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Materials Selection for HTR Power Turbine

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1. OBJECTIVE AND SCOPE

The aim of this document is to analyse the High Temperature Reactor (HTR) Power Conversion Unit and Turbine in order to contribute to the elaboration of the Design Use and Specifications for the HTR Power Turbine.

The work is carried out within the European project for the "Development of HTR technology, Materials for HTR", and in particular within HTR-M Work Package 2.2.

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2. HTR POWER CONVERSION UNIT

The HTR here described will use coated uranium granules as a fuel in a high temperature helium cooled reactor coupled to a gas turbine (standard Brayton) generator cycle. The design features would be a thermal power between 250 and 600 MW and a net electric power in the range of 100 to 300 MWe.

The HTR will consist of a vertical steel Reactor Pressure Vessel and a Power Conversion Unit. The latter comprising the following main components and systems:

- High pressure (HP) turbo compressor
- Low pressure (LP) turbo compressor
- Power Turbine
- Generator
- Recuperator
- Pre and Inter Coolers
- Hot pipe and valve system

Helium coolant will enter the reactor vessel at a temperature about 500ºC and 7 MPa and will leave –after having extracted heat from fuel– at a temperature about 900ºC. The helium with then flow through the first two of three gas turbines, both driving compressors, entering about 700ºC and 4,5 MPa the third turbine, which drives the electrical generator. At the power turbine outlet, the temperature of coolant will be about 500ºC at 2,5 MPa. Helium will then pass through the pre-cooler and inter-cooler and the low and high pressure compressors before returning through the recuperator to the reactor vessel.

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3. HTR POWER TURBINE

3.1 DESCRIPTION

The Power Turbine converts the thermal energy of the coolant into mechanical energy with high efficiency. It also provides helium circulation in the coolant circuit during start-up, power unit shutdown and cooling down.

3.2 OPERATING CONDITIONS

3.2.1 Steady-state conditions

In order to obtain the desired power level, the pressure and the helium inventory at the manifold (corresponding to the HP turbo compressor outlet pressure) has to be adjusted by means of the by-pass valves. However, the generator cavity pressure must stay above 1 MPa. To ensure this constraint when reducing the power level, the shaft valve –supplying pressure from the manifold to the generator cavity– would open if necessary. Moreover, to ensure that the manifold pressure does not fall below 1.1 MPa while at the same time reducing the power delivered to the turbine, the two compressor by-pass valves would also open if required.

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For different steady-state power levels of HTR, first approximations of the corresponding manifold pressures and helium inventories are given in Table 1.

Power level (%)	Manifold pressure (MPa)	Helium inventory (Kg/s)
100	7.0	130-150
40	3.0	50-70
10	1.2	20-30

Table 1: Steady-state power levels

The steady-state conditions for the HTR Power Turbine would likely be of the order of the values given in Table 2 for different power levels.

Power level (%)	Inlet Pressure (MPa)	Inlet Temp (°C)	Outlet Pressure (MPa)	Outlet Temp (°C)
100	4.2 – 4.5	670 – 690	2.6 – 2.8	515 – 535
40	1.8 – 2.0	675 – 695	1.1 – 1.3	525 – 545
10	0.7 – 0.9	695 - 715	0.5 – 0.7	575 - 595

Table 2: Power Turbine steady-state operating conditions

3.2.2 Transient conditions

The following transients are considered important enveloping transients that would affect the design requirements of the HTR Power Turbine components:

- Main Circuit trip (reactor and power turbine trip) with full load rejection
- Ramping in the load range of 0% to 100% (and 100% to 0%) at a rate of 10% per minute
- ± 10% load step within 30 seconds
- Sustaining a full load rejection without requiring reactor or turbine trip
- Sustaining a partial load rejection
- Continued stable operation at low power levels
- Start up from lower bootstrap point to full load
- Safety related transients events

A load rejection occurs when there is a loss of electrical load and the system tries to remain connected to the grid and keep the Brayton cycle functioning at a very low load level. In the case of a main circuit trip, the generator and the power turbine will over-speed and no attempt is made to keep the Brayton cycle functioning. Transients with load rejection are considered the most exigent for the power turbine since they lead to a rapid decrease in fluidic power through the turbine and associated changes in pressure and temperature throughout the circuit. Therefore, the following three transients with full load rejection have to be analysed:

- Main Circuit trip, where the gas cycle by-pass valve is fully opened until the Brayton cycle stops functioning

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- Full load rejection without cooling, where the gas cycle by-pass valve is opened only for a short period after which the power generated is controlled by means of the HP and LP compressors by-pass valves

- Full load rejection with cooling; same as with cooling except that the HP coolant valve is used to maintain the recuperator hot side inlet temperature below 600°C

The most important features of these three transients for the Power Turbine are summarised in Table 3. Estimated values of helium pressure, temperature and mass flow are given for HTR turbine inlet. The effects of the load rejections on the parameters are instantaneous. However, the complete transient lasts for a total given time (Tt parameter in Table 3). The considered initial conditions in the turbine inlet are of 680 °C at 4.3 MPa and 140 Kg/s (within the ranges given in Table 2).

Transient	Tt (s)	Final conditions			Maximum range		
		T (°C)	P (MPa)	Mass flow (kg/s)	T (°C)	P (MPa)	Mass flow (kg/s)
Main circuit trip	30	820	5.0	10	130	0.7	130
Full load rejection (no cooling)	1000	800	2.2	35	120	3.2	100
Full load rejection (with cooling)	1000	650	2.2	40	150	3.0	100

Table 3: Power Turbine transient operating conditions

A list of possible transient events that can be expected during lifetime of the HTR plant is given in Table 4. The expected frequencies of those transients are also given and are estimated for a design life of 60 years [1].

Transient Event	Frequency
Pressure Test	2 to 6 times/life
Operation with new core (start up)	5 to 7 times/life
0% - 10% load step (start up)	3 times/year
Mayor operating load steps	730 times/year
10% - 0%	3 times/year
Main Circuit Trip	3 to 5 times/year
Load Rejection	2 to 4 times/year

Table 4: Fatigue and Cycling Data (TBC)

3.3 LOADINGS

3.3.1 Mechanical and thermal loadings

The Power Turbine components are subjected to:

- Nominal rotation velocity of 3000 rpm (50 Hz), that leads to centrifugal forces in disks and blades
- Aerodynamic forces
- Thermal gradients
- Contact forces between blades and their corresponding disk
- Axial retention of blades in their disk socket

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The aerodynamic forces and thermal gradients are more exigent for the Power Turbine first stage since pressure and temperature decreases as helium passes through the turbine.

There is not detailed information available for mechanical and thermal loads.

3.3.2 Seismic loading

In order to assess whether the HTR Power Turbine will comply with the seismic requirements, a seismic response analysis is to be carried out. The earthquake input should be based on the design basis earthquake, which is defined as having a peak ground acceleration of 0.4 g, corresponding this level of accelerations with the definition of the safe shutdown earthquake for standard plants.

A preliminary estimation of the response spectra for the Power Turbine support could be like the one shown in Figure 1. This response spectra correspons to the envelope of the responses for various sites analysed, each site having different dynamic properties of the supporting soil varying from hard rock to a soft soil. A value of 4% for damping in the global, translational directions seems reasonable. Therefore, the envelope of the seismic response spectra shown in Figure 1 could be representative of a wide rage of potential sites. This pessimistic rough estimate for HTR Power Turbine response spectra shows that largest accelerations would be for frequencies in the range of 1 to 11 Hz.

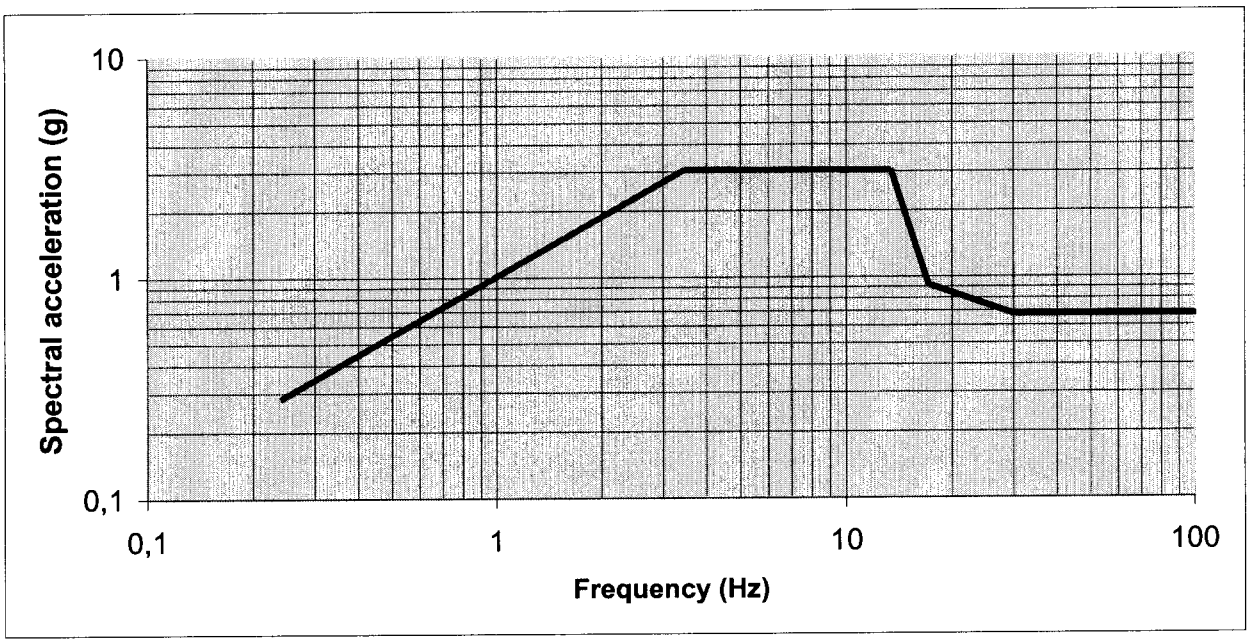


Figure 1: PBMR Power Turbine support preliminary estimated seismic response spectra

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However, the safety classification of the majority of the structures, systems and components specifies that they be designed for a level of earthquake lower than that specified for the safe shutdown earthquake. That is, it would be acceptable to use the operating basis earthquake having a peak ground acceleration of 0.2 g. Hence, the corresponding seismic response spectra would now be with half value of the spectral acceleration given in Figure 1 and the frequencies remaining the same.

The design of the Power Conversion Unit should ensure transfer to a safe state for the HTR Module for a design basis earthquake. The Power Turbine is designed for the operating basis earthquake, ensuring that no failure of the primary containment due to missile turbine will occur even for the design basis earthquake level.

4. MATERIAL REQUIREMENTS FOR HTR POWER TURBINE COMPONENTS

The materials selected for blades and disks of the turbine should meet a set of technical, performance and cost requirements, ensuring the reliability of the Power Turbine and the safety and feasibility of Modular Reactor Plant.

Moreover, materials should meet the strength requirements for high temperature reactor environment and design conditions. Therefore, high temperature tensile strength and tensile ductility, and resistance to damage mechanism such fatigue, creep and embrittlement are required.

The Power Turbine will work in a 99.9% high temperature helium environment. However, some active corrosion impurities will likely pollute helium during operation of the plant. Therefore, materials selected for turbine blades and disks should have good resistance against corrosion. On top of that, some solid particles will be present in the helium flow that could potentially cause erosion, damaging the turbine blades surface. This damage mechanism for selected materials should also either be prevented or developed in non-significant amount.

Finally, the direct cycle will deposit radioactive contamination on Power Turbine components exposed to the helium flow. Selected materials should have resistance to radiation and have low induced activity (even if remote maintenance is foressen). Values of activity on the order of 0.5 mili Sieverts per hour at the turbine inlet could be found during plant operation.

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5. CONCLUSIONS

The HTR power conversion unit and especially its Power Turbine have been analysed. Deeper analyses concerning materials mechanical behaviour in HTR environment, and geometry of the Power Turbine and its mechanical and thermal loads, should be carried out in order to assess candidate materials for HTR Power Turbine components. The level of impurities and solid particles present in the HTR coolant should also be investigated since it is essential to evaluate corrosion and erosion damages mechanisms for selected materials.

The information presented in this document may provide some elements for the design use and specifications and material selection for disks and blades of the European HTR Power Turbine. However, extrapolations to HTR design should be done cautiously and discussed and agreed within HTR-TN project.

Further information may be obtained throughout collaboration agreements between HTR-TN and other HTR projects being developed in other countries.

6. REFERENCES

1. A. Buenaventura et al, *Materials selection for HTR Reactor Pressure Vessel.* HTR-M 01/10 D.1.0.17, October 2001