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FIRST RESULTS FROM HTR-E PROJECT. "HIGH-TEMPERATURE REACTOR COMPONENTS AND SYSTEMS"

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and contributions from each HTR-E partner
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Abstract – *The European R&D project, called HTR-E, is part of the 5th Framework Programme and concerns the technical developments needed for the innovative components of a modern HTR with a direct cycle. These components have been selected with reference to the present industrial projects (GT-MHR, PBMR). They are listed here after and shared into different Work Packages. The main tasks to be performed within the HTR-E Work Packages are also specified :*

- *the helium turbine (WP1), the recuperator heat exchanger (WP2), the electro-magnetic and catcher bearings of the turbo-machine (WP3) and the helium rotating seal : dry gas system, fluid film barrier, canned magnetic bearings (WP4). For these components the specifications for a modern HTR will be defined and design studies will be performed. Experimental tests are also foreseen to validate the recommended concepts for electro-magnetic bearings and recuperator heat exchanger.*
- *the tribology (WP5). Sliding innovative components in helium environment are particularly concerned (stator seals, control rod mechanisms,…). The experience feedback will be analysed and complementary tests will be carried out.*
- *the helium purification system (WP6). This work package aims to provide recommendations on impurities contents in helium atmosphere for a modern HTR in accordance with the materials proposed for the innovative components.*

The HTR-E R&D project is a four years project and started on January 1rst, 2002. The total allocated budget is 3.5 million Euros (50% funded by the EC) to be shared between 14 partners involved in this project. These partners are issued from industry and research centres taking part in HTR development : Framatome ANP, CEA, Zittau university, NRG, FZ Juelich, Empresarios Agrupados, NNC, Jeumont, S2M, Ansaldo, von Karman institute, Heatric, EV Oberhausen, Aubert et Duval.
The first main results from the HTR-E R&D project are presented in this paper. They concern the specifications and first design recommendations for the selected components and systems. They are essentially based :

- *on experience feedback from European past helium test loops and reactors,*
- *on specific design studies, thermal-hydraulic and structural analyses,*
- *and on experimental tests.*

I. INTRODUCTION

The HTR-E R&D project, see reference 1, started in January the 1rst, 2002. The present paper aims to summarise the main technical achievements reached during the first year of this project. The developments performed in 2002 for the six work packages of HTR-E are presented here after.

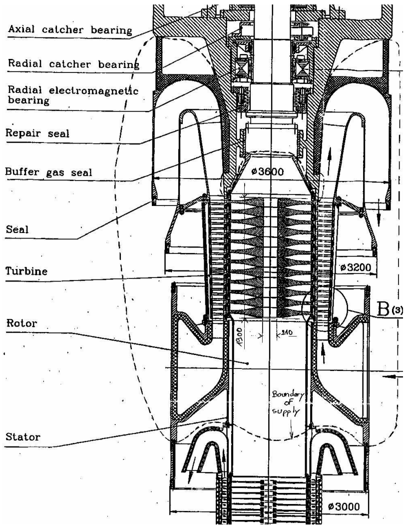
II. Scientific and Technical Progress

All documents and reports issued within HTR-E are available only to authorised persons involved in the HTR-E partnership. The data used for GT-MHR and PBMR are public, see reference 2 or data issued within ISTC funded projects. Due to the lack of open-literature documents, very few data can be provided for the PBMR components. Also since the design has evolved significantly over the last 12 months, those documents that have been published are already likely to be out of date.

II.A. WP1 Turbine

The requirements of the GT-MHR power turbine and PBMR high pressure turbo-compressor have been specified (using available public information for PBMR).

The GT-MHR turbine is composed of 12 stages, see hereafter an overall view of this component.



The turbine is not a safety classified component but, in order to confine materials fragments within the pressure vessel in case of deblading, a safety related function for the stator is recognised.

Note that for maintenance/repair operations the turbo-machine is removed and replaced by a spare unit in order to let the irradiated one in closed storage during 2 years before intervention.

The nominal operating conditions consider 850 °C at the inlet and an operating period of 60 000 hours without any intervention on this component. The nominal rotation 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 has to be 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. For the blades, materials are also proposed within the HTR-M/M1 project. It appears not necessary to cool the blades but a protective coating against corrosion is recommended. FANP studied the risk of a high Cobalt content for the turbine materials. The risk of erosion by graphite particles of the blades without coating (pessimistic estimate) has been analysed. The conclusion is that the additional activity generated in the primary circuit by Cobalt particles issued from the turbine by erosion and flowing to the core is not significant. Consequently, a Cobalt free material is not required for the turbine material of a GT-MHR type reactor.

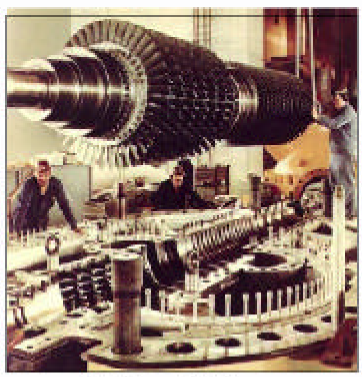
The requirements for the PBMR turbo compressor have been taken from available public information. This component is being totally redesigned and some kind of cooling is considered. This machine operates at 15 200 rpm that leads also to important stresses in the discs and blades even if the outer diameter is smaller than the GT-MHR one.

EVO provided to HTR-E partners many documents including :

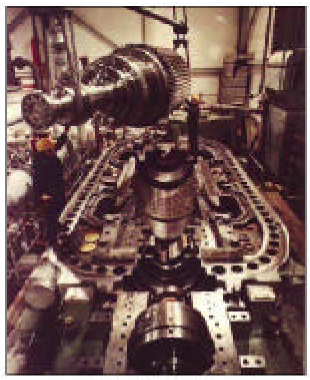
- Design, drawing, materials for components and helium turbine of EVO,
- Measured data corresponding to full load, start-up, emergency shut down as well as the troubles encountered,
- Experience feedback from EVO operation and recommendations for an optimised helium turbine design.

All these information will be scanned under an electronic form.

Note that the two helium turbines built in Germany (EVO and HHV) considered a cooling by cold helium of the blades roots at the periphery of the discs, see here after a view of these two helium turbines.



High Pressure Rotor from Oberhausen II Helium Gas Turbine

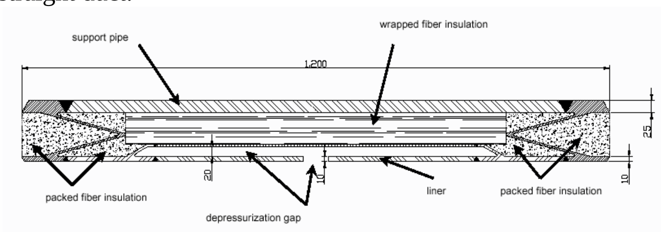


Rotor from HHV Test Facility

The next step of the work concerning the 'review of existing technologies', will focus on :

- Cooling system, materials, deblading analysis (CEA)
- Design and materials for helium turbine and thermal insulation (FZJ past experience on HHV and HHT project).

FANP issued also one report concerning the hot gas duct and thermal insulation based on HTR module experience. This concept is based on AL_2O_3 fibres, stuffed or wrapped behind a liner. Depressurisation gaps are provided through this liner in order to limit the overpressure within the insulation and the corresponding risk of damage in case of a sudden depressurisation of the duct. V thermo-sleeves are also provided to support the insulation and to adapt the thermal differential displacements. See hereafter a view of this concept for a straight duct.



The next step of the work about this topic will focus on the thermo-mechanical analysis of this concept by EA for the GT-MHR hot gas duct.

II.B. WP2 Recuperator

The requirements of the GT-MHR and PBMR recuperator heat exchanger have been 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 at the turbine outlet in order to heat the HP gas at the HP compressor outlet before the core inlet. 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. Here after the operating conditions for a GT-MHR type reactor.

Name of parameter	Value
♦ Thermal capacity	635 MWth
♦ Thermal effectiveness	0.95
Helium parameters on low pressure side	
• flow rate	316 kg/s
• inlet temperature	510 °C
• outlet temperature	125 °C
• inlet pressure	2.63 MPa
• pressure losses	not more than around 0.03 MPa

Name of parameter	Value
Helium parameters on high pressure side	
• flow rate	313 kg/s
• inlet temperature	105 °C
• outlet temperature	490 °C
• inlet pressure	7.07 MPa
• pressure losses	not more than around 0.07 MPa
♦ ΔP between the high and low pressure sides	4.5 MPa

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) :

- $\Delta T = 335$ °C for the LP recuperator inlet, in 5 seconds, from initial values : 508 °C
- (severe slope $\simeq 70$ °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 : 500
- lifetime 60 years

For the design accidental transients, the maximum temperature reaches 655 °C for the hot inlet early (in 1 second) at the beginning of the turbine deblading transient. Then the pressure difference ΔP between the low and high pressure sides is 0.7 MPa.

In term of in service inspection and repair requirements, note that a modular concept is specified in order to be able to locate and repair the leaky module by plugging.

The technological survey and consultation of manufacturers are in progress and will be finalised next year. It appears that the main concepts suitable for the recuperator application are mainly :

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

For the plate and plate fin concept note that a small hydraulic diameter (< 1mm) is required to optimise the design and the compactness of the component in terms of heat exchange and pressure losses performances. Here after some views of these concepts :

1- Printed Circuit concept based on plane sheets chemically etched and assembled by diffusion bonding.

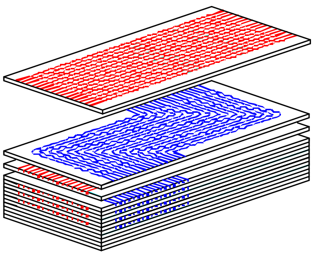
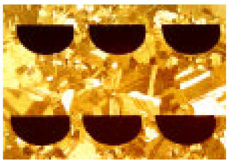
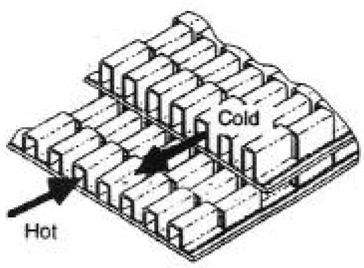


Plate stacking prior to diffusion bonding

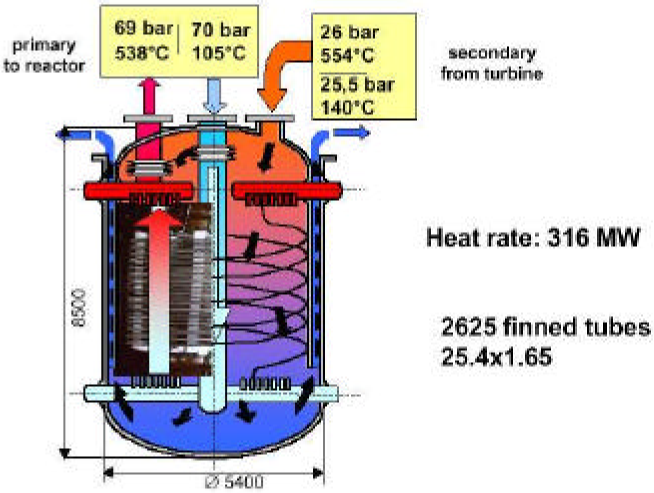


Section through diffusion bonded core

2- Plate fin concept. The fins are formed and assembled on plane sheets by brazing.



3- Tubular concept (e.g. helical tube fins proposed by Balcke-Duerr).



II.C. WP3 Magnetic Bearings

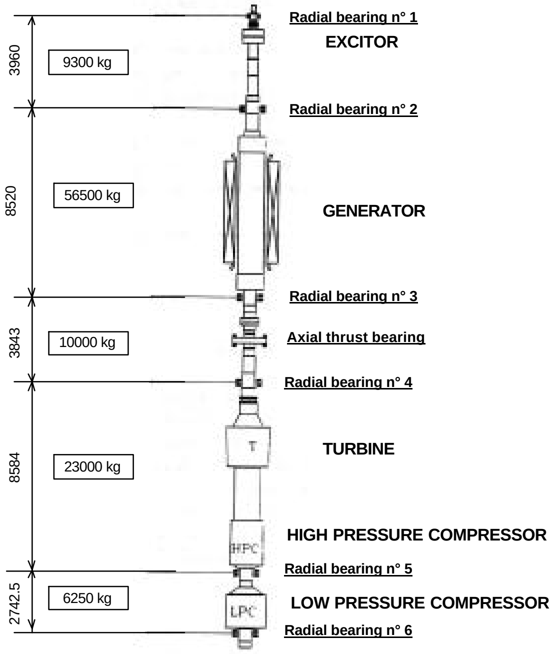
The functional requirements for the support system of two kinds of turbo-machines have been specified in one document issued by FANP.

These two machines are :

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

The functional requirements concern the axial and radial Active Magnetic Bearings (AMBs) and also the axial and radial Catcher Bearings (CBs).

Hereafter a sketch of the large and single rotor proposed for the GT-MHR with the location of the bearings. This rotor supports all the large rotating components of the direct cycle (turbine, compressors and electric generator).



The efforts to be withstood by the bearings for different operating modes were analysed. On the basis of these efforts, the required load capacity of the bearings has been defined by the HTR-E partners.

Bearing type	Required load capacity (x 10^4 N)						
	Radial bearings						Axial bearing
	1	2	3	4	5	6	
AMB	2	12	12	6	6	2	105
CB	2	20	20	10	10	2	450

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, the geometrical constraints and other requirements, S2M proposed a conceptual design for the AMBs support of such a machine. 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 proposed to support the GT-MHR rotor would be to consider two discs with two identical axial magnetic bearings (S2M proposal).

For the PBMR high pressure turbo compressor it appears that the requirements and loads are less demanding. The main features for normal operating conditions are estimated below :

- Environment : He
- Axial bearing load (104 N) : 0,7
- Normal rotational speed (rpm) : 15 200
- Medium pressure (MPa) : 7
- Medium temperature (°C) : max. 150 °C
- Life span (hr) : min. 53 000
- HPT shaft weight : approximately 700 kg
- The first bending critical frequency of the rotor is expected to be 15% higher than the first over-speed running order.

The HTR-E partners concluded that the support design by active magnetic bearings of such a turbo-machine should be achievable by standard bearings without R and D and it was proposed to focus the HTR-E work on the GT-MHR type reactor.

FZJ issued also one report concerning the requirements for helium circulators. For this kind of 'small' rotating machine, the support design by active magnetic bearings is also achievable by standard bearings without R and D.

The next step of the work will focus on the load analysis, the rotor dynamics, the feasibility of the catcher bearings and also the permanent magnetic bearings. The permanent magnetic bearings are a priori more suitable to support 'small' rotating machine like helium circulators.

II.D. WP4 Helium rotating seal

The functional specifications and state of the art of a dry gas rotating system has been specified by FANP for GT-MHR and PBMR type turbo-machine shafts.

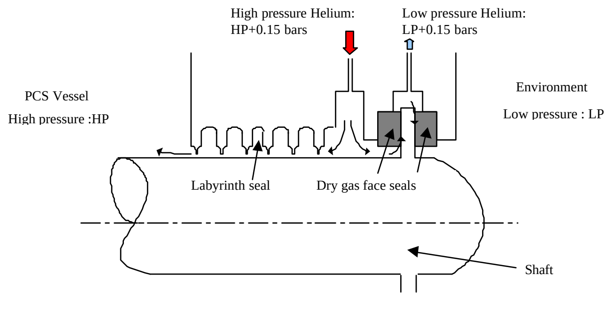
Such a system could be used for the shaft of the power turbine/electric generator in order to move this generator outside the pressure boundary. Then, the access for maintenance operations on the generator is facilitated and the support of the shaft could be ensured by conventional oil lubricated bearings. This kind of design seems to be proposed now for PBMR, seeing some recent publications.

Hereafter are summarised the main requirements for a GT-MHR type turbo-machine shaft.

Requirement	Design point
Operating Fluid	Dry helium
Operating pressure	26 bars
Operating Temperature (towards leakage rate)	110°C
Design Temperature (towards mechanical design)	150°C
Emergency mode Temperature (short time)	450 to 500°C
Operating speed	3000 rpm
Trip speed possibility	3600 rpm
Shaft diameter	450 mm at least
Axial gap	0.5 + about 10 mm =10.5 mm
Radial gap	0.4 mm
Seal life	60 years (with inspections and parts replacements)
Leakage rate (of the entire reactor vessel)	55 g/hr equivalent to 0.31 Nm3/hr

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). So the development of an innovative buffered dry gas face seal is recommended.

The principles of such a system are presented in the sketch below :



Buffered dry gas seal configuration

Note that with such a system using an auxiliary helium circuit with a light over pressure, the very small helium leakage to the outside consists of clean helium without activity. So there is no safety requirement about it but only economic requirement.

The next step of the work about this topic will focus on the design of such a concept by JT and NRG.

S2M provided also recommendations for the design of canned magnetic bearings. S2M recommended a non magnetic can 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 have been also specified.

II.E. WP5 Tribology

The objective of the work for the first year was to review the tribological problems from former HTRs and other gas cooled reactors and also to review and identify the typical tribology conditions for components for modern HTRs (GT-MHR and PBMR).

'Review of the tribological problems from HTRs'

One report issued by FANP makes the synthesis of the different contributions presented here after.

From Dragon experience, AGR, and FBR (PFR), see the report issued by D. Buckthorpe from NNC, the results lead to select future conditions of complementary experiments to be performed for further work within HTR-E such as :

- Use of coatings, resistant to wear
- Temperatures > 500° C
- Alternative movement (dwell sliding or fretting)
- It was noted :
- The low effect of impurities in helium environment
- No effect of helium pressure

CEA experience on FBR (PX and SPX) reactors, see the report issued by L. Cachon from CEA Cadarache. It deals with :

- Feed back experience from sodium (Na) and Argon + Na aerosols environment.
- Tests for several coatings. For thin coatings, aluminisation treatment was the best one. Structural materials (Fe and Ni based alloys) were used for bearings. The best alloys were tribaloy* 700 or Dgun Cermet (80 % Ceramic Cr_3C_2, 20 % metallic matrix type Ni Cr).

The study of ceramic materials is also recommended, with a potential candidate such as : $ZrO_2(Y_2O_3)$-NiCrAlY; NiCrAlY playing the role of interlayer adapting the dilatation coefficient difference between materials.

FANP first contribution, see the report issued by Edgar Ebert.

Main results obtained in the test loops in Germany were the following after 30 000 hours test :

- T up to 700° C $\rightarrow$ Cr_3C_2/NiCr-Cermets
- T up to 850° C $\rightarrow$ $Cr_{23}C_6$-$Cr_{23}C_6$/NiCr-Duplex
- T up to 950° C $\rightarrow$ $ZrO_2(Y_2O_3)$-NiCrAlY

These tests make appear that a long life time can be expected for these materials. The recommended coatings are similar to the CEA ones.

FANP second contribution, see the report issued by C. Falcand.

Feed back from Fort St Vrain (USA) :

- Most problems were due to moisture ingress, with an effect on control rods drop (780° C).

Feed back from HTTR (Japan) :

- Outlet T$\cong$ 950° C
- Coating of the hot gas duct with 3 µm TiN coating film on an Hastelloy surface.
- A study of impurities in helium (O_2, H_2, H_2O, CH_4 $\cong 10^{-3}$ ppm) was conducted on a test loop.
- Effect of H_2 and CH_4 contents was shown on Hastelloy (Ni base) friction coefficient variation
- The conditions which consider such compositions described by Japanese (HTTR) could be tested within the HTR-E WP5 program.

Feed back from HTR 10 (China) :

- Low information are available from HTR 10 which reached criticality in Dec. 2000.
- One experiment with a dry lubricant film of MoS_2 for the control rod system components was found.

Taking into account all this past experience, recommendations were provided for future complementary tests.

'Review of tribological conditions in GT-MHR and PBMR'

The contributions issued by HTR-E partners are summarised here after.

CEA focused his study on hot gas duct, stator seals and internals of the GT-MHR. The studied motion for hot gas duct is the motion due to thermal compensation unit against metallic tube and sealing strips.

FANP focused his study on control rods drive mechanism (CRDM) and tubes or structures subject to vibration of the GT-MHR.

It appeared from these information concerning GT-MHR components that, excepted the graphite internals working till 850° C, other components operate at lower temperature around 500° C.

NNC reviewed available published information on PBMR components. A recapitulative table of metallic components with type of motion and temperature was provided. Components working at T < 600° C are heat exchangers, low temperature part of recuperator, low temperature part of Control Rods Drive Mechanisms (CRDM), core conditioning system with essentially a sliding motion. The components operating at 700-900° C are the high temperature part of CRDM, of recuperator, power turbine and turbo-compressor units.

FANP made the synthesis of these different contributions and stated that these data are sufficient to identify the operating conditions to be considered for complementary tests within HTR-E.

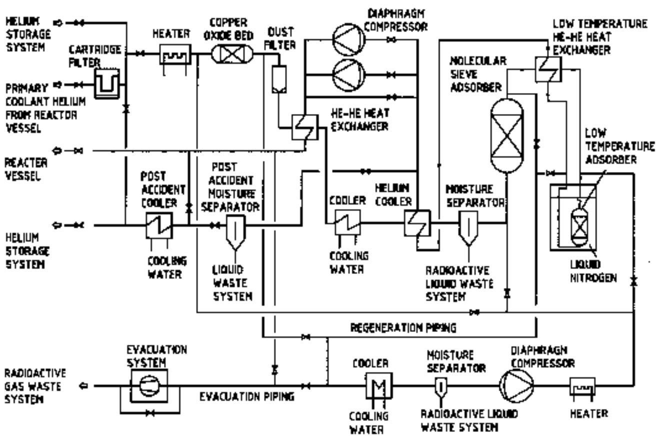
For the next step of the work from January to June 2003, FANP, NNC, FZJ are involved in one task aiming to «existing materials and coatings».

II.F. WP6 Helium Purification System

FZJ presented the synthesis of the state of the art information on the helium purification systems of different HTRs :

- in the UK, the Dragon project (one report issued by NNC),
- in Germany, AVR test reactor and THTR-300 (one report issued by FZJ),
- for HTR Module (one report issued by FANP),
- in Asia, HTTR and HTR-10 (one report issued by FANP).

The described systems are in principal similar. See hereafter the helium purification circuit of the HTR-10 Chinese reactor mainly based on German experience :



Two stages are applied :

- Removal of chemical impurities to limit the corrosion of the core,
- Removal and decay of radioactive gases.

In the first stage as a "by-product" tritium is removed. The second stage has become smaller during the history because of advantages in fuel elements. Differences in detail are mostly connected to changes of the techniques over the years (e.g. catalysts, compressors). Auxiliary duties of the gas purification system, which are connected to the fuel type and the fuel handling, result in design differences.

For the Dragon reactor the impurity content over several operation periods was specified by NNC. The dust experiments and measurements at the AVR were also specified by FZJ.

While the above mentioned reactors use the reactor heat indirect via heat exchangers or steam generators, the direct cycle is foreseen for HTR-E. It might be necessary, that because of this, the helium purification system gets as an additional task not only to fulfil the corrosion requirements of the core but also those of the gas turbine materials. Therefore one contribution to the report discussed the interaction of helium impurities with Ni-base alloys (report issued by FANP). Basically the best conditions are those that allow the formation of a stable oxide layer on the proposed alloys. The specifications of gas impurities contents (P_{CO}, P_{H2O}/P_{H2}, P_{CH4}/P_{H2O}) will depend on the chemical composition of these alloys and the level of temperature. A set of such alloys is proposed within HTR-M project.

The next step of the work will focus on the specifications on Helium impurities contents for a modern HTR with direct cycle.

III. CONCLUSIONS

Much important work has been carried out in 2002 for the first year of the HTR-E R&D project. This work was mainly devoted to the recovery of past experience from former HTRs and also to specifying the requirements for the innovative components of a modern HTR with direct cycle. Conceptual designs have been also proposed for some components (e.g. AMBs, helium rotating seal, canned magnetic bearings and thermal insulation for hot gas duct). Based on these first results, it was also possible to specify in more details the next tasks of HTR-E to be performed in 2003 including the analysis of the proposed concepts.

ACKNOWLEDGMENTS

With the acknowledgements to the HTR-E partners and to the European Commission (the HTR-E project is 50% funded by the EC).

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