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HTR-M Design use and specification for Turbine

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Summary

This document provides elements for design use and specifications of the material used for disks and blades of the first stages of the turbine of high temperature reactors. It contributes to the 5th PCRD HTR-M WP2.2 item. It refers to GT-MHR design.

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1. INTRODUCTION

This document provides preliminary elements for design use and specifications of the material used for disks and blades of the first stages of the turbine of high temperature reactors. It contributes to the 5th PCRD HTR-M WP2.2 item. It refers to GT-MHR design.

2. CASE OF A GT-MHR TYPE REACTOR

2.1 DESCRIPTION

2.1.1 Functions of the turbomachine

The turbine is one of the components of the turbomachine of the GT-MHR Design. The turbomachine is an equipment of the power conversion system (PCS) and is intended for :

- Conversion of thermal energy of the primary coolant (helium) to mechanical energy providing high effectiveness of gas-turbine cycle;
- Provision of helium circulation in the primary circuit during start-up, power unit shutdown and cooling down through PCS including fuel handling mode.

Besides, the turbomachine and its components must ensure the implementation of the following functions :

- Power unit start-up
- Operation in the mode of house load supply (7.5 MW)
- Power unit operation at steady-state power level within the automatic control range (from 30% to 100%) with supply of electricity to the external network
- Power unit variation to meet the requirements of the power system and due to internal reasons
- Scheduled shutdown of the power unit
- Power unit cooling down including refueling

2.1.2 Geometry

2.1.2.1 Power Conversion System

The system equipments of the PCS (turbomachine and heat exchange components) are arranged in a single vessel installed side-by-side the reactor vessel.

The heat exchange components are the following :

- the recuperator which is intended for provision of highly effective gas-turbine cycle by helium heating at core inlet due to helium heat at the turbine outlet

- the precooler and the intercooler which are intended for heat removal from the primary circuit upstream from the low pressure then from the high pressure compressor in all operating modes. They participate with the heat recuperation to the efficiency of the gas turbine cycle.

The turbomachine (fig 1) is a vertical assembly located in the central part of the PCS and consists of :

- Generator
- Turbine
- High pressure compressor
- Low pressure compressor
- Electromagnetic bearings and catcher bearings
- Seals for turbocompressor stator, repair and buffer seals

2.1.2.2 Turbine

The turbine blade system has been calculated basing on the requirements of maximum efficiency, minimum number of stages and provision of necessary axial unloading, compensating the load from the compressors and rotor weight.

Thereby, the average fraction of used pressure drop on working blades of turbine stage was approximately 0.45. To minimise the number of stages, heat drop of this turbine considerably exceed heat drops of gas and steam turbines of reactive type. The possibility to increase heat drops is connected with low values of Mach number in helium turbocompressors.

The turbine is composed of 12 stages with the following characteristics :

- Total Height of the stages : 1800 mm
- Blade height : 170 mm at the inlet and 225 mm at the outlet.
- Root diameter of the blading : 1400 mm
- Disk thickness : 150 mm at the centre and 40 mm at the periphery
- Disk bore ϕ (hub) : 210 mm

The turbine, low pressure compressor and high pressure compressor have common rotor. The stator has longitudinal joints along the rotor axis and form a single rigid cylindrical structure.

The attachment of working blades in turbine disks is made using "herring bone-type" lock. The blades are retained from movement along the grooves axis by plate type lock fastened in the recesses of the disk trapezoidal groove and bent over the blades roots.

The attachment between discs is performed by studs (fig 2).

Working blades and discs of the turbine are not cooled.

2.2 OPERATING CONDITIONS

2.2.1 Steady-state conditions

The required lifetime of disks and blades materials under operating conditions is 60 000 h.

The nominal steady-state characteristics are as follow :

Thermal power	600 MW
Nominal rotation speed	3000 rpm (50 Hz)
Circumferential rotation speed (last stage)	290 m/s
Flow rate	317 kg/s
Inlet temperature	848 °C
Inlet pressure	7.07 MPa
Outlet temperature	510 °C
Outlet pressure	2.62 Mpa
Adiabatic efficiency	not less than 93 %
Expansion degree	2.7
Pressure loss at the inlet	0.007 Mpa
Pressure loss at the outlet	0.02 Mpa

There are 3 shutdown states :

- Hot shutdown state : core average temperature is 470°C, helium inventory in the primary circuit is 7%, helium pressure of some bars (< 5 bar),
- Cold shutdown state : core average temperature is between ambient value and 100°C, helium pressure close to the atmospheric one,
- Shutdown for refuelling : this state is similar to previous one (cold state) but helium inventory is further reduced to achieve slightly sub-atmospheric pressure in the primary coolant system.

Two options of the turbogenerator synchronization with the grid are considered for the start-up : before the reactor start-up and when the reactor operates at minimum power.

A 4^{th} steady state is the house load after a plant load rejection (7.5 MW, turbomachine rotation speed : 3000 rpm). The plant is required to be able to hold the house load until the grid load is recovered, up to maximum of 30 hours.

2.2.2 Transients

In a preliminary way, the transients are separated into incidental and accidental categories. The classification of all operating conditions will be performed in a further stage of the project.

The table 1 provides functional specifications which can allow to define the most of thermal loadings for a GT-MHR type reactor turbine. The envelope representative values of the following parameters are indicated :

- helium temperature (level and range)
- helium thermal gradients dT/dt (t = time), mean and instantaneous maximum values
- helium pressure (level and range)
- helium pressure range dP/dt (t = time), maximum value
- possible over-temperature or rotation over-speed
- cumulated number of occurences for the operating lifetime of the component

The load-change transients (category 1), such as rapid load ramp within the control range, contribute to the determination of equipment useful life.

The limiting transients for the turbomachine are those during which the by-pass valves are fully open. These valves are used in a parallel way with the helium inventory control valves to reduce the gas flowrate both through the core and the turbine in order to avoid a great overspeed of the turbomachine in case of grid load loss, generator protection trip or during the reactor trip. Therefore, the envelope transients of category 2 and 3 have been selected as follow :

- Loss of offsite power with turbomachine trip. It subjects the turbomachine to maximum speed, rate of load change and fluid conditions change (strong pressure decrease at the turbine inlet and temperature rise at the turbine outlet).
- Emergency shutdown at 100% power. It induces a rapid decrease at the turbine inlet and strong pressure variations.
- Moderate primary coolant leak subjects the turbomachine to rapid depressurisation.
- Plant load rejection with hold of house load then load recovery. It subjects the turbomachine to very rapid load change rate and fluid conditions change with continued operation at minimum (house) load conditions.
- Accidental control rod or absorber elements withdrawal. It induces a temperature raise at the turbine inlet.

As regards category 4 or 5 transient, no data are available about the thermalhydaulic behaviour in natural convection of the Power Conversion System (therefore in the turbine) decay heat removal conditions after the loss of offsite power and the turbomachine trip.Temperature values in the turbine have been enveloped by the temperature maximum on the core barrel, which can be enveloped by the turbine inlet temperature at full power.

The overspeed of the turbomachine is indicated considering the protection system are effective to detect load loss. If for any reason the protection system fails to prevent the turbomachine speed from exceeding 110%, the protection system will sense this and induce the opening of an additional by-pass valve in order to prevent the turbomachine speed from exceeding 120 %.

Table 1 : functional specifications

Transient category	Envelope transients	He inlet Temperature range	He outlet Temperature range	He Average temperature variation dT/dt	Maximum He temperature variation dT/dt	Inlet He pressure range	Outlet He pressure range	Average inlet pressure variation	Maximum pressure variation	rotation speed	Occurrence number (for 6 years)
Normal operation	**Start-up, shutdown and load changes**	Ambient to 850 °C	Ambient to 510 °C	+/- 42.5 °C/h	+/- 240 °C/h	Ambient to 7.07 MPa	Ambient to 2.6 MPa	-0.11/ +0.7 MPa/h	+/- 0.7 MPa/h	100 %	1100
Incident	**Emergency shutdown at 100%**	850 °C to 710 °C	510 °C to 725 °C	3°C/s (outlet) -0.8°C (inlet)	60°C/s(outlet) -1.25°C/s(inlet)	7.07 to 3.8 MPa	2.6 to 3.7 MPa	-1.25 MPa/mn	-1 MPa instantaneous	101 %	50
Incident	**Spurious CD rod group withdrawal**	850°C to 866°C then 640°C	510°C to 720 °C	3.5°C/s (outlet) –0.4°C (inlet)	60°C/s(outlet) -1.2°C/s(inlet)	7.07 to 3.8 MPa	2.6 to 3.7 MPa	-1.25 MPa/mn	-1 MPa instantaneous	101 %	1
Incident	**Plant load rejection without turbomachine trip with hold of house load**	850°C to 820°C	510°C to 850°C	near constant after the initial variation	60°C/s (outlet)	7.07 to 8.25 then 3 to 3.6 MPa	2.6 to 3.6 MPa	-4.2 MPa/mn	1.25 to –5.25 MPa instantaneous	108 %	33
Incident	**Loss of offsite power with turbomachine trip**	850 °C	510°C to 800°C	60°C/s then constant	60°C/s (outlet)	7.07 to 8.25 then 3 to 3.6 MPa	2.6 to 3.6 MPa	-4.2 MPa/mn	1.25 to –5.25 MPa instantaneous	108 %	27
Accident	**Primary coolant leak (DN<250) (*)**	860°C to 840°C	510°C to 850°C then 710°C	2°C/s (outlet)	60°C/s(outlet) -7°C/s(inlet)	7.07 to 0.1 MPa	2.6 to 0.1 MPa	-5.25 MPa/mn	-5.25 MPa instantaneous	101 %	2
Accident	**Loss of offsite power with depressurised cooldown by RCCS**	850 °C	510 °C to 800 °C	60°C/s then constant	60°C/s (outlet)	7.2 to 0.4 MPa	2.6 to 0.4 MPa	-0.15 MPa /s	-1 MPa/s during 3 seconds	108 %	1

(*) Air ingress must taken into account in the primary circuit in addition to the thermal and pressure loadings

2.3 MECHANICAL LOADINGS

Calculations of centrifugal forces and gas-dynamic loading effect on turbine first stage blades and disk as well as calculations of external pressure and axial force effect on stator have been made.

Calculations have shown blades with a constant cross-section on height are not acceptable. To reduce the stresses the blades are made so that the area of the cross section is being decreased by height. Considering a linear law of changing the areas from the foundation (Fr) to the periphery (Fp), the coefficient of stresses decrease $\propto$ ($\propto = 1$ when Fr = Fp) from the centrifugal forces in the root section of the turbine blade can amount to $\propto = 0.6$.

On blades of the first stage : stressed state calculations have been performed at nominal rotation speed.

- Blade root section area : 827 mm^2
- Blade height : 170 mm
- Gas pressure on the blade : 0,177 MPa
- Max. stress : 266 MPa
- Centrifugal force created by the blade : 85400 N
- Radial tensile stresses : 92 MPa ($\propto = 0{,}6$) or 154 MPa ($\propto = 1$)
- Bend stresses : 68 MPa
- Total stresses : 160 MPa

On disk of the first stage : stressed state calculations have been performed at nominal rotation speed. Are considered the stresses by the centrifugal forces of the masses of the disk themselves, and masses of the blades fixed to them.

- Radial stresses : 116 MPa
- Annular stresses : 150 MPa

2.4 OTHER THERMAL LOADINGS

The respective thermal expansion between the blades and the stator of the turbine must be known to determine the values of the clearances between rotating and fixed parts. This differential expansion is not expected to be significant because stator and rotor are surrounded by the same gas at the same time. This point should have to be considered during transient conditions, if stator and rotor would have very different thermal inertia.

2.5 SEISMIC LOADING

The Power Conversion System requirements as concerns the seismic loading are both :

- to preserve operability after the design basis earthquake (magnitude 7 on the MSK-64 earthquake scale) after inspection and repair before restarting the reactor.

- to provide transfer to a safe state for the reactor module at the maximum design basis earthquake (magnitude 8 on the MSK-64 earthquake scale). In particular, a missile turbine must not lead to a failure of the primary containment.

2.6 HE FLUID VELOCITY

Under nominal conditions, the average helium velocity at the inlet of the first stage (resp. outlet of the last stage) is deduced from the flowrate (317 kg/s) and from the inlet (resp. outlet) parameters which are :

	Temperature	Pressure	Gas density	Internal ϕ	External ϕ	Azimuthal blade velocity	Sound speed	Average axial fluid velocity
Inlet	850 °C	7.02 MPa	3.01 kg/m^3	1400 mm	1740 mm	275 m/s	1970 m/s	125 m/s
Outlet	510 °C	2.62 MPa	1.61 kg/m^3	1400 mm	1850 mm	290 m/s	1650 m/s	171.5 m/s

The value of the Mach number at the turbine outlet is about 0.11. No precise data are available about the flow pattern and velocity into the turbine but the flow remains subsonic.

2.7 IRRADIATION LEVEL

Data about neutron fluence or irradiation level on the vessel of the power conversion system are not available at the present stage of the project.

2.8 FUNCTIONAL REQUIREMENTS

2.8.1 Corrosion

Corrosion damage of a material during the operation in helium coolant result from active corrosion impurities inevitability polluting helium during the operation of a plant. Corrosion activity of the gas flow in the turbomachine is mainly determined by the carbon-oxygen proportion :

C_{Zh}/O_{Zh}, where $C_{Zh}=P(CO) + P(CO_2) + P(CH_4)$ and $O_{Zh}=P(H_2O) + P(CO) + 2P(CO_2) + 2P(O_2)$

with P partial pressure of every impurity.

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If C_{Zh}/O_{Zh} >1, the processes of carburization predominate, if C_{Zh}/O_{Zh} <1, then oxidization and decarburization do. Theses processes influence steels and alloys operation under high temperatures.

Because nuclear reactors with helium coolant are obligatory provided with helium purification system and use graphite as a moderator and a resistant material, the process of carburization (C_{Zh}/O_{Zh} >1) should be considered during the choice of materials for the turbine.

2.8.2 Activation

As regards the maintenance aspects, the activation level of the component must be assessed. The main activation sources are both :

- The plate-out of metallic fission products coming from fuel elements which can deposit on the blades or the disks of the turbine (Cs, Ag, Te).

- Co which could be extracted by erosion from the blade or disk material itself then activated through the reactor core and deposited again on the turbine elements surface (and in the whole of the primary circuit).

The rate of metallic fission products in helium reaches an equilibrium state for steady state conditions (temperature and pressure). Strong variations of these parameters under incidental conditions can induce an additional release of metallic fission products coming from the core. The activation level due to the adsorption by the turbine material of such products is assumed to remain weak but must be defined more precisely.

In particular, at the present stage of the project, no data are available about the respective importance of activation due to this phenomenon and the activation due the deposit of Co. The knowledge of the characteristics of the Co particles population (number, size, mean free path) is required to quantify more precisely the activation then to provide decisional elements for the choice of the turbine material (with or without Co). In such an approach, the part of the helium purification services will have to be quantified.

2.8.3 Erosion

Erosion is linked with both previous processes :

- The presence of solid graphite particles in the coolant will induce the risk of surfaces damage and extraction of Co particles

- Metallic fission products can induce a possible embrittlement of the turbine material.

In a further stage of the project, the size and quantity of these graphite impurities will have to be known later to quantify the risk precisely.

2.8.4 Type of products expected

Materials for the fabrication of the turbine must be chosen on the basis of required physical-mechanical, life and cost characteristics, as well as on technological efficiency of fabrication and installation with account of their applicability in nuclear power.

The materials for blades and disk of the turbine should have a complex of high properties:

- high temperature strength, plasticity, fatigue and thermofatigue strength, resistance in helium medium (the turbine first stage will have to work at high circumferential velocities in 850 °C helium media without cooling, with a lifetime of 60 000 h). Possible wear- and temperature resistant coatings may be necessary.

- resistance to radiation, corrosion, and erosion both in purified working helium flow or with high impurities content in case of emergency situations. They must have low induced activity and will have to endure action of decontaminating acid solution.

But the material should also have the required level adaptability to manufacture in metallurgical and machine-building production.

As concerns the material of fastening articles, the main requirement is of high yield points and relaxation resistance at working temperatures. The material of fastening articles must exclude self-welding, seizure and assure the possibility for dissassembly after long term operation at high temperature.

A first selection of expected products could be as follow :

- Blades could be made by casting with directed monocristallic structure

- Disk could be made by powder metallurgy, with hot gas static pressing.

- Quality controls will be performed at all stages of fabrication (raw materials, process, finished product)

2.9 OTHER REQUIREMENTS

We have no available data about the allowable deformation of disk and blades.

2.10 IMPURITIES CONTENT

Gaseous species in purified helium during working conditions are within the range :

- $CO + CO_2 < 6$ ppm
- $H_2O < 2$ ppm
- $H_2 < 2$ ppm
- CH_4 , N_2 : low values < about 2 ppm

3. CONCLUSION

This document provides elements for design use and specifications of the material used for disks and blades of the first stages of the turbine of the GT-MHR design. Some data are not available at the present time (e. g. particles content in helium) and must be completed in a further stage of the project.

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Figure 1

Turbomachine

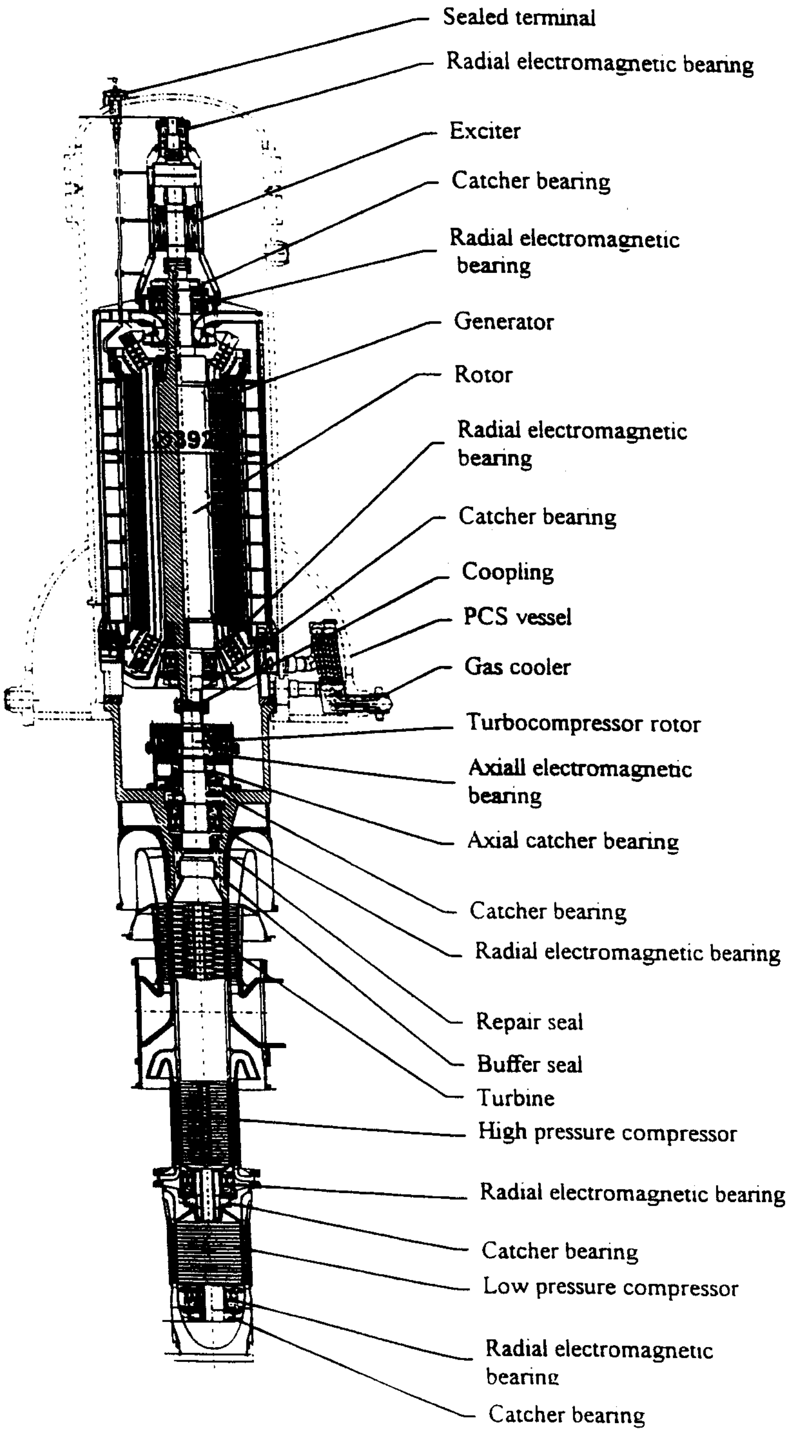

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Figure 2

Detail of the turbine