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Design use, system review, integration and in-service inspection and repair

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Summary

The general objectives of WP1 of the HTR-E program are to determine the critical issues, to assess and demonstrate the potential of success for the design of the helium turbine, mainly based on two concepts: power turbine (GT-MHR type reactor), high pressure compressor turbine (PBMR type reactor).

This note is devoted to specify the functions and design requirements for the GT-MHR type reactor turbine system, including also system review, ISIR and safety classification. It corresponds to FRAMATOME-ANP contribution to the deliverable D2 in the frame of HTR-E contract n° FIKI-CT-2001-00177 :"High-Temperature Reactor Components and Systems", see ref. (2).

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(1) HTR-E 02/12 D1-1-1-1
HTR – Recommendations of cobalt content in helium turbine materials

(2) HTR-E 02/03-D-1-0-1 ; Deliverable n°1
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HTR-M – Design use and specifications for turbine

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1. GENERAL IDENTIFICATION

1.1 Concerned equipment

This document is devoted to specify the functions and design requirements for a **GT-MHR** type reactor **Helium turbine** system.

1.2 Situation and environment of the component, general functions

The turbine is located within the Primary Conversion System (PCS) vessel of a GT-MHR type reactor module, this vessel being connected to the reactor vessel through a hot duct.

It contributes to the direct closed gas-turbine conversion cycle for electric power generation with efficiency more than 47%. The helium-cooled modular reactor and helium turbomachine are integrated into a single system (principle of Brayton cycle). Thus primary Helium directly flows from core outlet to the turbine inlet through the hot duct.

Figure 1 presents a general view of a GT-MHR type reactor module main features.

1.3 Inclusion in a system or a sub-system

The turbine is one of the components of the turbomachine system.

This turbomachine system is a vertical aggregate consisting of a generator and a turbocompressor. Turbocompressor and generator are rigidly joined by a coupling to provide torque transfer between the rotors and also the rotors alignment at the connection point. The turbocompressor is a package consisting of the here-concerned turbine and of a high and a low pressure compressors, all these three elements mounted on the same shaft. The turbomachine is supported by electromagnetic bearings and catcher bearings.

The turbomachine system itself is an equipment of the Power Conversion System (PCS). PCS is intended for conversion of the thermal energy to electrical energy. Besides PCS and its components must ensure 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 power variation to meet the requirements of the power system and due to internal reasons,
- power unit cooling down including refuelling.

The PCS includes the turbomachine system and the cooling system both in the same PCS vessel. The cooling system is made of heat exchangers :

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- 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 the low pressure compressor then from the high pressure compressor in all operating modes. They participate with the heat recuperation (recuperator) to the efficiency of the gas turbine cycle.

The PCS arrangement, the turbomachine and turbocompressor layouts are respectively presented in figure 2, 3 and 4. The helium flow simplified scheme is given in figure 5.

1.4 Particular functions of the component in this system

The turbine main functions are :

- to drive the common shaft of the turbomachine (turbine, low and high pressure compressors) and consequently the generator through the rigid coupling,

- to ensure gas expansion between core and recuperator in all operating modes,

- to transfer helium from the core to the recuperator (see figure 5).

1.5 Safety classification

The turbomachine (so the turbine) belongs to the vessel system (reactor, hot duct and PCS vessel) and external primary circuit-related systems forming the high helium pressure boundary. Because it does not participate to any safety function (reactivity control, containment and decay heat removal), the turbine is not safety-classified. Systems devoted to decay heat removal are Shutdown reactor Cooling System (SCS) and Reactor Cavity Cooling System (RCCS). Only RCCS system is safety classified.

First assessments have also been performed on the deblading accident in words of consequences on reactor safety and on vessels system integrity :

- the turbine blades break is one of the most dangerous faults of the turbomachine because of the rapid character of the process and a potential avalanche-like deblading process in one of the turbine stages. One of the hazards of this event associates with increase in a pressure drop across the core. If this parameter exceeds its allowable value the damage of the core support structures and its deformation would become likely, thus preventing the control rods insertion into the core and heat removal from fuel.

  A first assessment of this deblading accident shows that the opportunity of the core and its components dimensional changes is eliminated. Preservation of the core and graphite columns geometry ensure the possibility of uninterrupted insertion of the absorber rods into the core and subsequent removal of residual heat from the shutdown reactor. Moreover as can be seen on fig. 1 a concrete wall is set between reactor system and PCS in order to avoid any impact of PCS fall or of turbo-generator centrifuged missiles.

- during such an accident, the PCS vessel loss-of-integrity event is not considered since the vessel is protected by the robust structure of the turbomachine stator. So a safety-related

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function for this stator is recognized (This has consequences on stator design, see the following paragraph 1.6.

1.6 Quality level or design and construction classes

Because turbine is a not safety-classified component, the design and construction code retained is the same as for conventional industry.

It is recommended to use the standard documents from American Petroleum Institute (API) and particularly API standard 616 (last edition august 1998) : "Gas turbines for the petroleum, chemical and gas industry services".

It is also recommended to refer to API recommended practice 683 ("Quality improvement manual for mechanical equipment in petroleum, chemical and gas industries", first edition, September 1993).

French standards use for PWR turbines the RRC-TA code. This code is divided under 5 parts (general rules, materials, control methods, welding and manufacturing) but some parts are confidential because of manufacturer know-how. It may be used as preliminary design and construction guidelines. French AFNOR rules also get many recommendations on conventional steam or gas turbines.

German standards could also be used on account of BWR turbines in which primary flow (steam) flows, that is similar to HTR gas turbine. German standards are gathered in KTA rules (Kerntechnischen Ausschuss Regeln = Nuclear technical committee rules) for nuclear reactors. At this stage a specific turbine standard has not been identified within these rules but a detailed examination of them should certainly bring interesting informations. As in France, German standards for conventional industries gas or steam turbines exist and are gathered in DIN standards as DIN 4312, 4341, 4342, 45536 and 45537 for instance.

American code ASME section III Division 1 sub-section NC ("Rules for construction of nuclear power plant components") and section VIII division 1 ("Rules for construction of pressure vessels") are recommended for the stator design. Equivalent French RCC-M code volume I tome C can be used.

Other references are possible but regulations and guidelines to be used in the design of the structures are to be internationally recognized.

It is recommended to establish standards accepted by the whole partners in the project these are the Customer (plant operator), the Main Contractor and the turbine supplier (Manufacturer), as has been made for French code RRC-TA.

1.7 Leak-tightness level

The turbine stator shall be fixed in PCS vessel through the internal PCS support system. The joining between stator and PCS support system shall be a system that can be dismantled and accessible for mounting and dismounting. So helium leaks to be considered are those flowing through these stator seals. Figure 6 provides the location of the stator seals for the whole turbocompressor, the concerned turbine seals being identified by numbers 1, 2, 3 and 11 on the figure.

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The helium leakage value not to be exceeded for the turbine only is specified to 0,2% of helium flowrate at nominal operating conditions. For information, this leakage value should be of approximately 0,7% of nominal flowrate for the whole turbocompressor.

1.8 Definition of terms

BWR	:	Boiling Water Reactor
CB	:	Catcher Bearing
Customer	:	Plant operator
EMB	:	Electro-Magnetic Bearing
GT-MHR	:	Gas-Turbine Modular Helium Reactor
HP-C	:	High Pressure Compressor
HTGR	:	High Temperature Graphite Reactor
HSS	:	Helium Service System
HTR	;	High Temperature Reactor
I&C	:	Instrumentation and Control
ISI&R	:	In service Inspection and Repair
LP-C	:	Low Pressure Compressor
Main Contractor	:	contracts with the Customer, and gets sub-contractors as turbine supplier
Nominal operating conditions	:	the conditions at which usual operation is expected and optimum efficiency is expected.
PCS	:	Power Conversion System
PWR	:	Pressure Water Reactor
Supplier	:	turbine manufacturer, supplies the turbine to the Main Contractor.
TC	:	Turbocompressor
TCS	:	Turbomachine Control System
TM	:	Turbomachine

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2. COMPONENT DESCRIPTION

2.1 Design description and justification

The turbine belongs to the turbocompressor system. The turbocompressor is a package consisting of the here-concerned turbine, the high (HP-C) and low (LP-C) compressors mounted on the same rotor. Turbine and compressor stators form a cylindrical load-bearing package protection for PCS and vessels components against turbocompressor accidents (blades break for instance).

The turbine is of axial type and is multi-stage. Figure 4 recalls the turbocompressor design and figures 7 and 8 provide the general shape and the main dimensions of the turbine.

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

- Total height of the stages : ≈ 1900 mm
- Blade height (cold conditions) : ≈ 170 mm at the inlet and ≈ 225 mm at the outlet
- Root diameter of blading : ≈ 1400 mm
- Disk thickness : ≈ 150 mm at the center and ≈ 40 mm at the periphery (minimum value). At disk tip there exists a rim for blade fastening. This part is ≈ 153 mm thick in axial direction and ≈ 62 mm in radial direction.
- Disk bore (hub) : ≈ 210 mm.

The shapes of the blades and disks must be studied in detail. Figures 7 and 8 are only overviews and can be used for a first design to be optimized. Three-dimensional optimization of the blades shape is to be performed : straight type, or twisted type or bowed-twisted type (see figure 9).

The turbine, LP-C and HP-C have a common rotor.

The attachment of working blades in turbine disks is made by 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 blade roots.

The attachment between disks is performed by studs (see figure 8).

To support turbine (and also the whole turbomachine) rotors the electromagnetic bearings (EMB) are used which provide active damping of the rotor in different operation modes. Bearings number and location ensure optimum frequency characteristics of the rotor. In case of EMBs failure the load during turbomachine coast-down is taken by catcher bearings (CB) which are integrated with the EMBs. There are one axial and three radial EMBs, one axial and three radial CBs for the whole turbocompressor, see figure 4.

Turbocompressor design provides end seals for the rotor and double-stage seals for the stator which limit by-pass leaks (see §1.7) of coolant. End seal is a labyrinth comb-type seal limiting seals along the rotor between turbocompressor cavities with different pressure. Each stator seal stage consists of two rings which are multi-segment devices encased in a holder. Stator seals

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limit helium bypass leaks in turbocompressor and other PCS components interfaces. At the same time stator seals give radial frictional supports to the turbocompressor.

New designs are also proposed for the GT-MHR type reactor. Two designs of disks are envisaged :

- an assembled rotor disk solution (see figure 10),
- a welded rotor disk solution (see figure 11).

A new blade design is also proposed, see figure 12. A difference exists with reference design described here-above, there is a rim at blade tip for leakage flow reduction at rotor/stator clearance.

Main dimensions of these new designs are precised on figures 10 to 12.

2.2 Functional dimensions and design rules

- Functional dimensions : see paragraph 2.1
- Design rules : see paragraph 1.6.

2.3 Definition of component boundaries

2.3.1 Helium flow boundaries

- Hot duct outlet at turbine inlet
- Recuperator inlet at turbine outlet

2.3.2 Interfaces with other systems/components

- Buffer gas seal :

  Buffer gas seal is disposed above the turbine preventing the ingress of primary circuit active coolant into generator plenum and assuring normal temperature conditions for radial-axial turbocompressor bearing.

- PCS internal structures for boundaries turbine stator extensions (outlet duct of HP-C, outlet plenum of HP-C, half-coupling and upper radial-axial bearings casing).
- Electro-magnetic bearings (EMBs) are out of the supply.
- Automated power unit process control system.

2.4 By-pass valves

For the PCS parameters regulation, the turbine can be by-passed via pipelines of the turbomachine control and protection system. On these pipelines located between HPC outlet and turbine outlet are set valves (see figure 5, "block of valves") automatically regulated by both the Turbomachine Control System (TCS) and PCS Instrumentation and Control (I&C) system.

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So these by-pass valves belong to the TCS regulating means and they are devoted to very fast transients as in case of rapid load rejection. The valves complete opening specified duration is therefore as short as possible (quasi-instantaneous), the objective is to limit this duration (including the automatisms sequences) to a maximum value of few seconds (about 2 or 3 s).

These by-pass valves are included in the supply. Their number remains to be defined. Minimum value is 2 because of necessary redundancy. It is likely that during reactor and PCS operation studies another by-pass valve allowing a precise flowrate regulation will be necessary and this should get to a total number of valves of 4 taking into account redundancy. This remains to be studied.

For information, the other system used to regulate the PCS is devoted to slower transients, and is ensured by the Helium Service System (HSS) providing primary circuit helium mass variation in case of electrical load slow decrease or fast increase to maintain high cycle efficiency.

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3. TECHNICAL REASONS OF THIS CHOICE

3.1 Justification of the reference design

The GT-MHR type reactor design is an advanced reactor project of High Temperature Graphite Reactor (HTGR). The HTR project credibility depends on economic and technical efforts to be achieved in order to get as far as possible an achievable product with a significant progress in electricity energy production at general cost lower than that specific for alternative power sources. In that sense the highly effective gas-turbine cycle is used. So the turbine reference design has been chosen with advanced technical choices which are based on the previous HTR experience feedback but also on turbines industries know-how. This last often remains confidential and partnerships with these industries will be necessary. At this stage of the project, technical issues remain but will be a challenge for the future design.

3.2 Main options choice

3.2.1 Direct cycle

First main option for the turbine is the choice of the primary flow within the turbine. This is imposed by the general choice of the direct cycle (Brayton cycle) in order to increase the overall efficiency, with a thermal efficiency objective of electricity energy generation of about 47,5%. The direct cycle also allows to exclude the entire steam turbine circuit which is notably expensive and unreliable in operation, thus simplifies the entire power unit design.

3.2.2 Blades and disks cooling

The optimized concept considers that disks and blades of the turbine are not cooled. This choice is made on the basis of cooling solution drawbacks :

- it is source of efficiency loose due to the supplementary presence of a necessary devoted auxiliary circuit (cooling fluid should be helium extracted form HP-C outlet and sent to disks and blades inner ducts),
- it is difficult to realize because of geometrical complexity,
- there exist a leakages risk,
- the problem of hot helium (about 850°C) with cold helium (about 110°C) mixing should arise,
- the generating pressure of helium for disks and blades cooling is rather low and could generate inadequate flowrate.

But considering the creep resistance of available materials (e.g. material Udimet 720 for disks), a cooling of the disks (first stages) is recommended, see HTR-M results.

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3.2.3 Turbine supports

Classical fluid supports are avoided in order to avoid any fluid ingress within the primary coolant. In particular some problems occur on turbine bearings leak-tightness of reactor Fort Saint-Vrain, where water was used : this induced a lot of unavailabilities of this reactor.

For GT-MHR type reactor, electro-magnetic bearings (EMB) are used to avoid such problem. The number of EMBs has been determined taking into account the whole turbo-generator.

3.2.4 Design

The turbine is of multi-stage axial type. This is the only way to get the required flowrate within limited radial dimensions in order to integrate within the Primary Conversion System (PCS) vessel.

Blade design is to be optimized and calls for turbomachine industry specialists know-how, see paragraph 2.1. Three-dimensional aero-thermodynamic and structural computations are necessary for shape optimization, by turbomachine industry and/or research centers specialists (Von Karman Institute for instance).

3.2.5 Main technical issues

The first main technical issue is the selection of the optimum materials for blades and discs of the turbine first stage working at high circumferential velocities in about 850°C helium media without cooling (if possible) to assure the design minimum life time of 60000 hours (≈ 7 years). See paragraph 3.3 for the materials choice. In paragraph 8 in-service inspection and repair considerations lead to a very likely change of some turbine parts (hot, rotating, …) every seven years. But total lifetime of the plant is 60 years and it is wished to get the possible longest lifetime within this 60 years period of these turbine highly stressed elements.

Turbine design is integrated within the TC and TM designs, and is directly concerned by the following items :

- creation of TC design operating under considerable pressure drops between separate components and under high temperature conditions requires the solution of the validation of the design and choice of rotor and stator seals materials to assure minimum possible bypass leakage,
- use of EMBs and catcher bearings taking high loads and availability of a spectrum of TM rotor critical frequencies in the whole operating range requires the solution of the following problems :
  - creation of reliable EMB control system assuring static and dynamic stability of the TM rotor,
  - creation of reliable design of catcher bearings operating in dry friction mode in helium,
  - selection of wear resistant materials for catcher bearings.

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3.3 Material

The choice of materials for turbine stator, rotor, disks, blades and seals is in progress within the HTR-M project. The problem of choice is hard for first stages stator, disks and blades.

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 disks of the turbine should have a complex of high properties :

- high temperature strength, plasticity, fatigue and thermal-fatigue strength, resistance in helium medium (the turbine first stage will have to work at high circumferential velocities in 850 °C helium media without cooling (if possible), with a lifetime of 60 000 h),
- 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 disassembly after long term operation at high temperature.

For disks and blades, cobalt presence in the alloy is suitable for such mechanically and thermally stressed pieces. But as here-above mentioned this is a concern for activation problems due to possible erosion by helium impurities and also and above all by reactor core graphite dust particles. See paragraph 5 for this item.

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

HTR-M group will produce recommendations about the alloys choice suitable for each turbine part. They look for :

- high technology materials (most recent technology),
- more conventional fabrication process (forging or casting) materials to be adapted to GT-MHR type reactor turbine,
- high temperature conventional materials possibly used for some elements of this turbine,
- cobalt free or cobalt content high temperature materials.

It is important to note that due to HTR-M project present studies blades coating is highly recommended due to erosion/corrosion effects. Coating is necessary for long life turbine blades and must be of the same type (chromium oxide former or aluminium oxide former) than the base alloy. A base material with adequate corrosion resistance is regarded as essential even in case of coating. It can be noted that these coatings often contain nickel and/or cobalt, also tantalum, so for blades it is not the cobalt/tantalum of the alloy which is important but those of the coating.

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It is also envisaged to set a second layer upon this first coating, a thermal barrier coating. This could have an implication on the selection of turbine blades materials because for the same gas temperature an alloy less resisting to high temperatures could be used. Studies are in progress within HTR-M project.

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4. FUNCTIONAL DEFINITION

These data have been provided in the HTR-M note ref. (3) and are recalled here-after :

4.1 Steady state

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. The refuelling mode represents transferring the shutdown reactor to the state needed for core fuel loading :
  - refuelling interval is 280 days, i.e. 6700 hours,
  - refuelling duration is 20,7 days, i.e. 500 hours.

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This mode is characterized by low temperature of the core and low pressure of helium (close to the atmospheric one) in the primary circuit. For information, a third part of fuel blocks is to be reloaded after a fuel cycle end. So presence of one given block is 3 x 280 days = 840 days at equivalent full operating conditions.

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 4th 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.

4.2 Transient operating conditions

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.

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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 over-speed 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 %.

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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 inlet 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 2.8 MPa	-3.6MPa/h +0.35 MPa/min	- 0.2 / +0,35 MPa/min	100 %	1100
Incident	**Emergency shutdown at 100%**	850 °C to 725 °C	510 °C to 725 °C	-1.1°C/s (inlet) +1.0°C/s(outlet)	-1.25°C/s (inlet) +60°C/s (outlet)	7.07 to 3.8 MPa	2.6 to 3.7 MPa	-1.0 MPa/min	-0.2 MPa/s	101 %	50
Incident	**Spurious control rod group withdrawal**	850°C to 866°C then 640°C	510°C to 720 °C	–0.6°C/s (inlet) +1.3°C/s(outlet)	-1.0°C/s (inlet) +60°C/s (outlet)	7.07 to 3.8 MPa	2.6 to 3.7 MPa	-1.0 MPa/min	-0.2 MPa/s	101 %	1
Incident	**Plant load rejection without turbomachine trip with hold of house load**	≈ 850°	510°C to 850°C	nearly constant (inlet) +60°C/s then nearly constant (outlet)	nearly constant (inlet) +60°C/s (outlet)	7.07 to 3.8 MPa	2.6 to 3.8 MPa	-3.0 MPa/min (first minute)	-1.0 MPa/s	108 %	33
Incident	**Loss of offsite power with turbomachine trip**	≈ 850 °C	510°C to 850°C	nearly constant (inlet) + 60°C/s then constant (outlet)	nearly constant (inlet) +60°C/s (outlet)	7.07 to 3.8 MPa	2.6 to 3.8 MPa	-3.0 MPa/min (first minute)	-1.0 MPa/s	108 %	27
Accident	**Primary coolant leak (DN<250) (*)**	860°C to 840°C	510°C to 840°C then 710°C	nearly constant (inlet) ≈ 2°C/s (outlet)	nearly constant (inlet) +60°C/s(outlet)	7.07 to 0.1 MPa	2.6 to 0.1 MPa	-5.25 MPa/min	-1.0 MPa/s	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 be taken into account in the primary circuit in addition to the thermal and pressure loadings

4.3 Definition of an envelope cycle

For structural and creep-fatigue computations an envelope cycle is needed. Due to the very fast pressure shocks (maximum value of -1 MPa/s) compared to turbine inlet variations, it is suggested in a first stage to separately consider the pressure and the temperature cycles. These cycles are based on maximum shocks occurring for incidental conditions. The number of cycles is retained at a conservative value of 1350 for the total turbine life of 60 years. But as some parts of the turbine should possibly be changed at maintenance periods (see paragraph 8) every 7 years, these computations are to be performed by steps of 60 000 hours (≈ 7 years), so approximately every 157 cycles.

These produced cycles are hypothetic cycles and do not correspond to reality. They are only defined for creating conservative situations in words of shocks in transient conditions and of temperature or pressure differences in steady states. They are presented in appendix 1.

4.3.1 Temperature envelope cycle

The envelope temperature cycle is provided in figure 1 and 2 of appendix 1. It only concerns turbine inlet operating conditions, so core outlet conditions, because computations are to be focused in a preliminary step on the turbine first stage which is the hottest and most stressed equipment.

It considers a start-up from cold shutdown (helium at ≈ 30°C) up to 850°C with the maximum slope of +240°C/h, see table 1 of §4.2. A 15 days nominal steady state period occurs before a cold shock event. The maximum slope is -1.25°C/s, see table 1 of §4.2. It is conservatively taken from 850°C down to 30°C. After this shock a one day period is supposed at cold shutdown before restarting a new cycle. The total duration of 16,22 days fits with the 1350 cycles of the 60 years plant whole lifetime.

It can be noted that a part (3%) of "cold" helium flowrate is extracted at high pressure compressor outlet for disks and blades foot cooling. In nominal operating conditions, this "cold" helium temperature is 110°C so temperature difference with turbine inlet one is 738°C. In case of incidental conditions, this difference can reach 813°C and the cold shock maximum slope is -23°C/s.

So on figure 2 of appendix 1 the temperature envelope cycle of cooling helium is also shown. It is detailed on figures 3 and 4 of appendix 1. At start-up, the maximum slope is taken into account, it is + 120°C/h. At nominal steady state mid-period, it is supposed to get a cooling helium cold shock of -80°C with the slope of -23°C/s. Turbine inlet temperature is not changed for conservatism reasons. One hour period is retained in final state in order to simulate the maximum thermal difference between hot and cold helium in steady conditions which nearly occurs in reality. To recover 110°C cold helium is supposed to be heated with the same slope as at start-up (120°C/h). At end of cycle, at turbine inlet cold shock event time, the same cold shock (-1.25°C/s) is considered.

Helium pressure and flowrate are kept constant at their nominal values 7.1 MPa ; 317 kg/s for hot helium and 7.1 MPa ; 9.5 kg/s for cold helium.

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4.3.2 Pressure envelope cycle

From table 1 of §4.2 it can be seen that the maximum pressure variation is -1 MPa/s in incidental and accidental conditions. Retaining a 0.35 MPa/min maximum slope for start-up and a one day period after the depressurization shock leads to the pressure envelope cycle shown on figure 5 of appendix 1. Helium temperature and flowrate are kept constant at their nominal values 848°C (turbine inlet) and 317 kg/s.

If cooling flowrate is considered in the model, its pressure variation is to be taken identical to the turbine inlet one. Helium temperature and flowrate are kept constant at their nominal values 110°C (turbine inlet) and 9.5 kg/s.

4.4 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 could be significant, in words of stresses consequences and of tip clearance. This point is to be considered within the design, in normal and in transient operating conditions.

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5. FLUID

5.1 Helium characteristics

5.1.1 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

Helium should carry dust due to core graphite. Concentration and size of the dust particles (graphite) flowing within the primary circuit of a GT-MHR type reactor is based on the experience gained in German experimental reactor AVR. Reference 1 provides some informations concerning these parameters. From this reference, it can be extracted :

- the average dust concentration is within the range [0.5 $\mu g/m^3$; 5 $\mu g/m^3$],
- the average dust particle diameter is about 0,6 μm. Most of the particles are within the range [0.2 μm ; 1 μm]

These data will be confirmed by HTR-E WP6 (Helium purification system).

5.1.2 Helium velocities

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

5.2 Activation

The main activation sources are both :

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- 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),

- cobalt 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.

5.3 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 cobalt particles,

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

The consequence of cobalt particles erosion is assessed in the following paragraph 5.4.

5.4 Recommendations for cobalt content for turbine disks and blades

Reference (1) is devoted to these recommendations. With the hypothesis of homogeneous alloys used for disks and blades, and with the results of dust concentration and size of the above paragraph 5.1.1, an estimated erosion rate prediction leads to the conclusion that the recommendation of a selection of cobalt free material as candidate material for a GT-MHR type reactor turbine is not required.

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6. MECHANICAL LOADINGS

Calculations of centrifugal forces and gas-dynamic loading effect on first stage blades and disk as well as calculations of external pressure and axial force effect on stator have been preliminary made on a GT-MHR type reactor turbine, see ref. (3).

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.

On blades of the first stage : stressed state calculations performed at nominal rotation speed lead to the following results :

- Maximal stress : about 270 MPa
- Total stresses : about 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 : about 120 MPa
- Annular stresses : about 150 MPa

These preliminary results are to be used as first informations because they strongly depend on the disks and blades shapes to be optimized by the turbine designer.

7. SEISMIC LOADING

The PCS requirements as regards seismic loadings 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).

It is to be noted that GT-MHR type reactor is of silo concept. This underground arrangement has a positive effect in words of horizontal accelerations because induced amplification is weaker than for a not underground reactor type. Consequences of plane fall and sabotage remain to be considered but are not included within this HTR-E program.

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8. CONTINUOUS AND PERIODIC IN-SERVICE INSPECTION AND REPAIR

In service inspection and repair (ISI&R) is an important concern for the design of the future reactor which requires demonstration that safety protection system and the structural integrity of components Important For Safety (IFS) are in good state and in compliance with the design specifications. Possibility for examination and repair must be included in the conceptual design at the earlier stage of the project to give the conditions for high load factor which is also a criteria for sound design and maintainability.

8.1 Continuous In-Service Inspection

As mentioned in paragraph 1.5, the whole turbomachine is not safety classified.

So continuous in-service inspection by classical monitoring (operational instrumentation) is only required to detect if the turbine becomes faulty. If this is the case, the TM can be extracted from PCS without major difficulty because its possible dismounting is a main option of the design.

8.2 Periodic inspection

It must be recalled that the whole turbine required lifetime is 60 000 hours (see paragraph 4.1) that is about 7 years. This operating time is lower than the time required for inspection program of other safety classified components (minimum of 10 years between successive inspections except the first inspection at 3 years). Therefore there is no need of specific periodic inspection for the turbine.

8.3 Maintenance - Repair

Because of its design lifetime, the turbomachine is maintained every 7 years for maintenance/repair/change. For this intervention the turbomachine is removed (needed time assessed to about 13 weeks) and replaced by a spare unit in order to let the irradiated one in closed storage during 2 years before intervention. So the equivalent dose rate is reduced by a factor 6 corresponding to the Ag110m which is the "most" hard" source of gamma radiation (half-decay period is 250 days). After this decay time a complete investigation of the turbine can be made in order to assess the possibility of its re-use for a future period, dynamic pieces (rotor, disks, blades, rotor seals, EMBs) should probably be changed.

After accidents, if required not-planned inspections and examination of the turbine must be performed. But it is likely that the whole turbomachine should be removed in order to facilitate these inspections and necessary repairs. Contamination aspects should induce difficulties and a spare unit during a sufficient decontamination time should likely be used.

For such an integrated and underground design, ISI&R operations to be performed on a GT-MHR type reactor PCS should be difficult and costly with a prior dismantling of some components to access to the others.

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Figure 1
GT-MHR type module arrangement in the reactor building

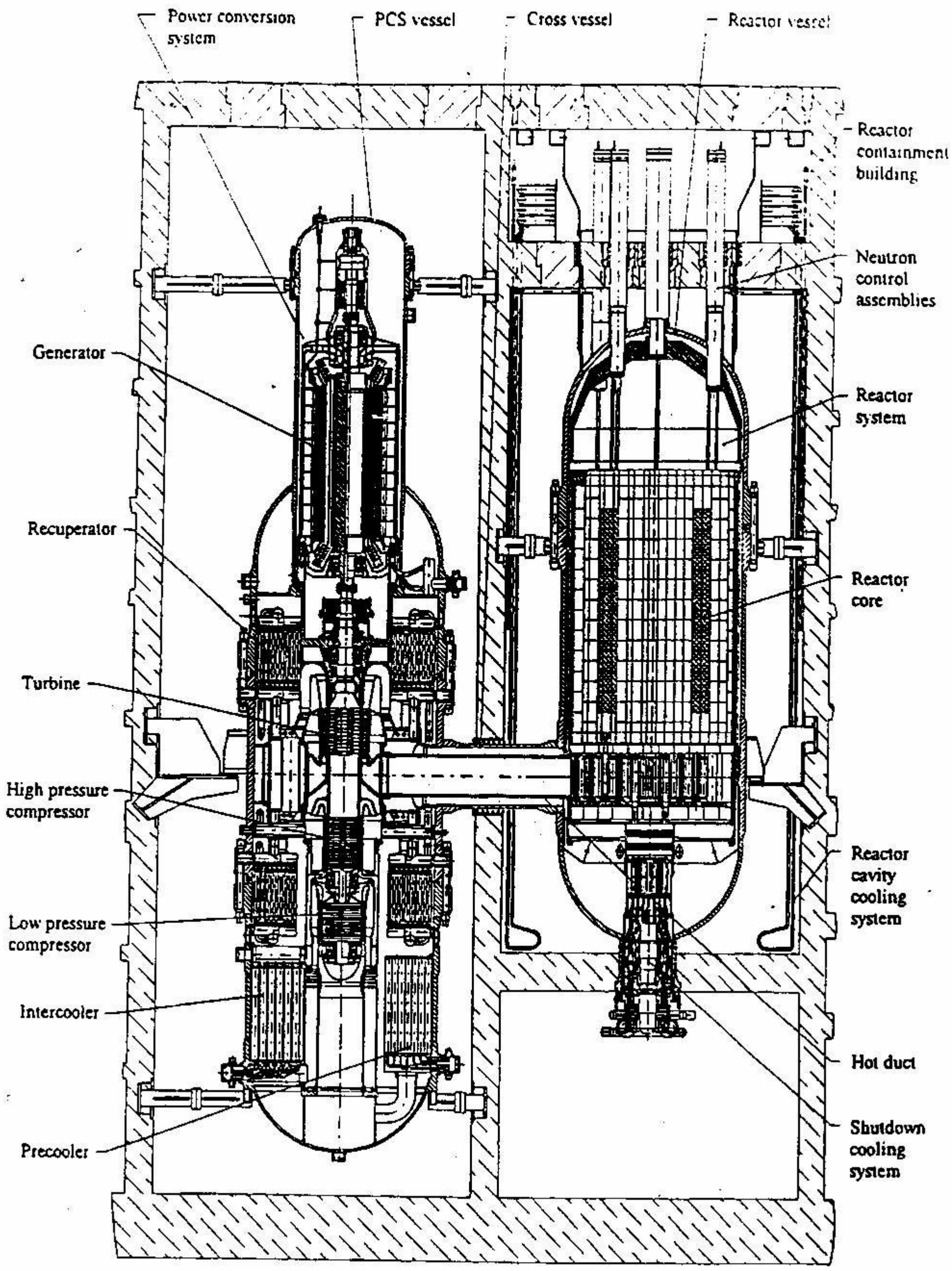

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Figure 2
GT-MHR type reactor - PCS arrangement

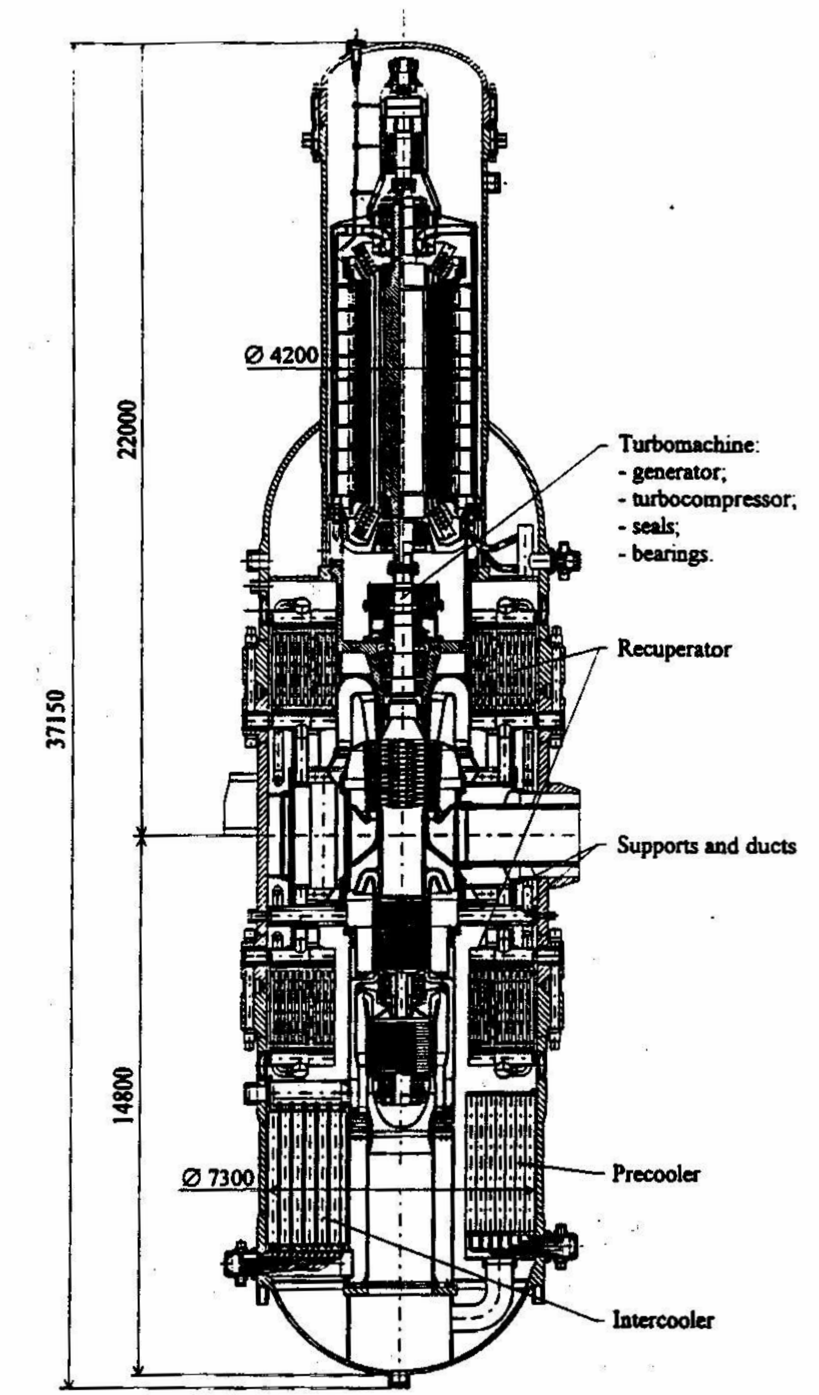

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Figure 3
GT-MHR type reactor - Turbomachine arrangement

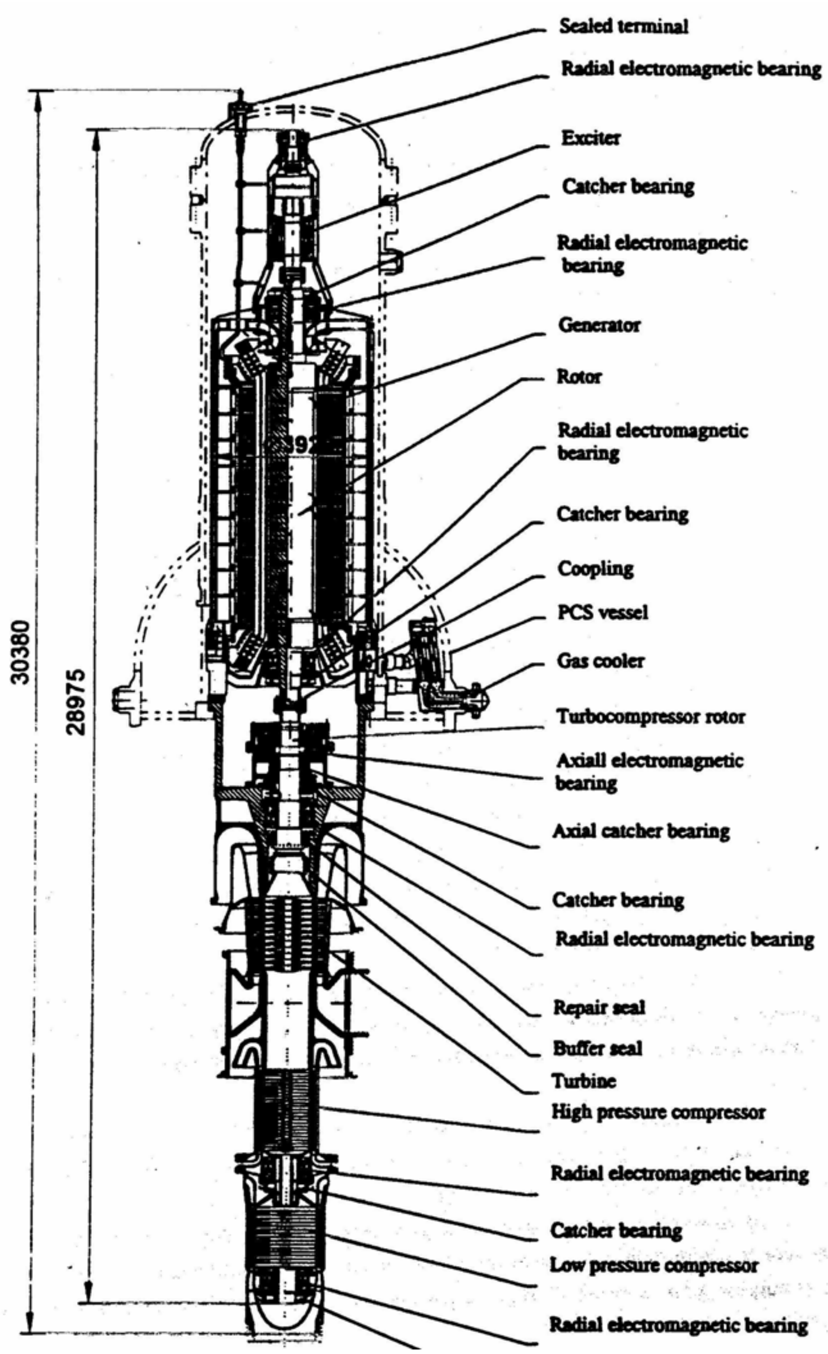

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Figure 4
GT-MHR type reactor - Turbocompressor arrangement

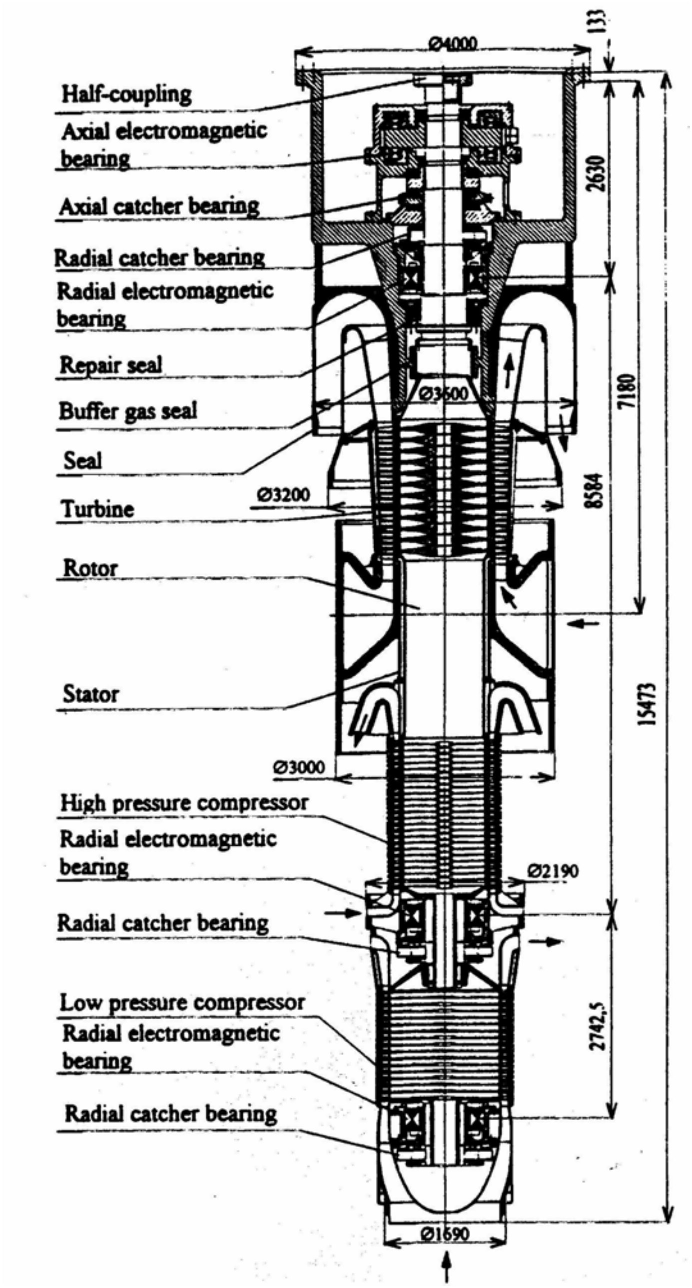

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Figure 5
GT-MHR type reactor - Simplified flow diagram

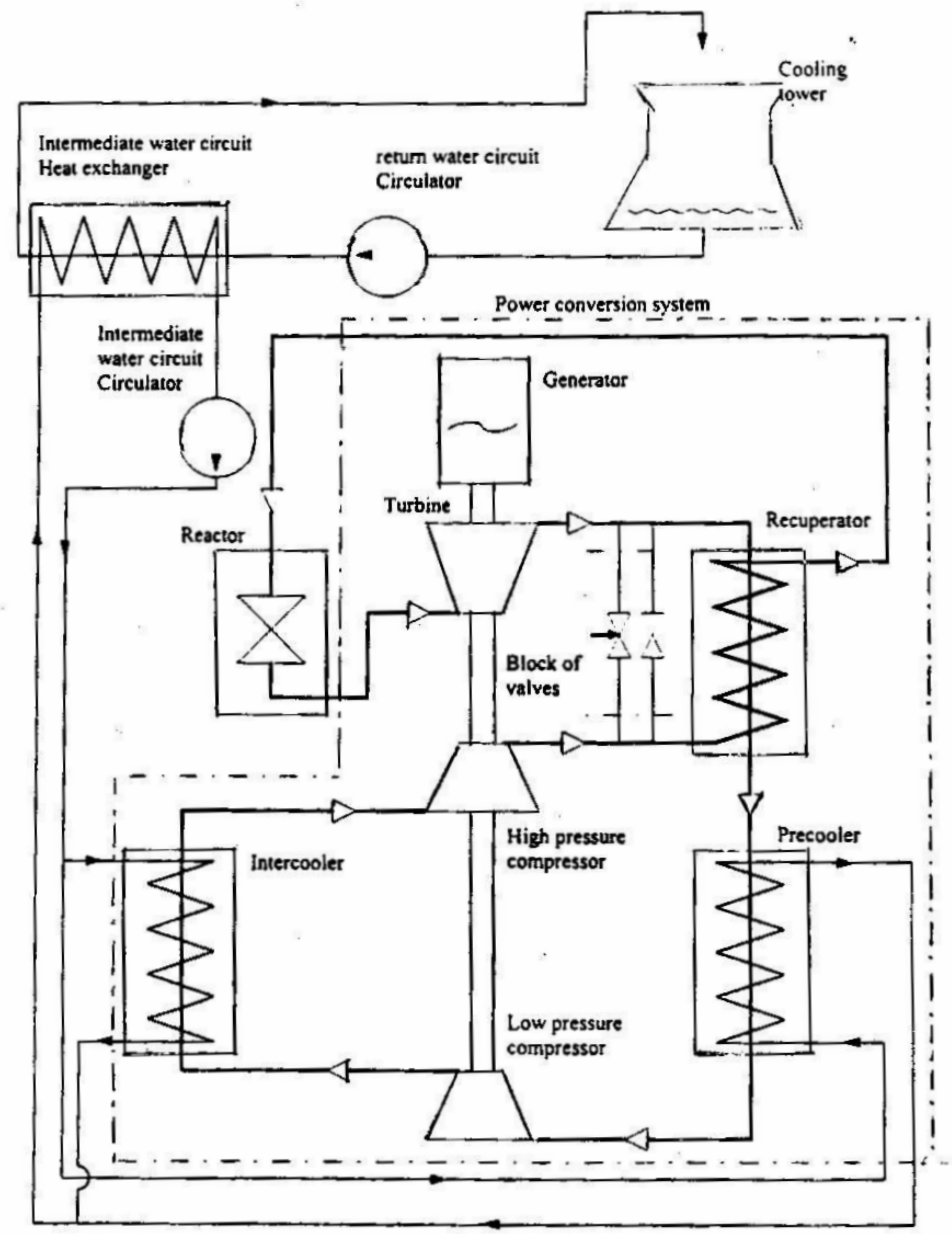

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Figure 6
Turbocompressor stator seals arrangement

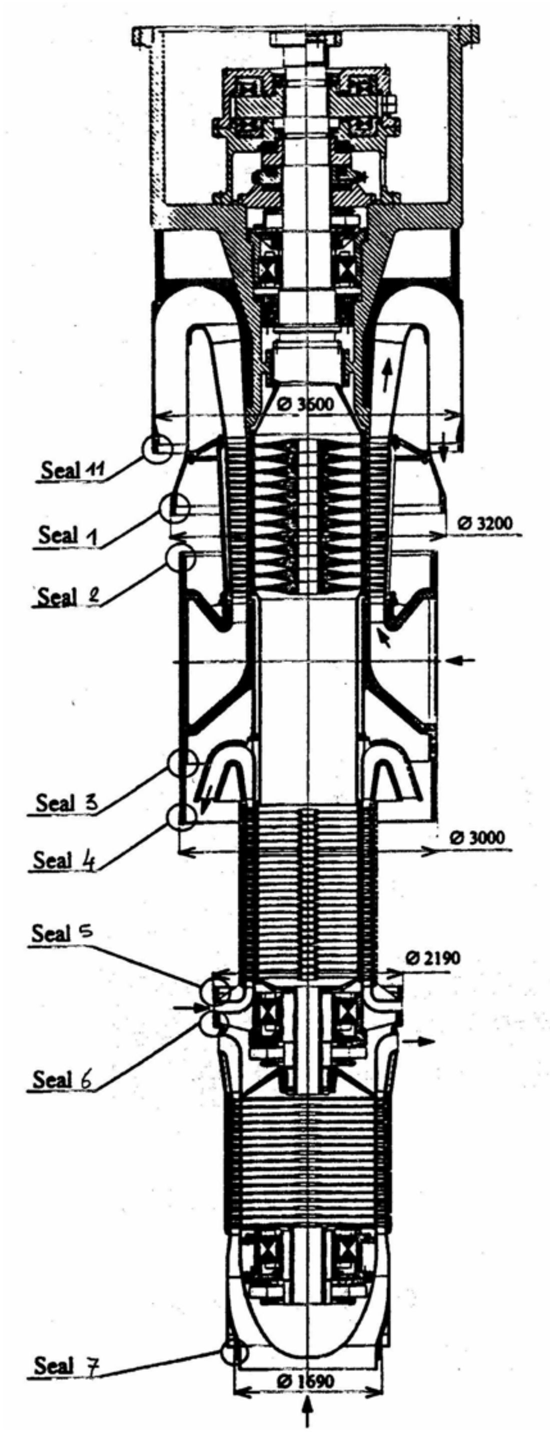

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Figure 7
Turbine overall arrangement

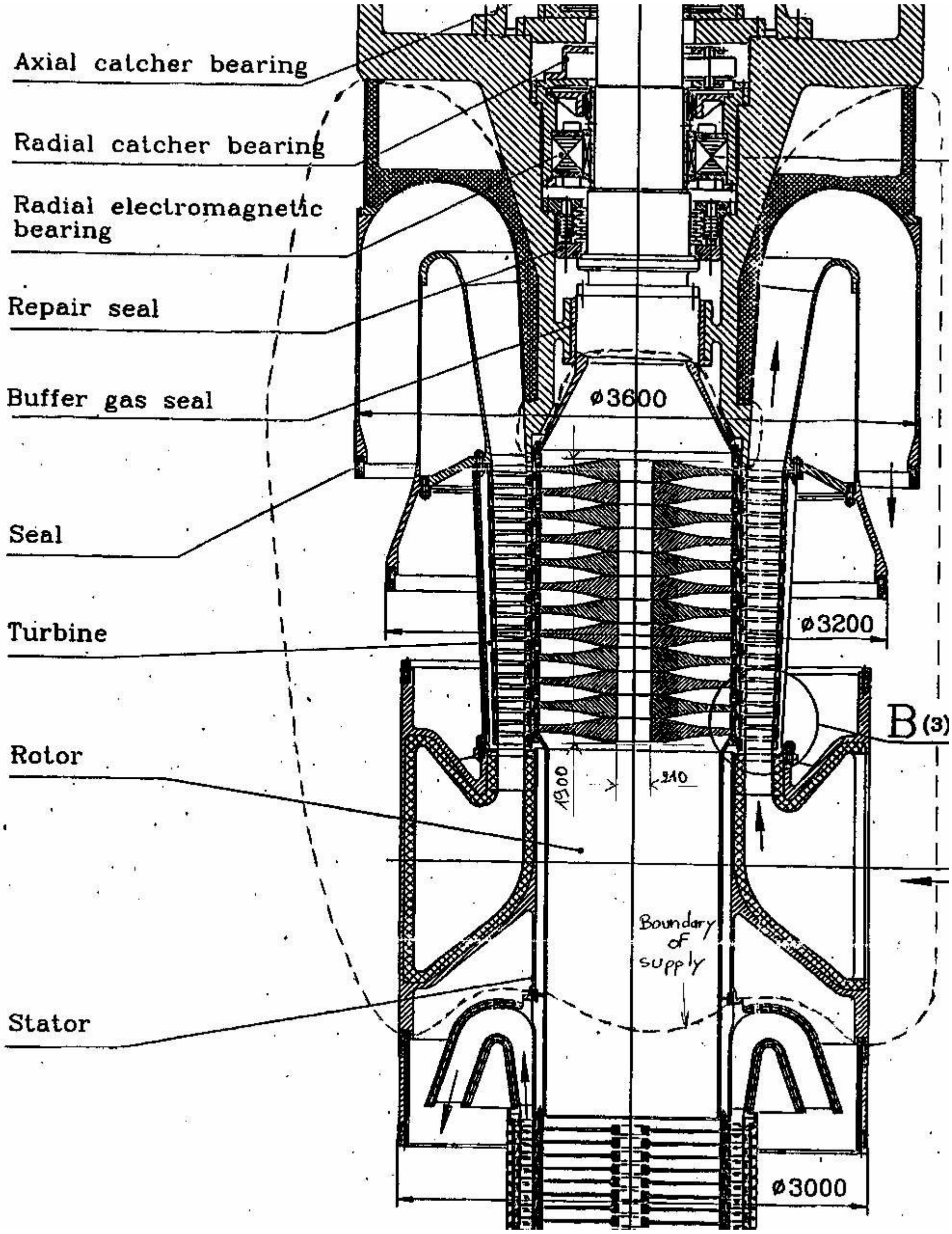

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Figure 8
Turbine disks and blades main dimensions

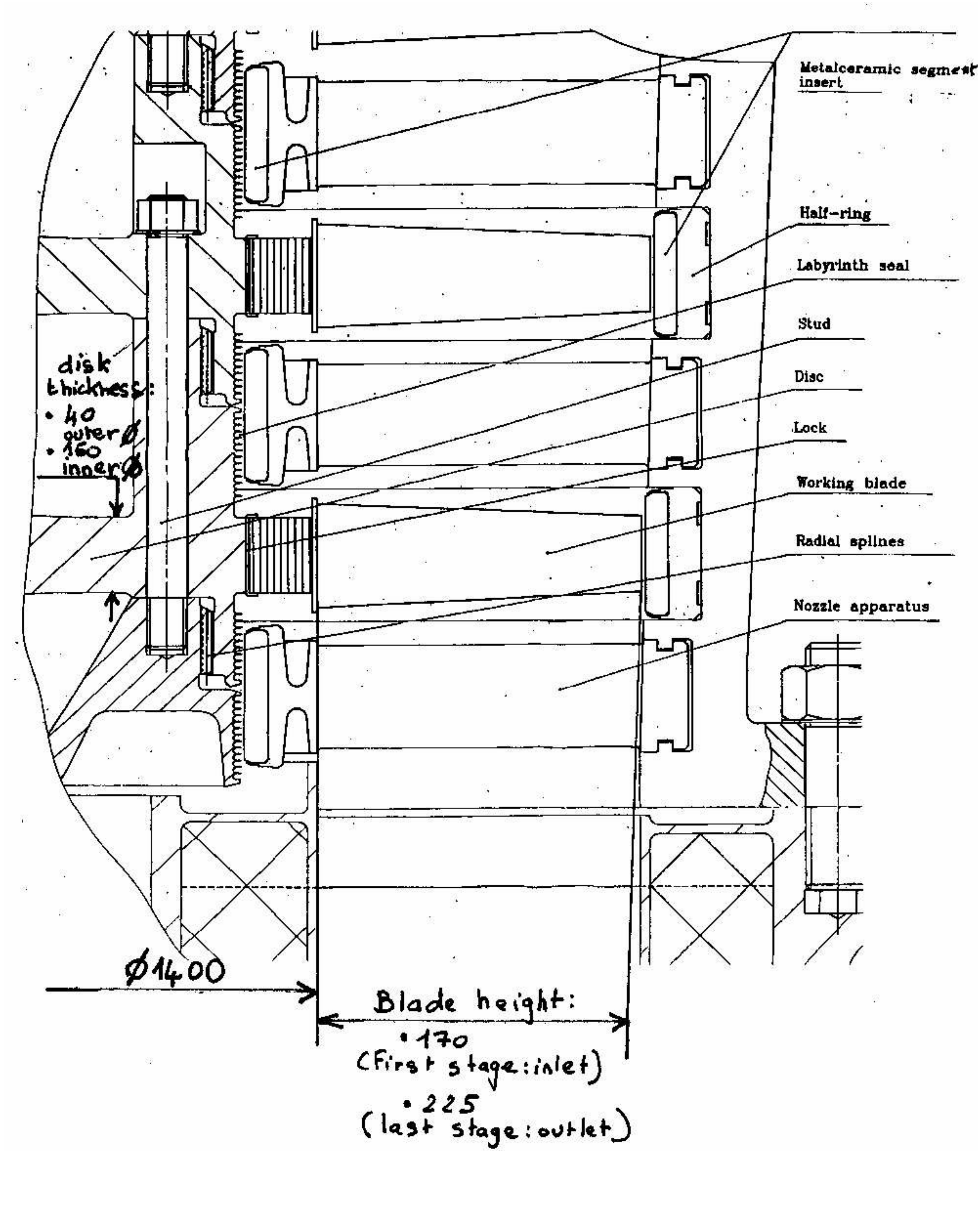

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Figure 9
Turbine blades potential designs

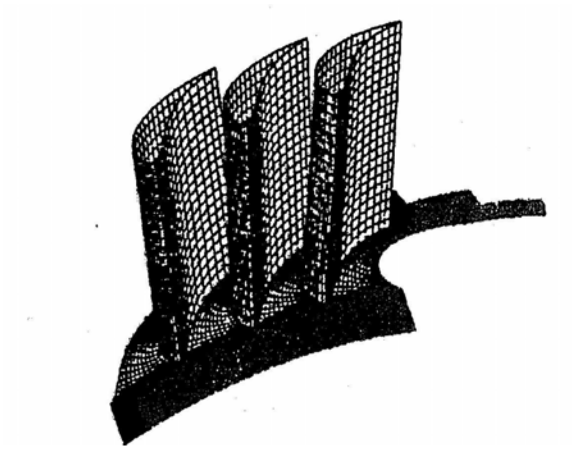

Figure 9a : Straight blade design

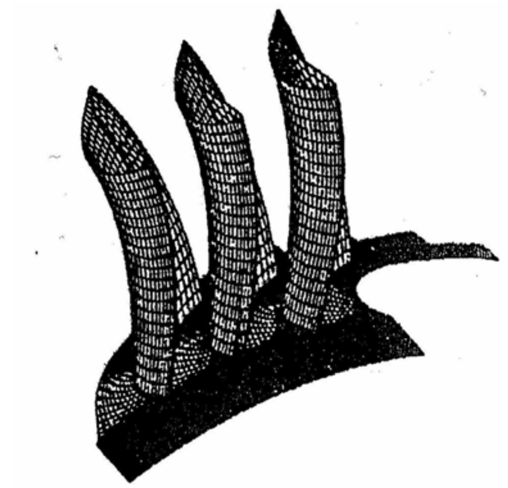

Figure 9b : Twisted blade design

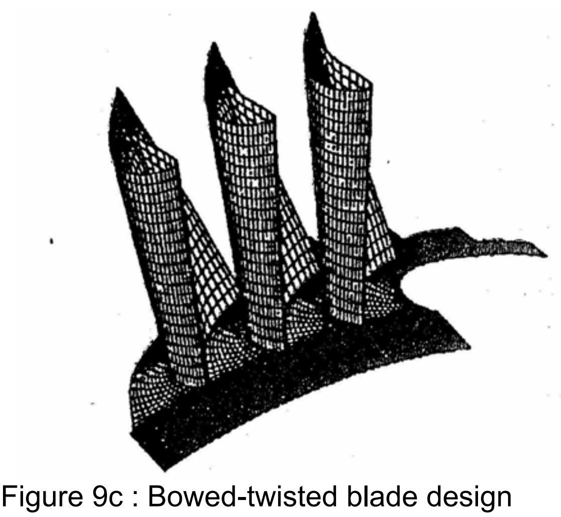

Figure 9c : Bowed-twisted blade design

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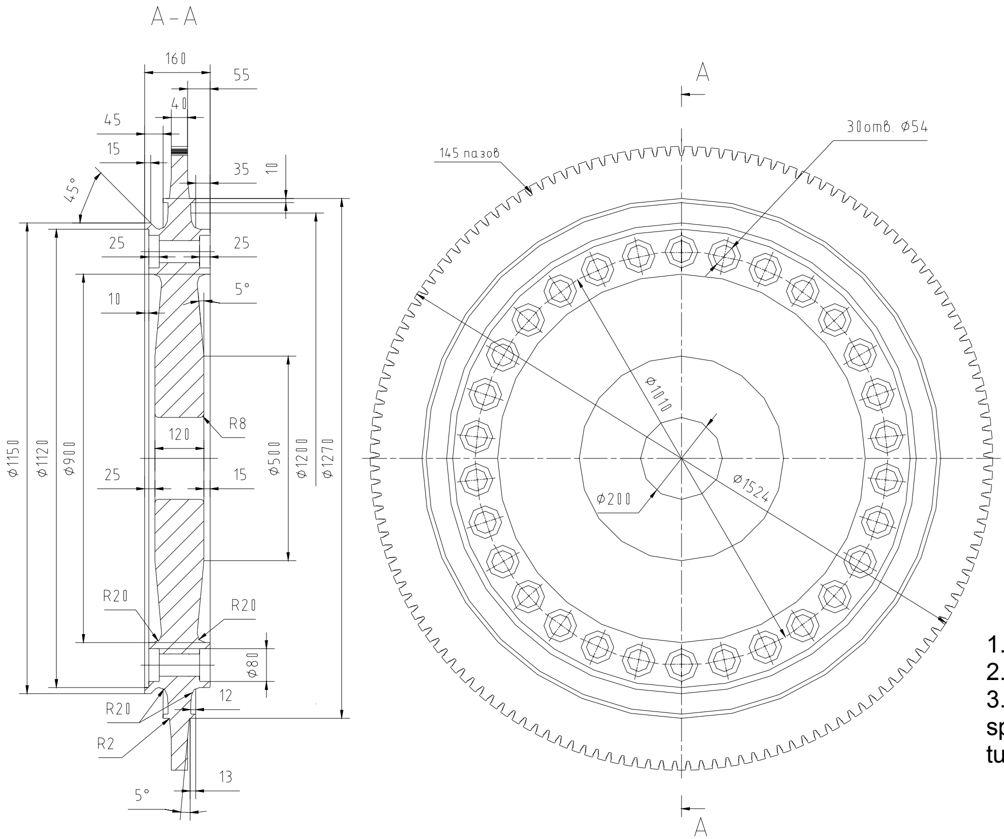
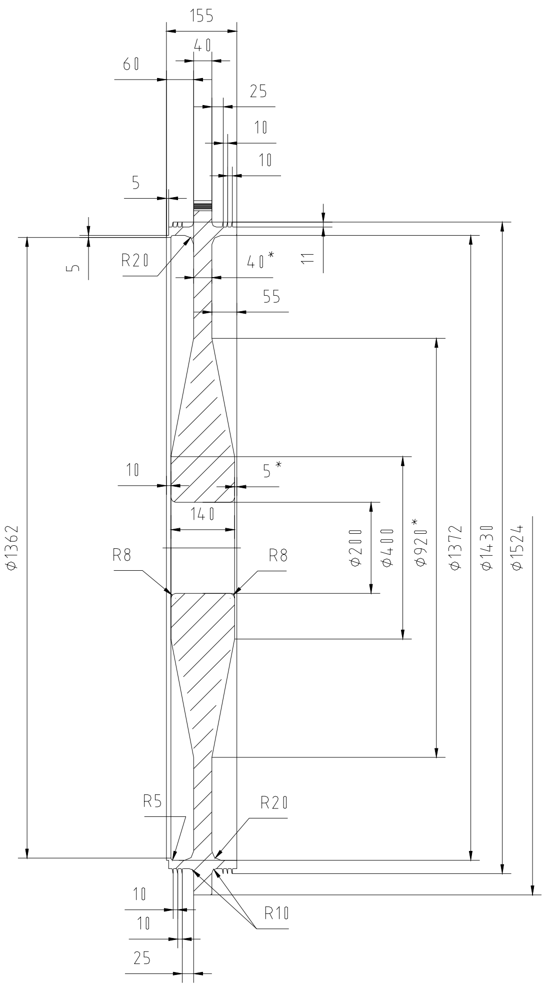
Figure 10
GT-MHR reactor type turbine new designs : sketch of assembled turbine rotor disk



1. This disk is intended for turbine rotor assembly.
2. Material density is taken as 8.32 g/cm^3.
3. Requirements for mechanical properties of the material are specified in technical requirements for materials for main turbocompressor elements.

Figure 11
GT-MHR reactor type turbine new designs : sketch of welded turbine rotor disk



1. This disk is intended for welded turbine rotor.
2. Material density is taken as 8.32 g/cm^3.
3. Reference dimensions.
4. Requirements for mechanical properties of the material are specified in technical requirements for materials for main turbocompressor elements.

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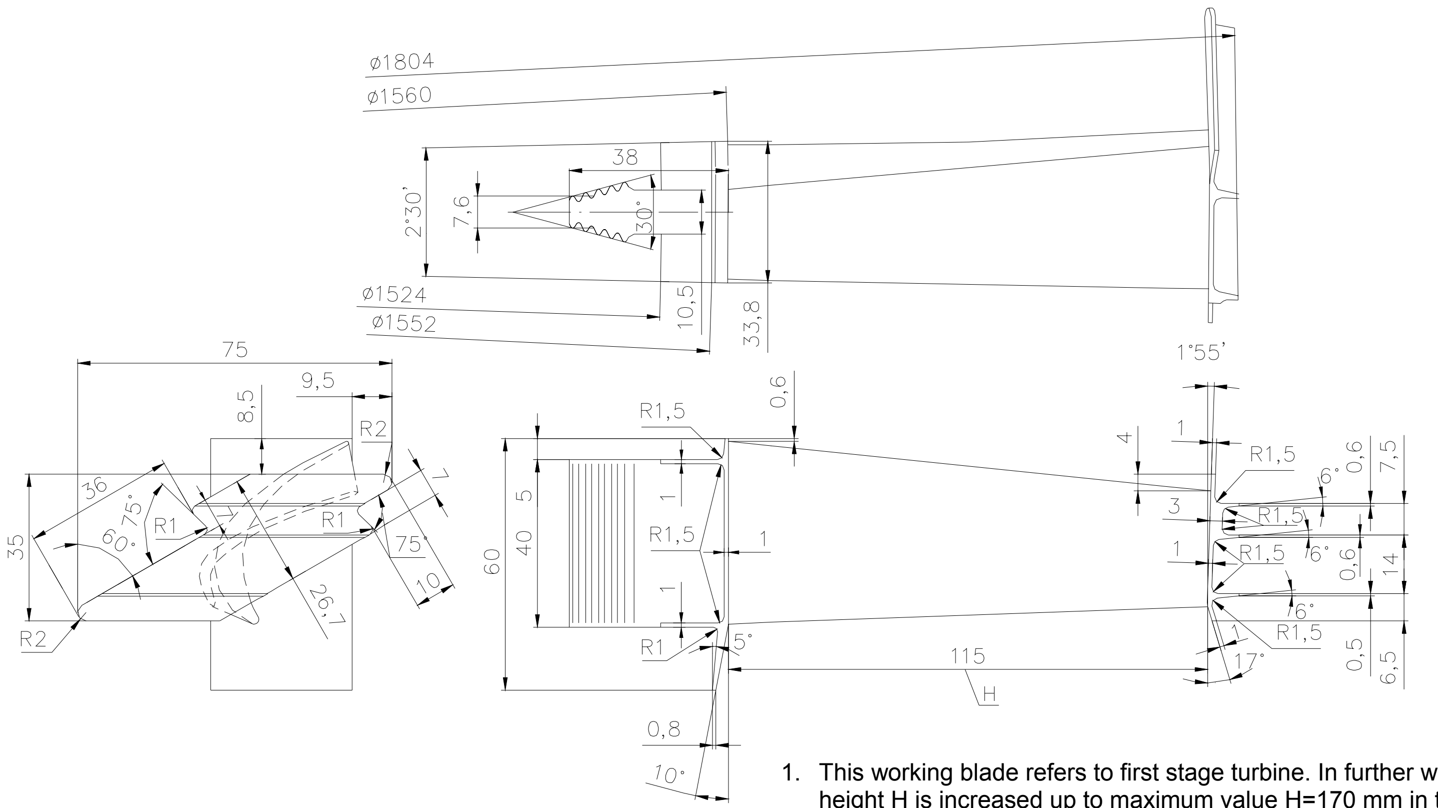
Figure 12
GT-MHR reactor type turbine new designs : sketch of the turbine first stage blade



1. This working blade refers to first stage turbine. In further working blades height H is increased up to maximum value H=170 mm in the last stage.
2. Material density is taken as 8.4 g/cm^3.
3. Requirements for material mechanical properties are specified in technical requirements for materials for turbocompressor main elements.

Appendix 1

Turbine inlet first stage
Envelope thermal and pressure cycles

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Table 1 : Envelope cycles : numerical data corresponding to figures 1 to 5 of appendix 1

	HTR-E ; D2 - ENVELOPE CYCLE FOR TURBINE FIRST STAGE							
	Temperature cycle ; 1350 cycles							
	TURBINE INLET = core outlet							
time ident.	time (days)	time (hours)	time (minutes)	time (seconds)	Inlet temperature	Transient duration (s)	Transient rate	
t0	0	0	0	0	30	12300	"240°C/h"	
t1	0,1423611	3,41666667	205	12300	850	1302244	0	
t2	15,21463	365,151111	21909,06667	1314544	850	656	"-1,25°C / s"	
t3	15,222222	365,333333	21920	1315200	30	86400	0	
t4	16,222222	389,333333	23360	1401600	30			
	Total duration of the 1350 cycles :							
	time (days)	time (hours)	time (minutes)	time (seconds)	time (years)			
	21900	525600	31536000	1892160000	60			
	HP compressor outlet (disk and blade foot cooling)				HP compressor outlet temperature			
time ident.	time (days)	time (hours)	time (minutes)	time (seconds)	Cooling helium	Transient duration (s)	Transient rate	
τ0	0	0	0	0	30	2400	"+120°C/h"	
τ1	0,0277778	0,66666667	40	2400	110	653070	0	
τ2	7,5864583	182,075	10924,5	655470	110	3,5	"-23°C/s"	
τ3	7,5864988	182,075972	10924,55833	655473,5	30	3600,5	0	
τ4	7,6281713	183,076111	10984,56667	659074	30	2400	"+120°C/h"	
τ5	7,6559491	183,742778	11024,56667	661474	110	653070	0	
τ6	15,21463	365,151111	21909,06667	1314544	110	64	"-1,25°C/s"	
τ7	15,21537	365,168889	21910,13333	1314608	30	86992	0	
τ8	16,222222	389,333333	23360	1401600	30			
	Pressure cycle ; 1350 cycles							
time ident.	time (days)	time (hours)	time (minutes)	time (seconds)	Inlet pressure	Transient duration (s)	Transient rate	
tp0	0	0	0	0	0,1	1210	"0,347MPa/min"	
tp1	0,0140046	0,33611111	20,16666667	1210	7,1	1313983	0	
tp2	15,222141	365,331389	21919,88333	1315193	7,1	7	"-1 Mpa/s"	
tp3	15,222222	365,333333	21920	1315200	0,1	86400	0	
tp4	16,222222	389,333333	23360	1401600	0,1			

Figure 1 of appendix 1

HTR-E ; turbine - Envelope cycle - Turbine first stage

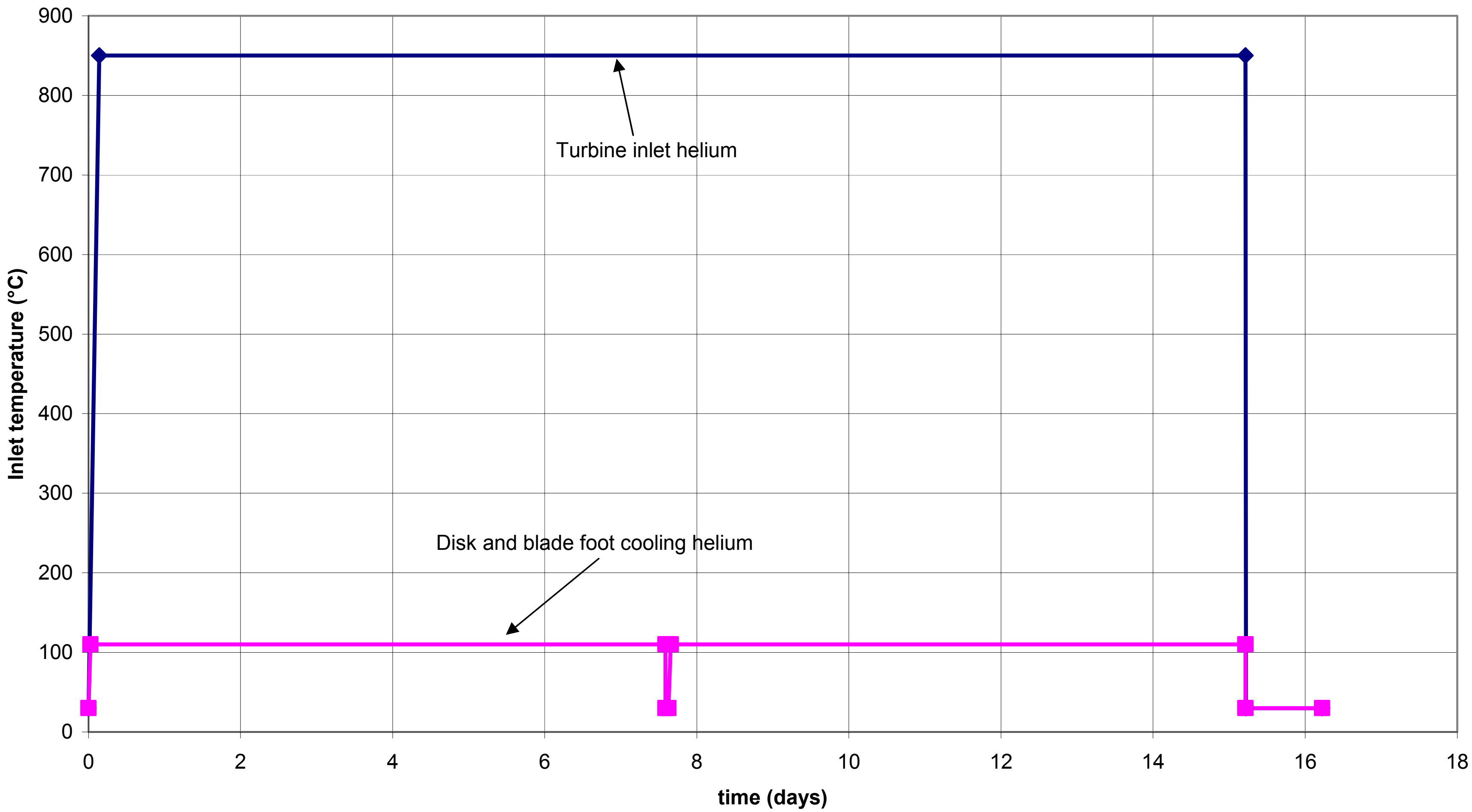

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Figure 2 of appendix 1

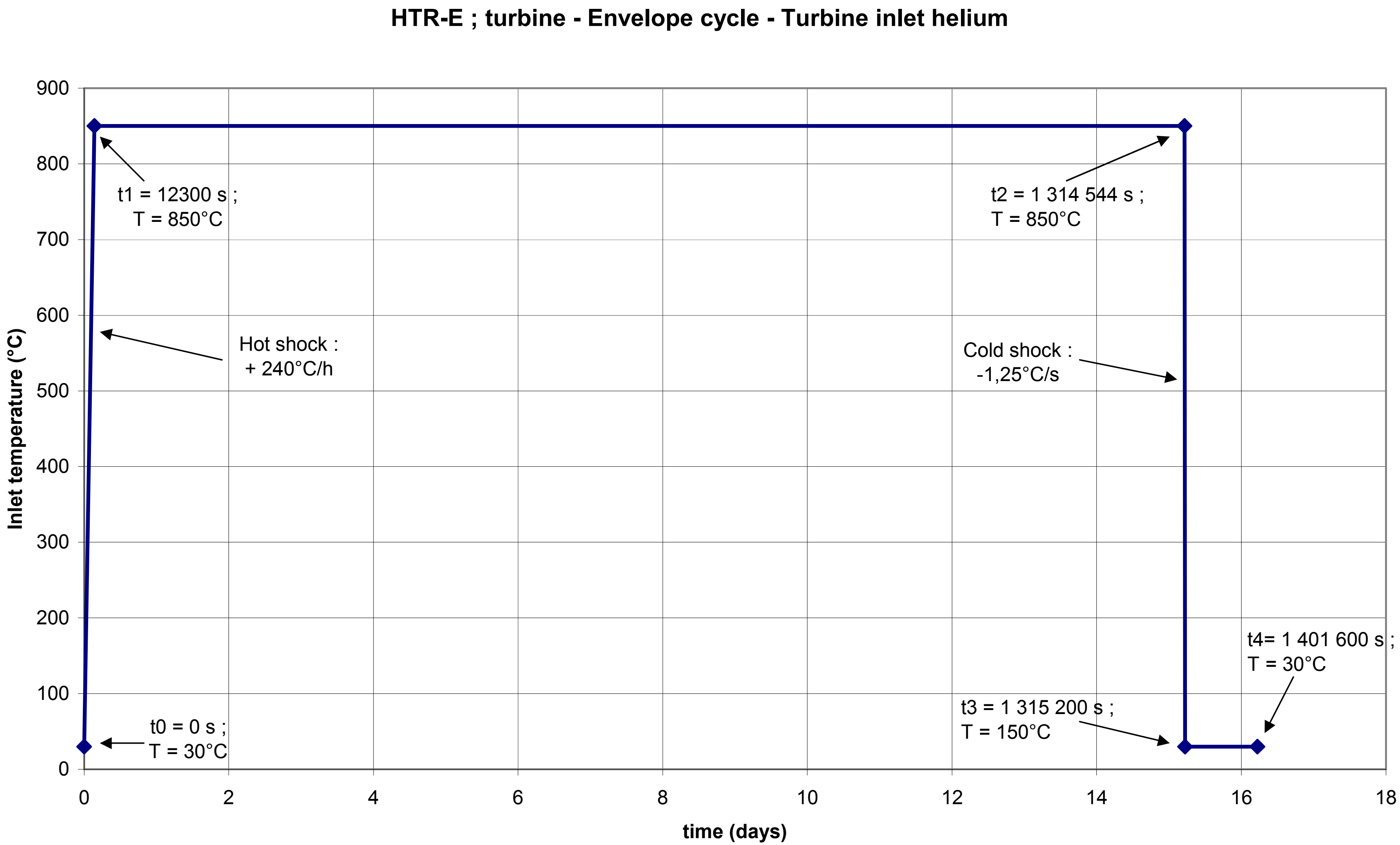

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Figure 3 of appendix 1

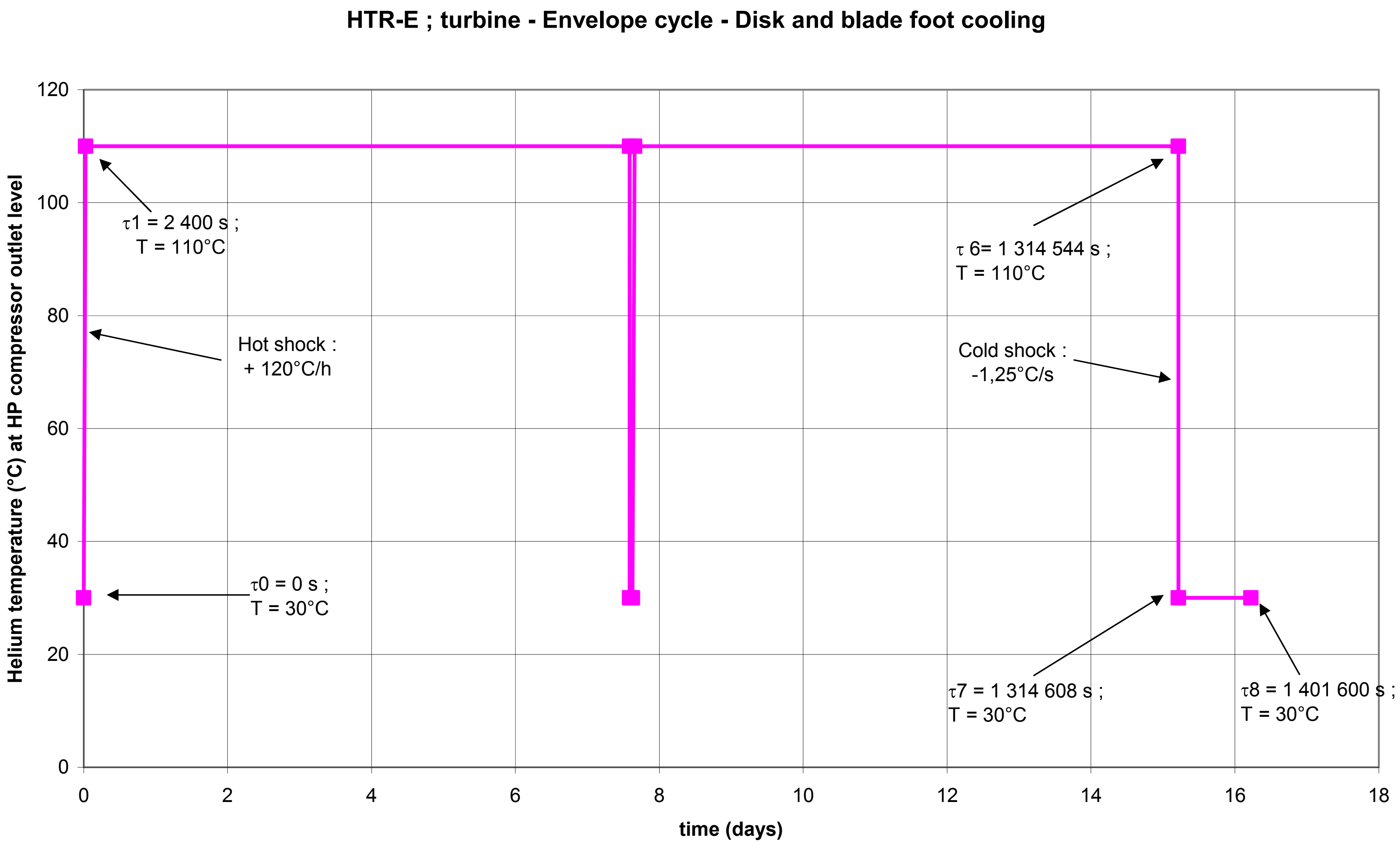

Figure 4 of appendix 1

HTR-E ; turbine - Envelope cycle - Disk and blade foot cooling - Detail

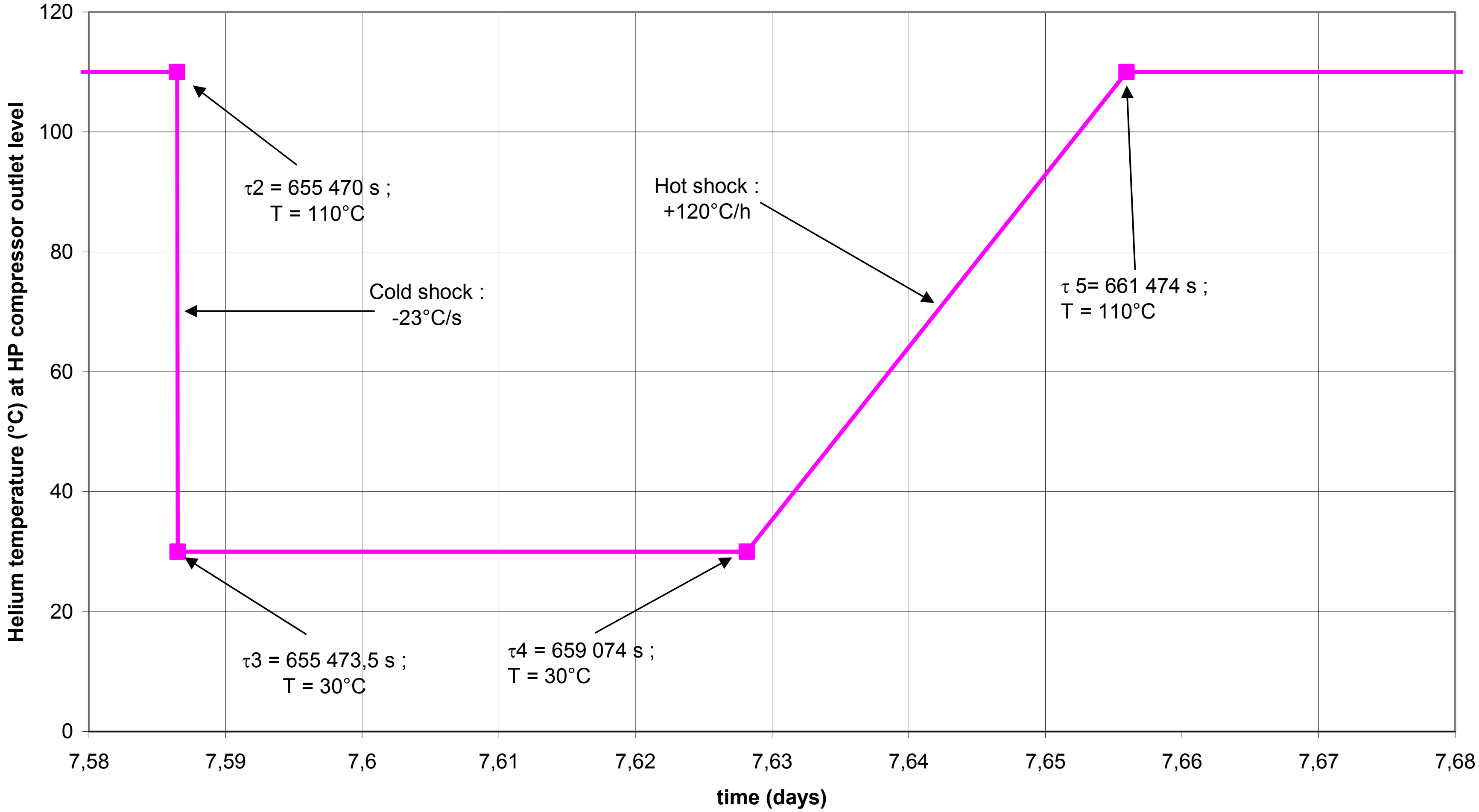

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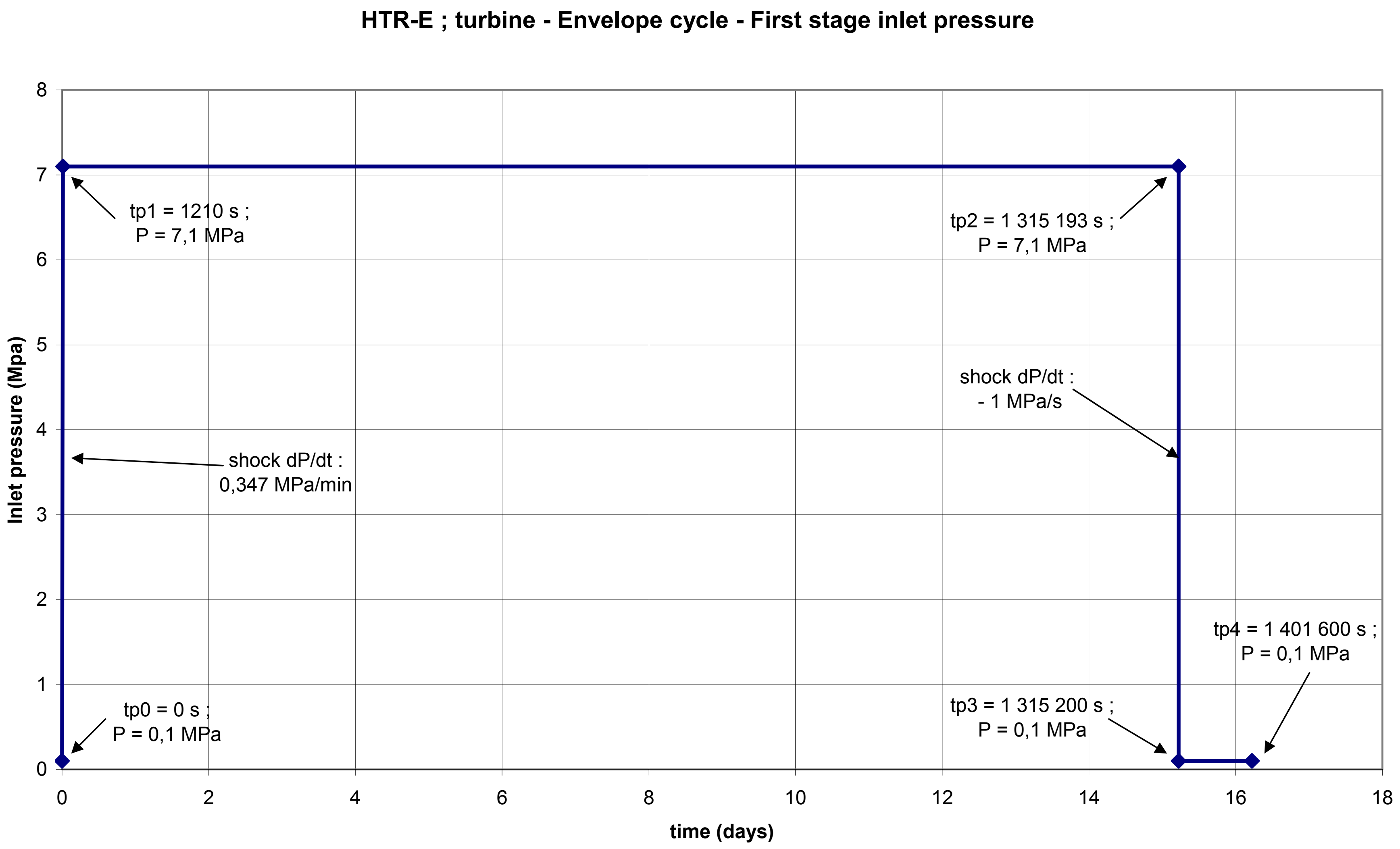
Figure 5 of appendix 1



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