1.

The direct cycle concept is the main feature of a competitive and safe modern HTR. Then the feasibility of a high efficiency helium turbine, inserted in the primary cycle, is the most important technological key issue for the components of a modern HTR. An important work program has been made in HTR-E. It is complementary to the material development work program carried out in the HTR-M framework.

- the helium/helium heat exchanger called recuperator, WP2.

The recuperator is a helium/helium heat exchanger inserted in the primary circuit to recuperate a part of the remaining energy at the turbine outlet to preheat the helium at the core inlet. This component is specific to the direct cycle and its main function is to increase as high as possible the efficiency of the cycle. The competitiveness of a modern HTR is directly linked to the feasibility of this key component.

- the large capacity magnetic bearings, WP3.

These components are used to support the rotating shafts of turbo-compressors or turbo-machine inserted in the direct cycle of a modern HTR. This kind of support has been selected for a modern HTR to avoid the risk of leakage and fluid ingress in the primary circuit induced by the concept of mechanical and lubricated bearings (bad experience feedback in US and German former HTRs). So, the magnetic bearings for rotors support are considered as key components with regards to the safety and competitiveness of a modern HTR.

- the helium leak-tightness rotating seal, WP4.

The helium rotating seal is associated with a rotor of the turbo-machine penetrating through the primary vessel. In this case the generator is located outside the primary circuit that simplifies the maintenance operations and that allows to use mechanical bearings for the support. So this concept can be considered as an alternative of a fully immersed rotor in primary helium and consequently fully supported by magnetic bearings. The feasibility of such a seal is a key issue to increase the competitiveness of a modern HTR by reducing the maintenance campaign duration.

- the tribology, WP5.

Sliding and new components (stator seals, hot gas duct seal,…) of a modern HTR with direct cycle are particularly concerned. It must be noted that a bad operating of these sliding components will dramatically impact the safety and availability of the reactor.

- the helium purification system, WP6.

The performances of this system impact directly the safety of a modern HTR as it controls the level of impurities in the primary helium. It is a key system to limit the corrosion risk of the graphite and materials of all components of the primary cycle.

The experience feedback from former HTRs, the survey of the existing technologies from other industries and the rescue of existing know-how are elementary tasks performed in each work-package.
The sources of information were European past helium test loops and reactors (EVO, HHV, KVK, Dragon, AVR and THTR) but also from outside Europe reactors (Peach bottom, FSV, HTTR, HTR-10), and also from other projects and industries (FBR, AVR, PNP plant,…).
Some data from these installations have been collected and issued in the delivered reports of HTR-E. For EVO, the data (measurements) have been scanned and transferred on digital media.
For the GT-MHR and PBMR projects public data has been used.

The HTR-E project also complies with the programme strategy of the 5th EU Framework Programme with a visible European added value in combining complementary expertise from different European organisations. Together with the other HTR-related projects, it strengthens the position of European industry and R&D organisations on a global basis and helps to advance the level of competence in HTR key technologies for future European application or participation in international projects.
The HTR can be seen as a significant step towards sustainable nuclear energy supply systems, being also compatible with the social objectives, especially concerning the exclusion of unacceptable releases of radioactivity from the power plant and the spent fuel repository, and with respect to minimal waste streams and operational exposures.

As part of the European HTR FP5 projects, the main collaboration and interface issues are:

- with HTR-M : these issues are managed by holding joint meeting e. g. HTR-E WP1/ HTR-M and by exchanging specific reports e.g. ‘Materials and manufacturing discs’ from G.Raisson : Aubert and Duval : see HTR-E04/06D1122,

- with HTR-L : These issues are also managed by holding joint meeting e.g. International Workshop on Safety Approach and Licensing Issues for High Temperature Gas Cooled Reactors. This meeting has been held at Brussels on September 10th 2004,

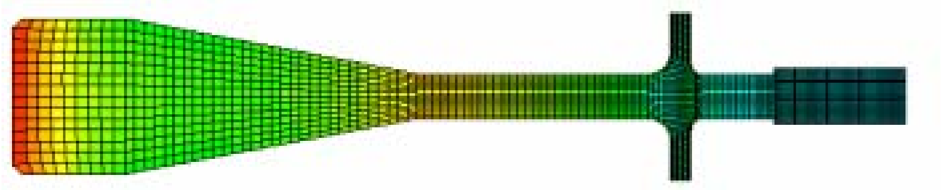
- with OKBM: ISTC project 1261 on GT-MHR turbo-machine support and with ISTC 1313 on GT-MHR turbine materials have been received through a letter from EC dated on November 16th. Both projects have been reviewed by the partners (mainly HTR-E WP1 and WP3 with also HTR-M).
- With HTR conferences: FANP-SAS presented in Beijing on September 22 to 24th, 2004 a paper related to HTR-E: “Last results from HTR-E project”.

3 Scientific and technical assessment

3.1 WP1 Helium turbine

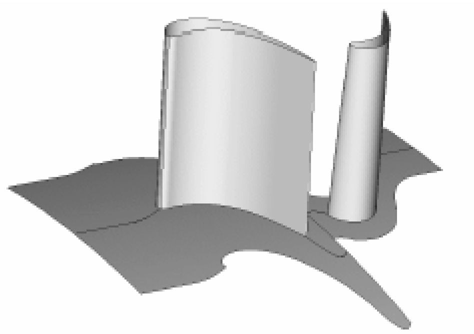
The partners involved in this WP1 were: Framatome (France and Germany), CEA, FZJ, EA, VKI with two subcontractors: EVO for experience feedback and A&D for materials.
The helium turbine is not a safety classified component but to confine material fragments within the pressure vessel in case of deblading a safety related function for the stator is recognised. Indeed, based on HTR-L project comments, the deblading accident and the risk of disk rupture, a horizontal shaft was recommended.
The nominal operating conditions consider 850 °C at the inlet and an operating period of 60 000 hours without any intervention on this component, inducing a spare part unit for maintenance and repair. The nominal rotation speed is 3000 rpm that leads to important stresses in the disc (diameter = 1400 mm) and in the blades. Then, the creep damage after 60 000 h for the first stages of the turbine was analysed carefully.
Taking into account the proposed materials within the HTR-M/M1 project, an acceptable damage can not be achieved without a cooling of the discs of the first stages by helium derived from the compressor outlet. A&D proposed the Udimet 720 grade for the disk, without any limit related to the cobalt content. At the opposite, OKBM in ISTC 1313 project limited this cobalt content. The disk material is out of the present stage of the art but seems achievable by conventional cast and wrought or by prealloyed powder metallurgy process. For the blades, materials (Ni-based super alloy) were also proposed within the HTR-M/M1 project. It appears not necessary to cool the blades but a protective coating against corrosion may be needed.
After a preliminary design phase (see reference 1), the stress field was calculated thanks to CAST3M and ANSYS codes, for the discs and the blades to assess the thermo-mechanical damages on these elements (creep, fatigue,..).
In a first step. A simplified axisymetrical model using linear mechanical behaviours was simulated in order to have an idea of the temperatures and stresses fields likely to occur within the turbine disks (see next figure).

Although the stress concentrations due to the 3D geometry, near the blade foot for instance, were not considered, this simulation shows that with the foreseen materials a cooling of the first stages is necessary. Thus, an estimation of the necessary derivated helium flow were performed and it is shown that such a cooling should not lead to a dramatic decrease of efficiency.
In a second step, the life time of a turbine disk at several temperatures was estimated by Finite Element Method (CAST3M) with the following mesh:



The detailed life time was determined using a non linear mechanical behaviour (viscoplastic Chaboche law) based on the experimental data (tensile, low cycle fatigue and creep tests) of U720 Coarse Grain material obtained within the HTR-M program. It is shown that cooling the disk down to 750°C should be sufficient to reach a lifetime of 60000 hours. However, these simulations raised the lack of experimental data for such long durations. Thus, the proposed results were based on the extrapolations of the mechanical behaviour to such long creep steps.
Aerodynamic design and CFD calculations (DACAT and BLADES codes, inverse method) were performed by VKI for typical operating conditions to optimise the shape of the blades. The main conclusions obtained are the following ones:
The compressor performance exceeds the requirements and initial predictions. The main reason is the careful blade design with rather low loading. This low loading results in a larger

number of stages (21 instead of 18 for the HP compressor). This increases the shaft length and could eventually lead to rotor dynamic problems. The turbine efficiency is lower than the initial target value. This is a direct consequence of the small number of stages at 3000 RPM. Increasing the number of stages or increasing the rotational speed to 3600 RPM would allow lower loading per stage, hence higher efficiency as clearly shown by the Smith correlation. Here again this would increase the shaft length and could eventually lead to rotor dynamic problems.



3D view on optimized turbine stator and rotor.

The amount of cooling flow needed to keep the first turbine rotor root below a given maximum temperature is very small and without measurable impact on the gas turbine efficiency. One single hole in the blade root of 5 to 10 mm diameter is sufficient.
Related to the aerodynamical tests definition, a model is proposed to define the conditions for a correct experimental simulation of the steady performance of each component as well as the unsteady interaction between each component of the circuit. In particular, one wants to avoid surge and stall, excessive overspeed of the rotating components, overheating or thermal shocks. It is shown that the main requirements are:

- a model compressor/turbine performance map that is similar to the one of the real compressor/turbine
- conservation of the ratio between the different volume of reactor, heat exchangers and coolers
- conservation of the length over area ratio of the ducts.

As an example, two ways of controls have been analysed: inventory control or by-pass. The first one is found more efficient while the second one may induce strong thermal gradients although it looks more reactive. The proposed approach will be very useful to design an appropriate test facility with smaller size, air instead of helium.
Regarding, the mechanical tests necessary to fully investigate the mechanical behavior of the foreseen turbine disks and blades materials are addressed. It was concluded that the mechanical specimens will have to be machined from an ingot not far from the full scale. This is the only way to be representative of the micro structural heterogeneities as well as chemical segregations. Concerning the disks, a test matrix was proposed including the following tests: tensile, creep, Low Cycle Fatigue, fatigue crack growth. The effects of ageing on tensile and LCF and the effect of carburization were considered. An analysis of the anisotropy and discrepancy of properties within the disk is proposed. Concerning the blades materials, the same types of tests were proposed. Moreover, high cycle fatigue tests were added. Higher temperatures and corrosion effects were considered. After the completion of this program, it is possible to launch a detailed design of the turbine, the manufacture of a mock-up and the tests of this mock-up on a large scale facility or in international collaboration (e.g. test loop at HTTR/HTR10 or others). However, the final design of the turbine components (especially the turbine disks as well as blade foot cooling system) will have to be optimized by a turbine manufacturer.
The main overall conclusions drawn from this WP1 are as follows:

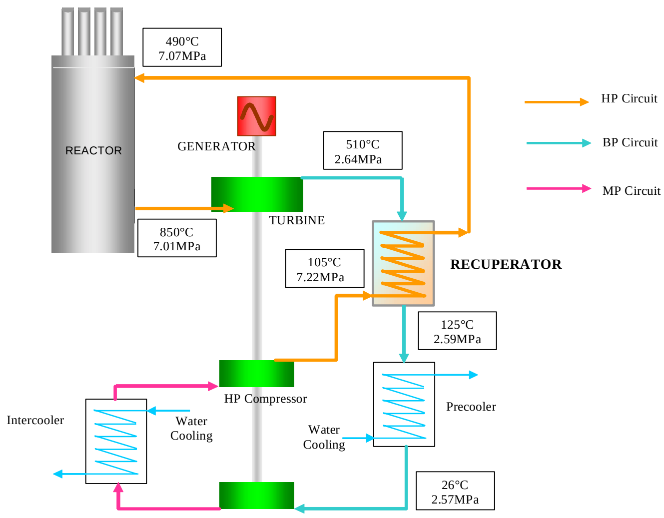
- A horizontal shaft is preferable than a vertical one, for safety reasons (deblading accidents) and due to catcher bearings limitations,
- 3D design of the blades is feasible, a coating is necessary against the corrosion effect. The effectiveness and the number of stages are as follows:
    * Turbine with 12 stages and η= .90,

* LP compressor with 15 stages and η= .940,
* HP compressor with 21 stages and η= .938.

- Cooling is necessary at the blade foot and also for the disk, but a small flow rate is sufficient,
- Disk made of U720 is achievable with a diameter of 1,5 m.,
- Further developments need a manufacturer (cooling design, coatings,..),
- An important R&D effort has to be done in order to determine the thermal and mechanical properties of the U720.

3.2 WP2 Recuperator

The partners involved in this WP2 were: Framatome (France) , CEA, FZJ, NRG, ANSALDO and HEATRIC. The requirements of the GT-MHR and PBMR recuperator heat exchanger were specified by FANP (using available public information for PBMR). This component is used to 'recuperate' a part of the remaining energy in the LP gas (2.63 MPa) at the turbine outlet (510 °C) in order to heat the HP gas (7.07 MPa) at the HP compressor outlet (105 °C) before the core inlet (490 °C). This component is not located on the primary barrier but it is fully immersed inside the pressure vessel. Consequently, it is not safety classified. Note that there is a strong incentive to consider a compact design for this component in order to limit the impact on the size of the pressure vessel.
The preliminary GT-MHR analysis of normal and design transients based on the magnitude of temperature and pressure by comparison with the normal operation shows that the most severe transients is the loss of offsite power with turbo-machine trip (cold shocks):



- ΔT = - 335 °C for the LP recuperator inlet, in 5 seconds, from initial values : 508 °C,
- (severe slope ≈ 70 °C/s), then, the temperature rises again in 508 °C in 120 seconds after initiation,
- temperature maximum = 650 °C at the end of the turbo-machine run-out,
- number of scram occurrences: 300.

In terms of in service inspection and repair requirements, note that a modular concept was specified in order to be able to locate and repair the leaky module by plugging. The main concepts suitable for the recuperator application are mainly (see reference 1):

- Tubular concept based on past HTR experience on steam generators and heat exchangers,
- Printed circuit concept (Heatric company),
- Plate-fin concept (Nordon, MHI, Ingersoll Rand,…).

The engineering studies (NRG) were performed on two basic concepts (Heatric and Nordon) including preliminary design, CFD analysis of flow distribution, heat exchange and pressure losses performances and identification of potential high temperature region, thermo-mechanical resistance analyses (ANSYS code). The main results obtained on the Heatric mock up from a 3D analysis were as follows:

- Hot side of IHX mock up is subject to the most severe loads,
- Steady state after cool down is reached after 1-2 hours. However, most of the temperature evolutions are within the first 20 minutes.

- Life prediction is difficult (very sensitive to the code used). Depending on the code (ASME or RCC-MR), the minimal fatigue life changes drastically (safety factor over than 20). So no reliable fatigue life prediction is possible for the mock up with the available fatigue data.

The same type of analysis was performed by NRG on the NORDON concept. The results show an increase of the thermo mechanical stresses in comparison with the Heatric concept inducing a reduction of the corresponding life time duration.

The Heatric mock up was equipped with a series of gages and thermocouples as showed on the following picture and then tested on the Claire test loop of the Esther platform:

The main conclusions on HEATRIC mock up tests are as follows

- **In steady state** :
  * The hydraulic performances are in good agreement with Heatric predictions,
  * But related to the thermal performances, CEA observed important discrepancy between Heatric predictions and experimental results due to fluid properties, longitudinal conduction and a flow mal distribution between channels linked to the design of the headers.
  Nevertheless 95% efficiency was reached.
- **In transients:**
  * Submitted to temperature transients, HEATRIC mock up withstands 100 cycles without any leak (Helium tests were performed every week)
  * Experimental stresses are higher than those calculated.

The Nordon mock up was manufactured with delays and then not tested due to the lack of time.

The main overall conclusions drawn from this WP2 are as follows:

- Heatric mock up is able to fit with the steady state requirement but caution should be taken for flow distribution design,
- The Heatric heat exchanger resists after 100 cold/hot shocks, but plastic deformation occur inside,
- For final statements, need of tests under real gas environment,
- The PFHE remains a potential candidate for Recuperator technology but caution have to be taken on the design of small height fins and lateral bars
- The FEM analysis seems to predict more mechanical problems than PCHE.

3.3 WP3 The large capacity magnetic bearings

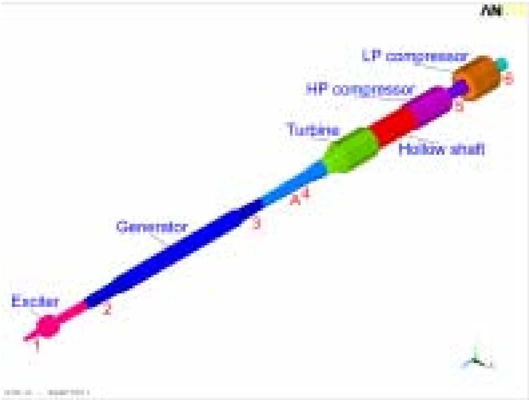
The partners involved in this WP3 were: Framatome (France) , S2M, NRG, FZJ and Zittau University with EDF as observer.

The functional requirements (see reference 1) related to the axial and radial active magnetic bearings and the axial and radial catcher bearings are based on the two following machines:

- the power turbine of a GT-MHR type reactor,
- the high pressure turbo compressor of a PBMR type reactor.

Note that the AMBs by themselves are not sized to withstand the seismic loads and that; in this case, the catcher bearings will react to support a part of these loads.

Taking into account these required load capacities, geometrical constraints and other requirements detailed, a conceptual design has been elaborated for the AMBs support of such a machine, see the figure hereafter. This conceptual design is suitable for a maximum temperature < 150 °C. Note that the axial magnetic bearing is not sized for 105 tons and that one solution to support the GT-MHR rotor would be to consider two discs with two axial magnetic bearings.



The load analysis was performed with dynamic simulation. The simulation tool MLDyn was parameterised with the values given from the requirements and the design study. With help of the simulation tool, all operating modes (start up, unbalances, speed levels, static and dynamic loads) were investigated for stiff rotors.
The required modal analyses, harmonic response analyses as well as the frequency response analyses were performed with Finite Element analyses (ANSYS code). The numerical results provided the boundary and loading conditions for the design and the simulation tool (MLDyn).
An alternative of Active Magnetic Bearings for the rotating components support considering Permanent (Passive) Magnetic Bearings was investigated by a feasibility study. The fail safe characteristics of this system are particularly interesting to reduce the loads to the catcher bearings in accidental conditions (loss of power).
A specific feasibility study on mechanical catcher bearings was performed. As part of catcher bearing tests, the study covers the past experience from the German HTR R&D Programme. In this study, it is pointed out one important item which is the retainer bearing in the case of AMB technology. The role of this retainer or catcher bearing is to prevent contact between rotor and static circulator parts upon unintended de-energisation of the magnets or malfunction of the electronics. The reference design for the test of the catcher bearings was the HTR-500 auxiliary blower for decay heat removal having an impeller diameter of 1.25 m. A specific test facility was built (FLP500 which was transferred to Zittau University, see picture hereafter) to simulate the conditions during coasting of the blower from 6000 rpm.

FLP 500 Test Facility

The magnetic, thermal and structural behaviour of the magnet supported system for the various load cases were determined by means of transient Finite Element analyses (MSC.Marc code).

The main overall conclusions drawn from this WP3 are as follows:

Permanent Magnetic Bearings

- PMBs could be used in addition to the investigated AMBs
- The main features of PMBs are:
  * gained permanent radial stiffness
  * guidance of the shaft
  * additional load capacity
- that promises:
  * reduced loading on the CBs,
  * thereof the expected lifetime of the CBs may increase,
  * otherwise the manufacturing problem of the proposed CBs (size of ceramic balls) may be solved.

It has to be noticed that PMB concept will be investigated in frame of RAPHAEL SP-CT WP2.

Catcher Bearings

- required load capacity of radial CBs is determined by seismic loadings,
- further investigations and experiments are necessary,
- limitation of the axial CB capacity is a feasibility issue for heavy rotor.

Rotor arrangement of the turbo machine

- a horizontal shaft or an arrangement of two vertical shafts with a flexible coupling was recommended to be developed.

Tools

- the use of MLDyn for dynamic simulation, MLDia for Diagnostics and ANSYS for FEM-calculations was proofed.

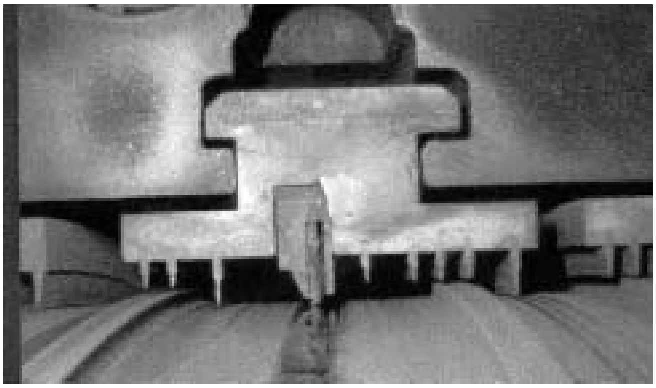
3.4 WP4 Helium leak tightness rotating seal

The partners involved in this WP4 were: Framatome (France) , S2M, NRG, FZJ and Zittau University with EDF as observer.
For a direct cycle HTR (GT-MHR type reactor) considering a single shaft for all rotating components (turbo-compressor and generator), it is interesting to locate the generator outside the pressure vessel. Then, the support design of the shaft can be different and simpler (located outside the pressure vessel, using a mechanical bearing, generator and turbo-compressor shaft separately supported). In addition, as the accessibility to the generator becomes possible without opening the pressure vessel, the maintenance operations on this component are easier. But this arrangement (outside generator and fully immersed turbo-compressor) leads to insert a helium leak-tightness rotating seal on the primary helium containment barrier to allow a passage for the rotating shaft.
It is first of all necessary to evaluate the maximum leakage objectives, taking into account the potential gas activity, the radio protection and the safety objectives.
In a second step the different leakage points on a modern HTR design were listed and classified (static joints, welds, gliding joints, rotating joints...).
State of the art is established for each joint class, in order to check that there is an industrial solution, adapted to the modern safety and radio protection requirements.
The main requirements were extracted from a GT-MHR type turbo-machine shaft and PBMR type power turbine shaft. The experience feedback on oil seals used is not satisfactory and a dry seal was recommended.
Different available concepts are already tentatively identified and analysed taking into account the state-of-the-art and feedback experience on similar systems used in industry:

CMBs

With help of a single effect analysis on basis of theoretical investigations for Canned Magnetic Bearings it is planned to find an innovative technical solution for helium leak-tightness rotating systems. A non magnetic can is recommended and depicted the influence of the can (thickness 0.2 to 0.5 mm) on the bearing capacity/size and also on the sensors sensitivity. This influence will be much more significant for small machines. The experimental tests to be performed in order to analyse such conceptual designs are also specified. In connection with the analysis of the existing devices, a suitable concept of dry system as regards the HTR conditions is defined, and justified by theoretical analysis. The state of the art shows that the present industrial systems can not meet the objective of admissible leakage for a modern HTR (10 to 30 % of total primary helium mass per year). That's why the development of an innovative buffered dry gas face seal is recommended.

Dry gas seal was studied. The proposed solution is composed of a tandem of two hydrodynamic seals with Raleigh pads, a labyrinth between the vessel and the first seal, and an injection of clean helium between the labyrinth and the first seal. The large shaft size is the challenge of this work package due to the lack of experience. Hydrostatic seal concept with an orifice controlling element is another alternative solution if necessary. The potentiality of brush seal is underlined (see here after)



The experimental tests program required for the best promising concept were defined. It is also analysed the capability to carried out these tests on HTTR and HTR 10 test loops. At the end of this feasibility study, the best promising concept was identified. The manufacturing of a mock-up and the experimental tests campaign is possible, after the 5^{th} FWP, on a large scale facility or in international collaboration (e.g. test loop at HTTR/HTR10). Based on the study results performing during the first two years of the contract (2002-2003), the following conclusions can be elaborated:

- The admissible leakages were defined by the partners,
- A design based on a buffered dry gas face seal was proposed by Jeumont,
- The rotating seal with an initial gap meets the requirements: the seal face deformation is less than one µm and the stress level in the seal ring is smaller than 70 Mpa,
- Dry rotating seal (hydro-dynamic seal with injection of clean helium under pressure) is feasible and meets the leakages limits even with a higher Delta P induced by pressure fluctuations in the circuit, coming fro HTR-L design recommendation.

3.5 The tribology in helium conditions

The partners involved in this WP5 were: Framatome (France and Germany) , NNC and FZJ
Due to the lack of oxygen in the Helium circuit, and to the elevated operating temperatures, gliding or rotating surfaces are not covered by the usual protective and lubricating oxide coating. Nevertheless, it is known from 1975's years from work on THTR reactor that the HTR Helium used is not completely an inert gas since it contains impurities such as CH_4, H_20 (steam), which are able to modify the material surfaces. This environment could result in enhanced jamming risks for mobile parts. As components such as control rods, fuel handling machine, turbine, ... could be affected, the safety and plant availability are strongly concerned by a bad operating of these gliding components.
It is therefore necessary to collect the available information and lessons from previous experiences, to evaluate the risks (safety, investment, availability) and to define the further developments that could appear useful to reduce these risks at the appropriate level. Jamming or seizing up of mobile parts (gliding seals, rotating parts, gliding parts) is enhanced in non-oxidising and/or particular environment conditions. In some cases, sticking can even be observed. It appears that the work in this field could take several complementary ways to be defined prior to any development. It would take into account the following items: materials selection, surface treatment or coating, usual operating conditions (temperature, temperature or pressure variations...), tribological operating conditions of the component such as contact load or torque, contact velocities, kind of contact, transient or stationary operating conditions...
A review of the knowledge concerning tribology in non-oxidising and/or particular conditions such as Helium + CH_4, H_20 (as steam), was first established. This is performed by using surviving operating and design experience from HTR such as Dragon project (UK), or others

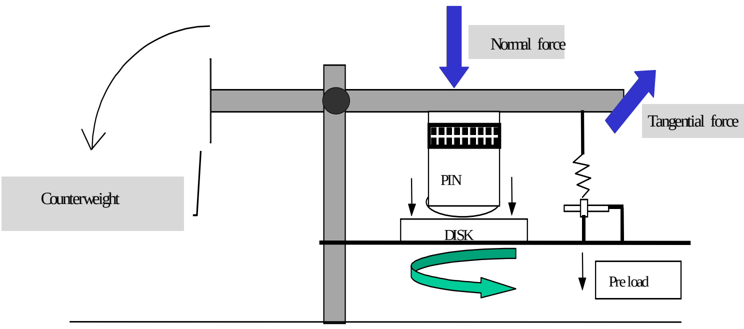
such as THTR 300 (D), or Fort Saint Vrain (USA)...when available, and FBR reactors, experience from other industries if possible and literature.
Both tribometers were used:

- the new tribological equipment of the CEA, based on a former GA design and presented hereafter:

Figure 1a: View of CEA He tribometer

This tribometer used a plane-plane contact with an alternative motion of 6 Hz and can applied load up to 20 MPa. The environment can be a temperature level up to 1000 °C and He with impurities under a pressure level of 5 bar. The gas sampling shall be made through the furnace, near the samples to be tested, in the hot part of the helium volume.

- The pin on disk tribometre bench from <u>FANP Technical Centre </u>can reach at a temperature level of 600° C with a load capacity up to 500 MPa (representative of real loading conditions). The maximal pressure of helium with or without impurities is 1 bar.



In parallel, a review and a classification of the tribological problems on a HTR design was established (on the basis of GTMHR or PBMR design) : this review particularly pointed out for the different involved components, the potential materials, the tribology type (gliding, rotating, continuous or not), the environment conditions (temperature, gas, pressure variations,...), the typical contact conditions (contact pressure, shift, speed, acceleration, frequency, ...) and will specify if it occurs during transient (start or outage periods, control rod drop) or operating conditions.

From the bibliography, it appears particularly that contacts such as metal-metal contact would not be allowed, but compromise with contact metal-carbide could be studied for different carbide content / metallic matrix ratio. Other materials could present a good tribological behaviour in such HTR Helium atmosphere (Molybdenum based coating for rod mechanism, new composite materials for heat insulator,..). A review of the existing technologies (coating, surface treatment, composite materials) on the basis of an analysis of

available data base, and of their performances with respect to the requirements and to the operating conditions is reported.
A selection of materials and antagonistic couples were made for two principal test campaigns. It could represent a first step before a bigger experimental approach of the tribological problems understanding in HTR.

Tests of these materials were performed on samples in representative configurations (sliding + fretting, sliding + bearing (to be chosen from the result of the State-of-the-Art among gears and pinions / racks of control rod drive mechanisms, hot gas duct and insulator) and in as representative as possible conditions: approached chemical environment (Helium with oxidising agents or carbide containing Helium, from possibly applicable WP6-data), temperature 500-750°C according to the components, without pressure (1 to 5 bar) but with concentrations representative to the partial pressure of additive elements at the working temperature.

Tests were performed with a common methodology, common material procurement, machining and surface preparation of samples to allow a better comparison of the results obtained on the materials or coatings, and antagonistic couples proposed for components. The selected base materials are either HR230 or 9%Cr with different type of coatings such as ZrO_2/ Y_20_3; ZrO_2/CaO; SiC; CR_3C_2. Tests are realized without impurities.

The main overall conclusions drawn from this WP5 are as follows:

- The best results have been obtained at 700°C on CERMET coating (Cr3C2-NiCr) deposited by HVOF,
- The Coating Zirconia (ZrO2/Y2O3) + solid lubricant (CaF2) has to be improved (adhesion) for a resistance at 900°C,
- SDG2005 (WC, WC3 / Cr2C3, Ni) deposited by Super Detonation Gun has a good behaviour at 250°C,
- Necessity to elaborate a specification for coating realization,
- Need of regulation about tribological tests,
- Tests have been realized with a sliding movement, and in the future, need to test other types of movement (sliding, dwell motion, …).
-

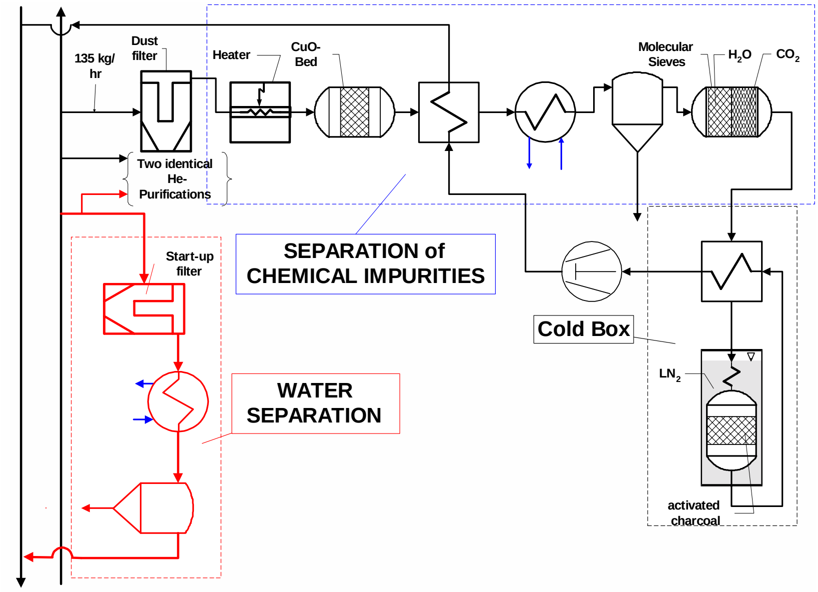
3.6 Helium purification system

Reliable Helium Supply and Purification Systems (HPS) are essential for the safe operation of a modern HTR. They partially also serve for additional functions with respect to operation or control of accident sequences to keep radiological releases as low as reasonably possible. The HPS is of utmost importance with regard to the material behaviour under high temperatures (corrosion, erosion) also under normal conditions because impurities and humidity is inserted via fuel loading, coolant replenishing and any opening of the circuit for maintenance and repair. This point is particularly important for the turbine materials.

Specific experience is available from former and present HTRs (DRAGON, Peach Bottom, AVR, THTR, FSV, HTTR, HTR-10) and from the operation of large test loops like HHV, KVK and EVO. But these rather complex and expensive system are mainly based on the state of the art in the 1960^{th} - 1970^{th}. Meanwhile more advanced processes are available and have to be evaluated for actual direct cycle plant concepts with TRISO particle fuel.

Available literature and data from former HTR projects were collected and additional relevant knowledge from other sources (HTTR, HTR-10, Magnox, AGR, helium test loops) were included in a state-of-the-art information on the helium purification systems of different HTRs (Dragon, AVR, THTR-300, HTTR, HTR-10).

Hereafter is presented the helium purification circuit:



It should be noticed, the importance of the cold trap in liquid nitrogen for the noble gases.
In conclusion, in term of impurity level (or contaminants) the proposed values are as follows:

- Normal operation :

Contaminants	Values (vpm)
H_2O	< 0.1
CO	< 2.0
N_2	< 1.0
H_2	< 5.0
CH_4	< 1.0

- Purified helium returned to the primary circuit: all contaminants < 0,1 vpm expected for each impurity.

4 Conclusion

The achieved results and the beneficial collaboration within the project provide a clear motivation to continue the related issues in V/HTR-IP in the field of Intermediate Heat exchanger (IHX) at the highest temperature as far as it is feasible and in tribology tests in order to select the most appropriate coatings and substrates.
The main results obtained in HTR-E project, are design recommendations for components of direct cycle HTR based on experience feedbacks, design studies and experimental tests. These results are as follows:

- As part of the turbine, the design results obtained in terms of aerodynamic and thermo mechanical behaviour analyzed the feasibility of a large helium turbine working at 850 °C with a thermal power of 600 MWth. The large disk material (Udimet 720 from Aubert & Duval) should be manufactured for a maximal temperature of metal below 775 °C in operating conditions which requires a disk and foot blades cooling system. Nevertheless, for safety reason related to deblating accident, the partners recommended a turbine with a horizontal shaft instead of vertical shaft as proposed in the GT-MHR project. In any case the failure of the disk has to be excluded, which seems difficult to assess. The large amount of data collected from two helium loops, namely EVO and HHV, will be very useful to validate numerical codes for such helium loops.
- As part of the recuperator, the main obtained results from design studies and tests performed in air on CLAIRE loop, valid the concept of plate heat exchangers (based either on PCHE :Printed Circuit Heat eXchanger or PFHE : Plate fin Heat eXchanger) operating at a temperature level of 510 ° C without significant effect of the creep damage. Upgrading of CLAIRE loop has been done.
- As part of the Active Magnetic Bearings (AMB), the design studies and tests performed on FLP500 test facility from Zittau University, valid the algorithms and the numerical model. Seismic loads seem difficult to be controlled by an Active Magnetic Bearing, the use of catcher bearing is recommended by switch off the electrical power. The axial Catcher Bearing (CB) stays a very difficult point from design point of view, if an axial shaft is preferable. In case of horizontal shaft the CB issue is solved.
  And for PMBs (Permanent Magnetic Bearing) conceptual design for small load capacity have been developed and tested.
- In the frame of dry rotating seal, dry helium rotating seal is feasible, if the pressure fluctuations of the helium is low (0.2 bar). In order to accommodate normal pressure fluctuations of primary helium (2 to 3 bar), improvements of the design have to be done. Partners recommended a concept based on a buffered gas dry seal with an additional helium circuit. The admissible leak tightness has been defined for this concept (clean helium without any activation is leaking trough this seal)
- In tribology, from the results of all tests performed on tribometers at high temperature (1000°C), specific base materials and coatings have been selected. Friction and wear performances in Helium environment are quantified by these tests.
- And in Helium Purification system (HPS), the main recommendations of this work package related to Helium Purification System, are focused on impurity content of the helium for a NPP of 600 MWth.

REFERENCES

[1] E. BREUIL and D. BESSON (Framatome ANP). HTR-E project. High-Temperature Reactor Components and Systems. Last results from HTR-E project. Beijing, China, September 22-24, 2004.

[2] E. BREUIL (Framatome ANP), R. EXNER (Borsig Energy GmbH). HTR-E project. High-Temperature Reactor Components and Systems. HTR-TN 2002, Petten Netherlands, April 22-24, 2002.

[3] Current status and future development of modular high temperature gas cooled reactor technology. IAEATECDOC-1198 February 2001.

[4] E. BREUIL (Framatome ANP). First results from HTR-E project "high temperature reactor components and systems". ICAPP 2003, Córdoba Spain May 4-7, 2003.

ACRONYMS

HTR	High Temperature Reactor	WP	Work Package
GT-MHR	Gas Turbine Modular Helium Reactor	PBMR	Pebble Bed Modular Reactor
IHX	Intermediate Heat eXchanger	ISTC	International Science and Technology Center
EVO	Energieversorgung Oberhausen	HHV	High Temperature Helium Test Plant
EA	Empressarios Agrupados	VKI	Von Karman Institute
S2M	Société Mécanique Magnétique	NRG	Nuclear Research and consultancy Group
HP/LP	High Pressure/Low Pressure	MHI	Mitsubishi Heavy Industries
AMB	Active Magnetic Bearing	CB	Catcher Bearing
AGR	Advanced Gas cooled Reactor	FBR	Fast Breeder Reactor
PX/SPX	Phenix/Superphenix	FEM	Finite Element Method
FP	Framework Program	FZJ	Forschungszentrum Jülich
A&D	Aubert and Duval		