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LIST OF ABBREVIATIONS

GT-MHR	Gas Turbine – Modular Helium Reactor
HP	High Pressure
HTR	High Temperature Reactor
LP	Low Pressure
PBMR	Pebble Bed Modular Reactor
PCU	Power Conversion Unit

1. PURPOSE AND SCOPE

This document is the contribution of Empresarios Agrupados to the HTR-E project, Work Package 1 “Turbine”, Deliverable 2 “Design Use, System Review, Integration and In-Service Inspection and Repair”.

The Power Conversion Unit of the South African PBMR and the Russian GT-MHR high temperature reactor concepts have been reviewed. The Thermal Cycle, the design parameters and main features of both reactor concepts have been studied.

The HTR Power Conversion Unit has been analysed on the basis of these two high temperature gas reactor projects currently underway.

The work has been carried out within the 5th Euratom Framework Programme, contract No. FIKI-CT-2001-00177.

2. INTRODUCTION

The general objectives of Work Package 1 “Turbine” within the HTR-E project are to determine the critical issues and to assess and demonstrate the potential of success for the design of the helium power turbine for the European HTR.

The main features of the HTR Turbine are:

- Helium turbine, direct cycle
- Inlet temperature 850ºC, no cooling system
- Long term operating conditions with high reliability
- 100 – 300 MWe range

There is no industrial experience for Gas Turbines and Gas Compressors with this HTR operating conditions. In a first step, to assess the Design Use and Specifications for the HTR helium power turbine, two developments based on direct cycle plants currently in the design phase will be considered as basis: the turbines of PBMR (see Figure 1) and of the GT-MHR (see Figure 2).

The input data used in this study have been obtained from a bibliography search. It is important to note that the available published information is not complete.

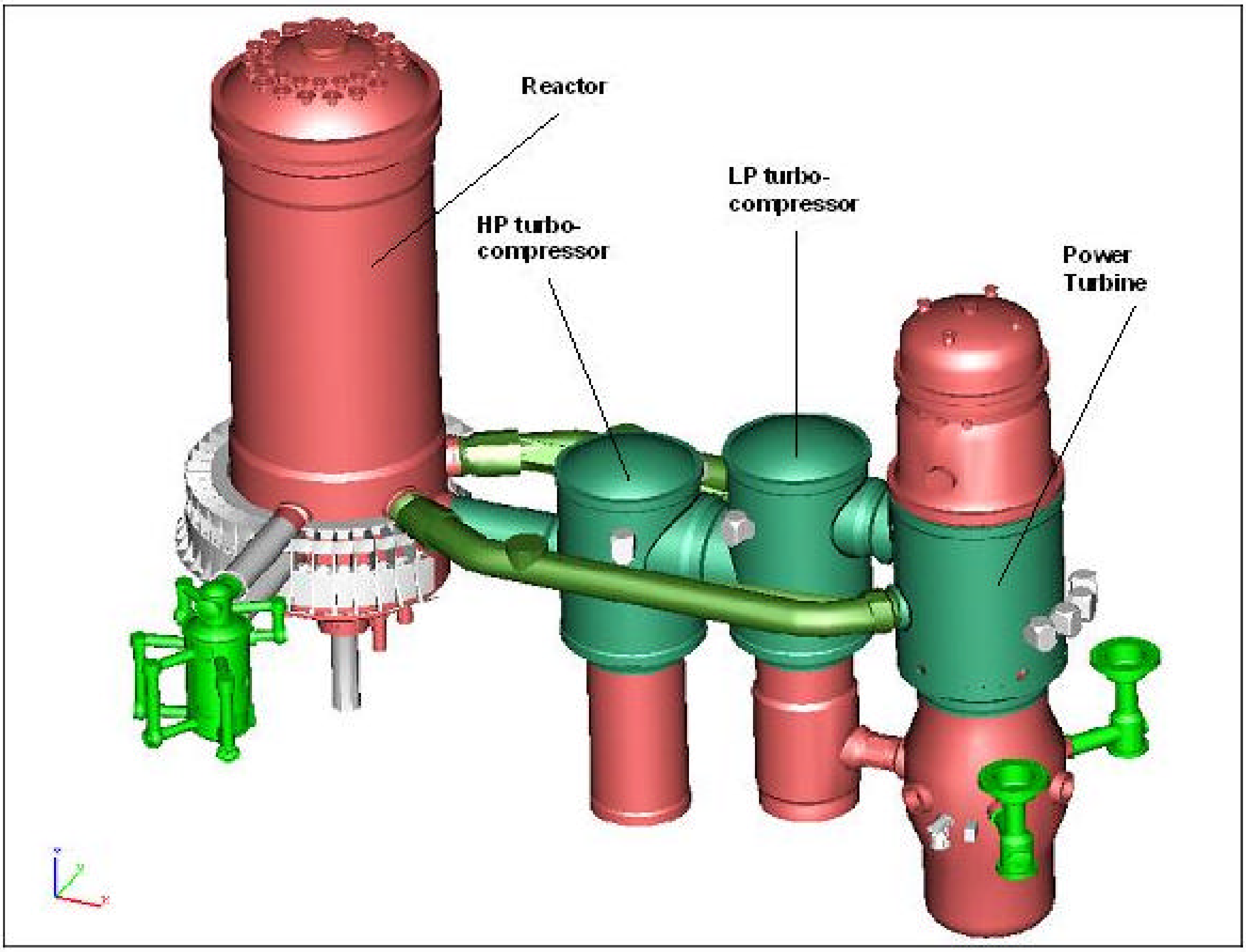

Figure 1: PBMR

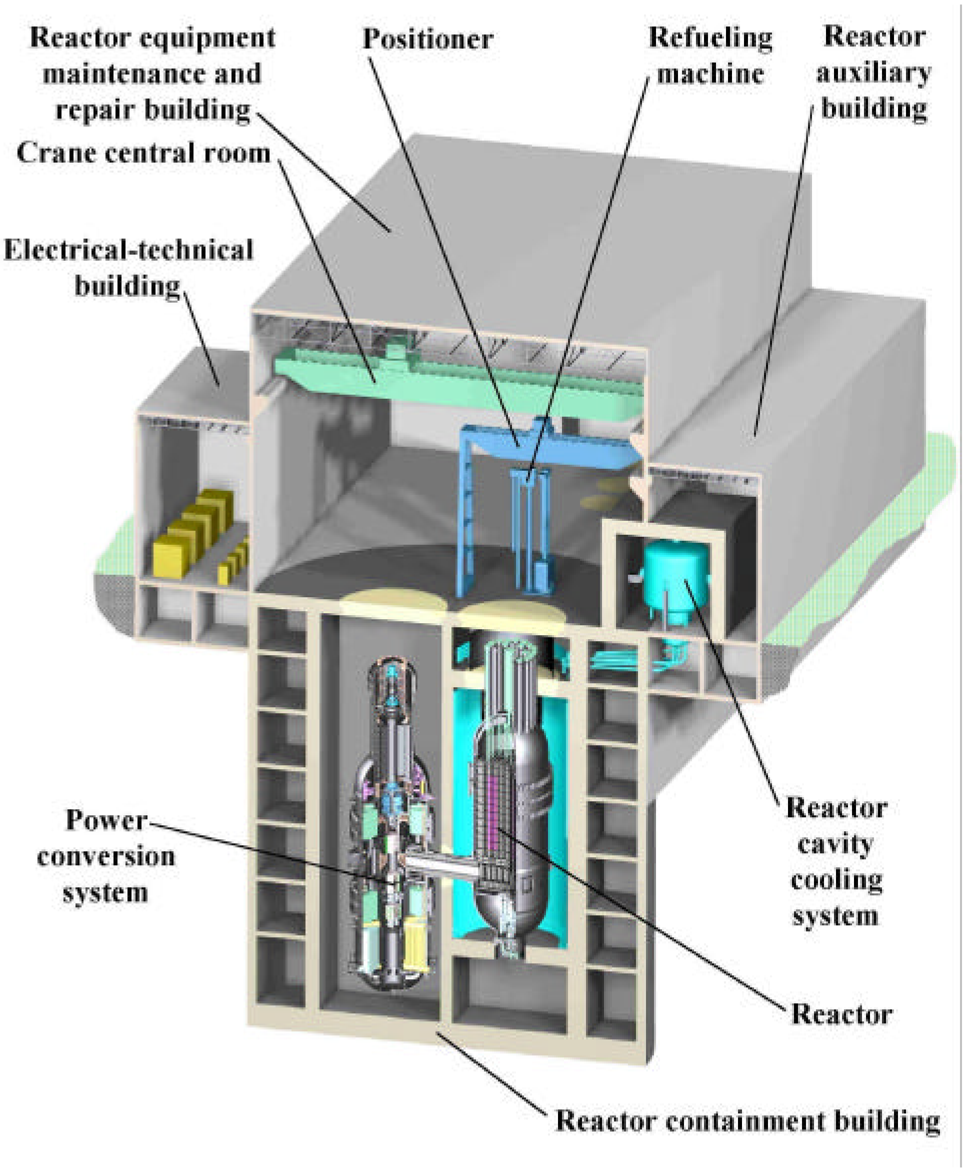

Figure 2: GT-MHR

3. PBMR POWER CONVERSION SYSTEM

3.1 DESCRIPTION

The PBMR power conversion system consists of two stage intercooled compression, recuperated Brayton cycle to operate in direct mode with the reactor [1] (see Figure 3).

The main components of the power conversion system are:

- The multistage axial flow power turbine, suspended with electromagnetic bearings, with the rotor mounted directly on the generator shaft, and with a turbine bypass valve to protect turbine and generator from an overspeed condition in case of normal control malfunctions
- The high (HP) and low (LP) pressure multistage parallel flow axial turbo compressors, each in an independent shaft with different rotating speeds and both suspended with electromagnetic bearings
- The recuperator consisting of four cassettes stacked on top of each other, each cassette based on a large number of sectors joined together by a top and a bottom mounting ring to form a donut-shaped cassette
- The precooler and intercooler, where identical units may be used for both, with water supply at such low pressure that leakage into helium system would be impossible

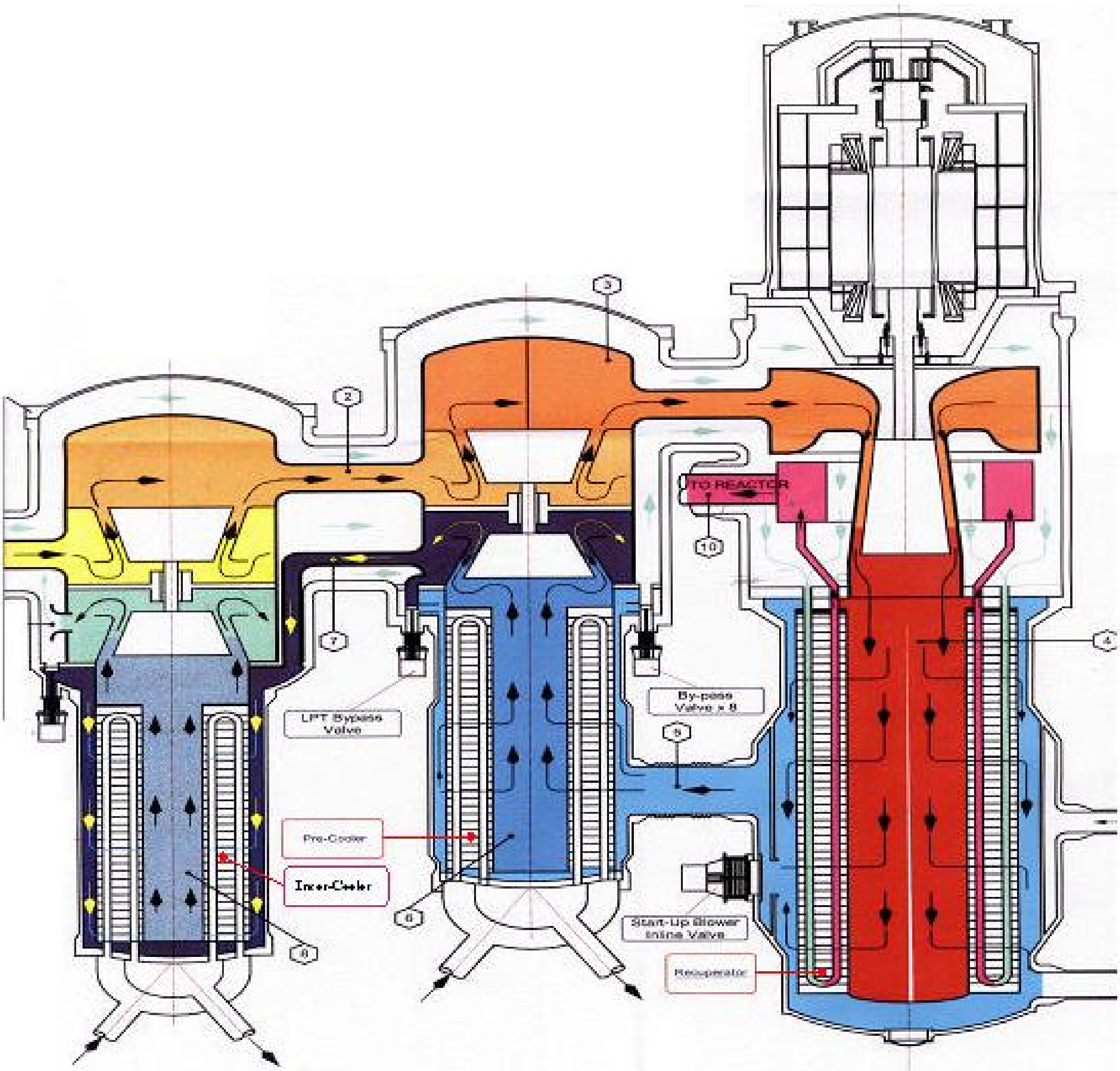

Figure 3: PBMR Power Conversion Unit

3.2 DESIGN PARAMETERS

PBMR design parameters at 100% load are the following:

Table 1: PBMR Design Parameters (100% Load)

Reactor Power (MWth)	290
Core Inlet / Outlet Temperatures (ºC)	530 / 900
Core Inlet / Outlet Pressures (MPa)	6.95 / 6.81
Helium Mass Flow Rate (kg/s)	140
Power Turbine Inlet / Outlet Temperatures (ºC)	735 / 555
Power Turbine Inlet / Outlet Pressures (MPa)	4.48 / 2.61
Recuperator Hot Side Inlet / Outlet Temperatures (ºC)	555 / 140
Recuperator Cold Side Inlet / Outlet Temperatures (ºC)	105 / 530
Net Electrical Output (MWe)	116
Net Plant Efficiency (%)	40

3.3 FLOW DIAGRAM

The PBMR flow diagram is the following:

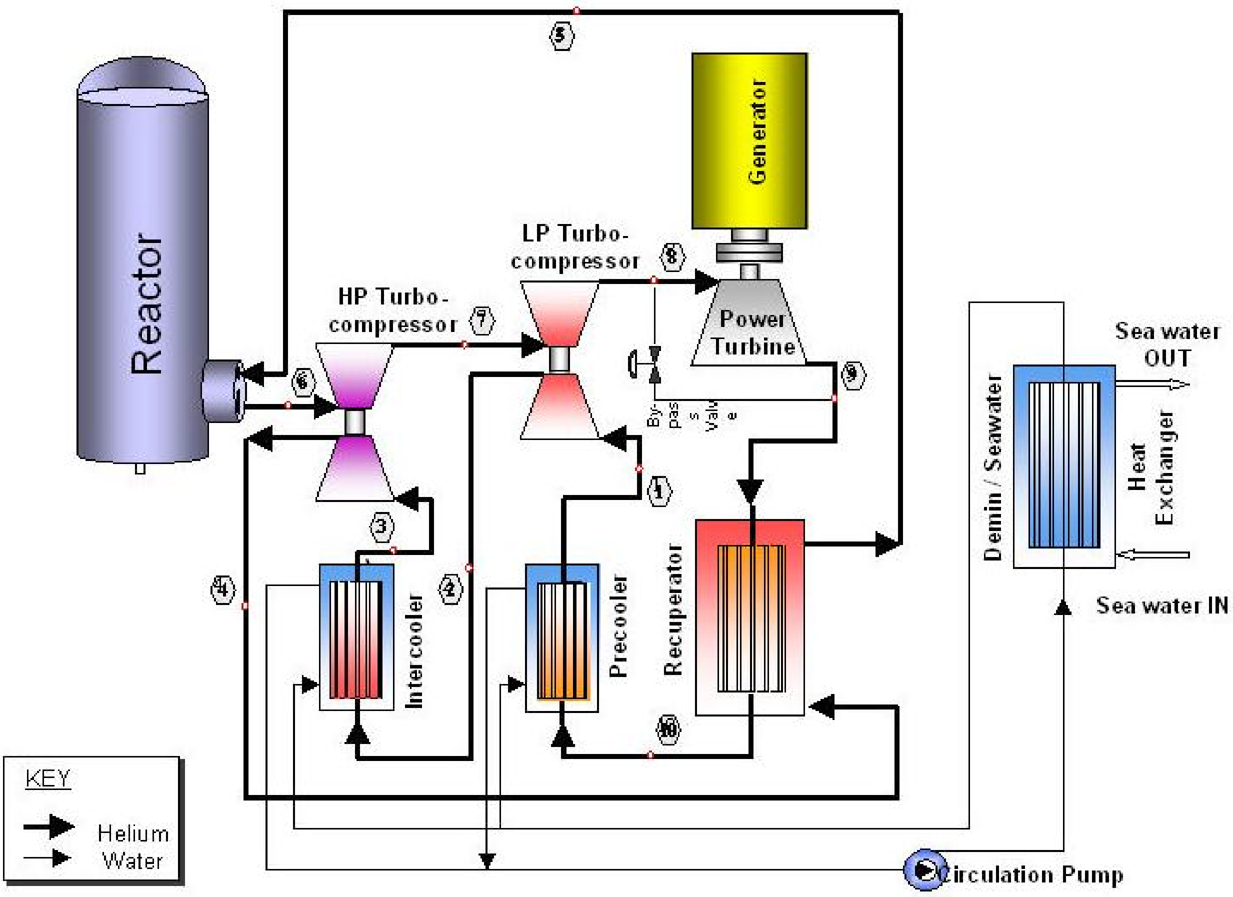

Figure 4: PBMR Flow Diagram

3.4 THERMAL CYCLE

The PBMR Brayton cycle is the following:

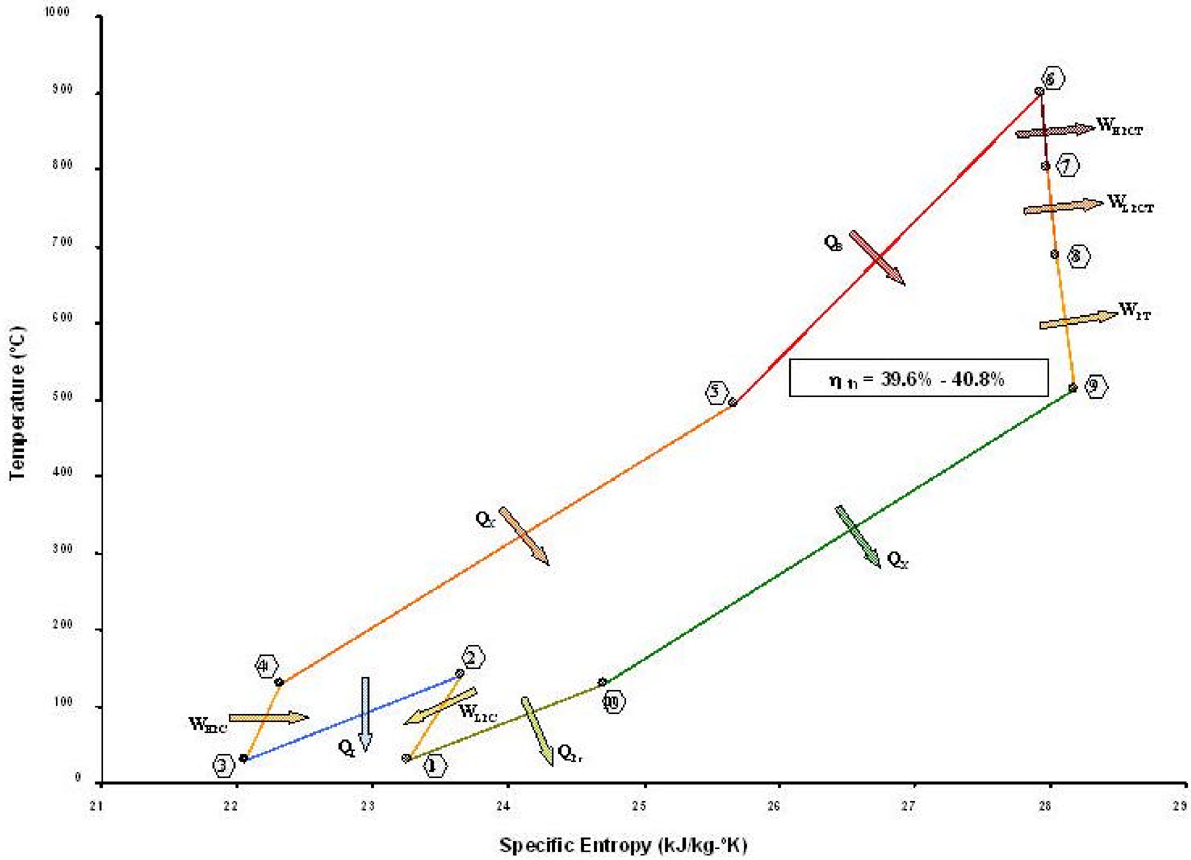

Figure 5: PBMR Brayton Cycle

The Brayton cycle obtained is based on the PBMR cycle input data given in Appendix A.

The PBMR design considers a bypass valve around the power turbine. This valve is required in order to control the PCU during normal operating conditions and during incidents. It allows controlling the amount of helium passing through the power turbine. To ensure sufficient control capacity, normal operation with 6.32 kg/s of helium through the bypass valve would be considered. The maximum PCU capacity is when 100% of the helium passes through the power turbine (same as without bypass).

The resulting states 1 to 10 of the Brayton cycle are described below in Table 2 and Table 3.

Table 2: PBMR Brayton Cycle States (without bypass)

State	P (MPa)	T (ºC)	s (kJ/kg-ºK)	h (kJ/kg)	Flow (kg/s)
1	2.20	30.0	23.3	26.0	140.0
2	3.92	138.8	23.7	591.1	140.0
3	3.91	30.0	22.1	26.0	140.0
4	7.0	128.6	22.3	538.0	140.0
5	7.0	492.8	25.7	2428.9	140.0
6	6.83	900.0	27.9	4543.5	140.0
7	5.36	801.4	28.0	4031.5	133.0
8	3.92	686.8	28.0	3436.6	133.0
9	2.22	511.9	28.2	2528.4	133.0
10	2.22	128.6	24.7	537.8	133.0

Table 3: PBMR Brayton Cycle States (with bypass)

State	P (MPa)	T (ºC)	s (kJ/kg-ºK)	h (kJ/kg)	Flow (kg/s)
1	2.20	30.0	23.3	26.0	140.0
2	3.92	138.8	23.7	591.1	140.0
3	3.91	30.0	22.1	26.0	140.0
4	7.0	128.6	22.3	538.0	140.0
5	7.0	501.1	25.7	2472.1	140.0
6	6.83	900.0	27.9	4543.5	140.0
7	5.36	801.4	28.0	4031.5	133.0
8	3.92	686.8	28.0	3436.6	133.0
9	2.22	520.7	28.2	2573.9	133.0
10	2.22	128.6	24.7	537.8	133.0

4. GT-MHR POWER CONVERSION SYSTEM

4.1 DESCRIPTION

The GT-MHR power conversion unit consists mainly of the same components that in the case of the PBMR. However, the rotors of the power turbine, the high (HP-C) and low (HL-C) compressors are mounted on the same shaft together with the generator (see Figure 6).

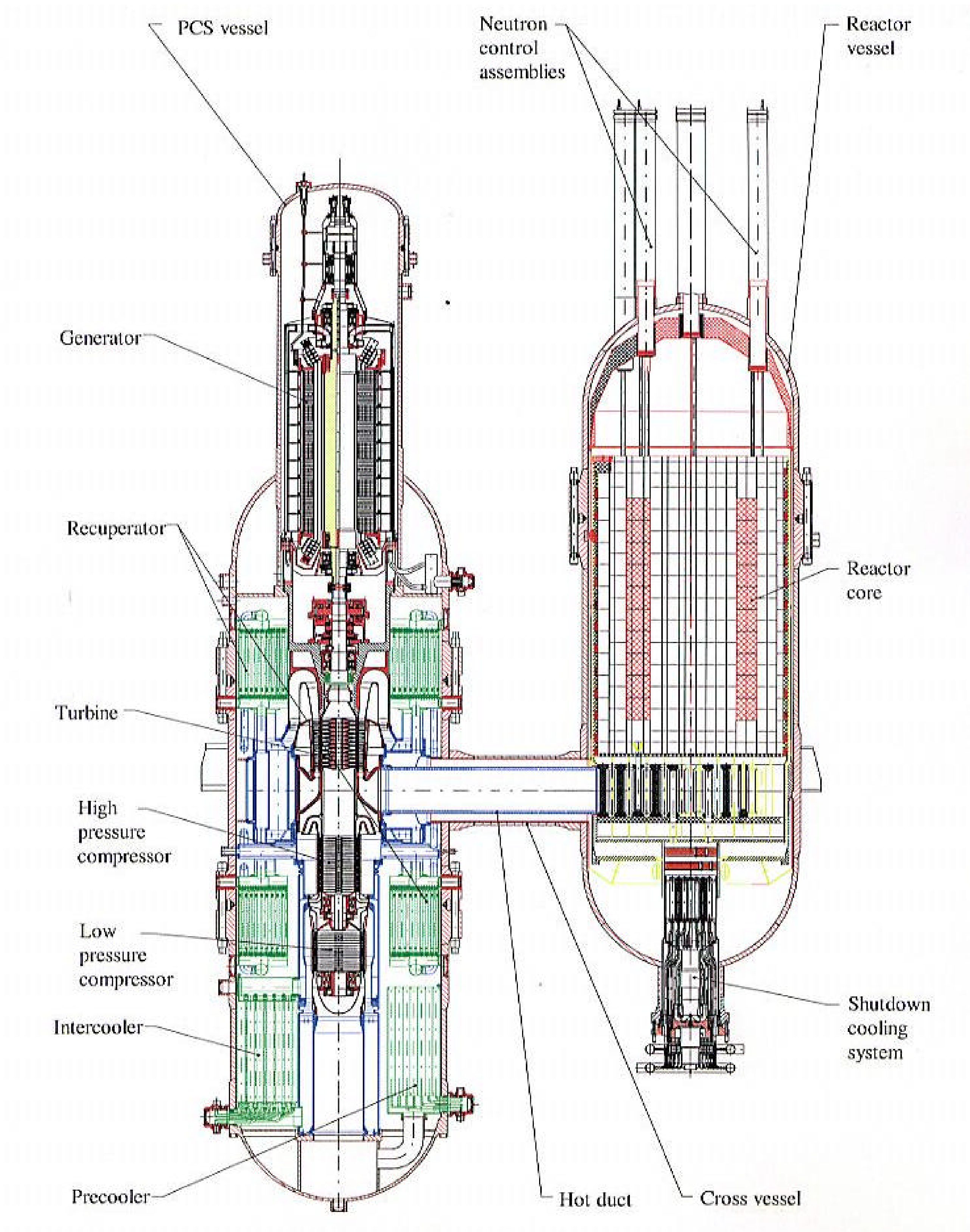

Figure 6: GT-MHR Power Conversion System

4.2 DESIGN PARAMETERS

GT-MHR design parameters at 100% load are the following:

Table 4: GT-MHR Design Parameters (100% Load)

Reactor Power (MWth)	6000
Core Inlet / Outlet Temperatures (ºC)	490 / 850
Core Inlet / Outlet Pressures (MPa)	7.07 / 7.02
Helium Mass Flow Rate (kg/s)	316
Power Turbine Inlet / Outlet Temperatures (ºC)	850 / 510
Power Turbine Inlet / Outlet Pressures (MPa)	7.01 / 2.64
Recuperator Hot Side Inlet / Outlet Temperatures (ºC)	510 / 125
Recuperator Cold Side Inlet / Outlet Temperatures (ºC)	105 / 490
Net Electrical Output (MWe)	285
Net Plant Efficiency (%)	47.5

4.3 FLOW DIAGRAM

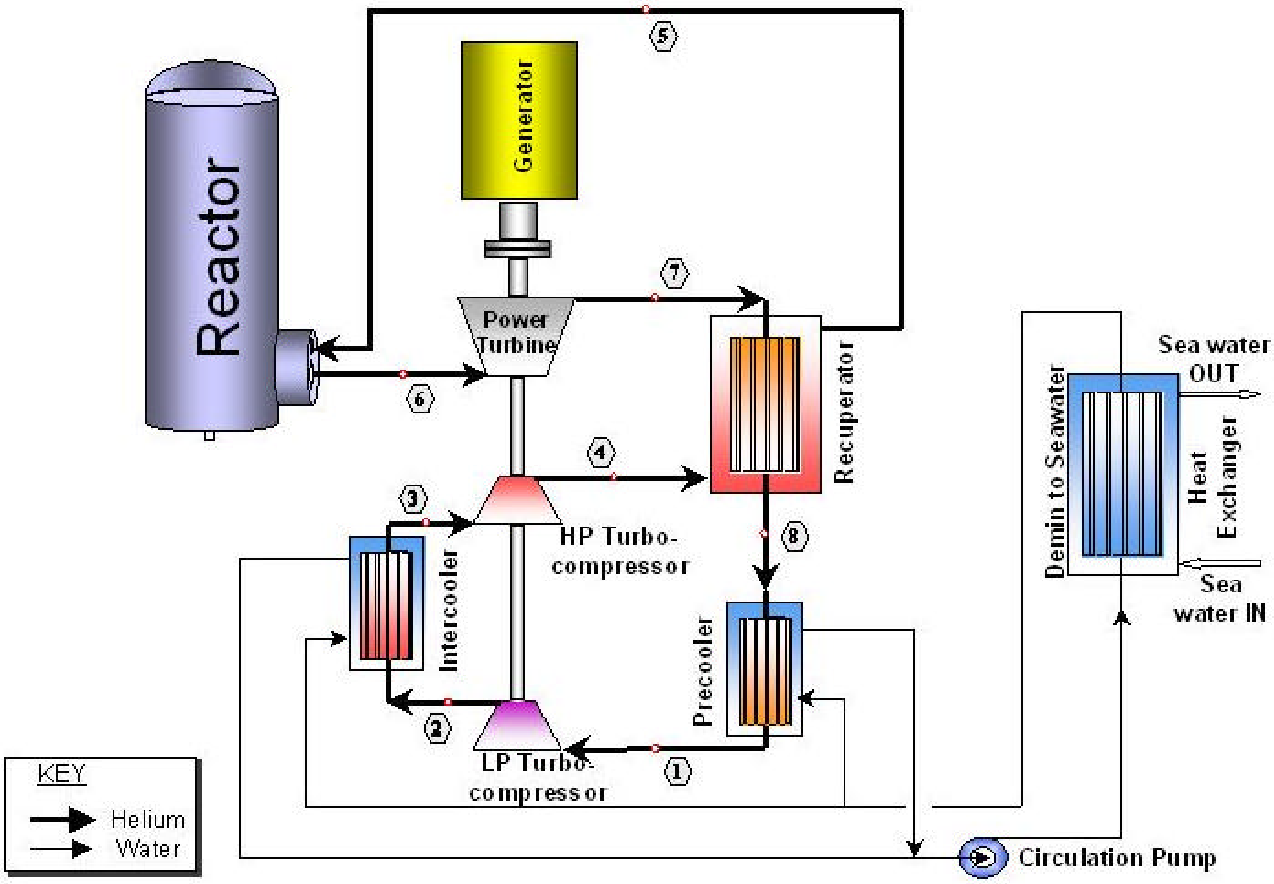

Figure 7: GT-MHR Flow Diagram

4.4 THERMAL CYCLE

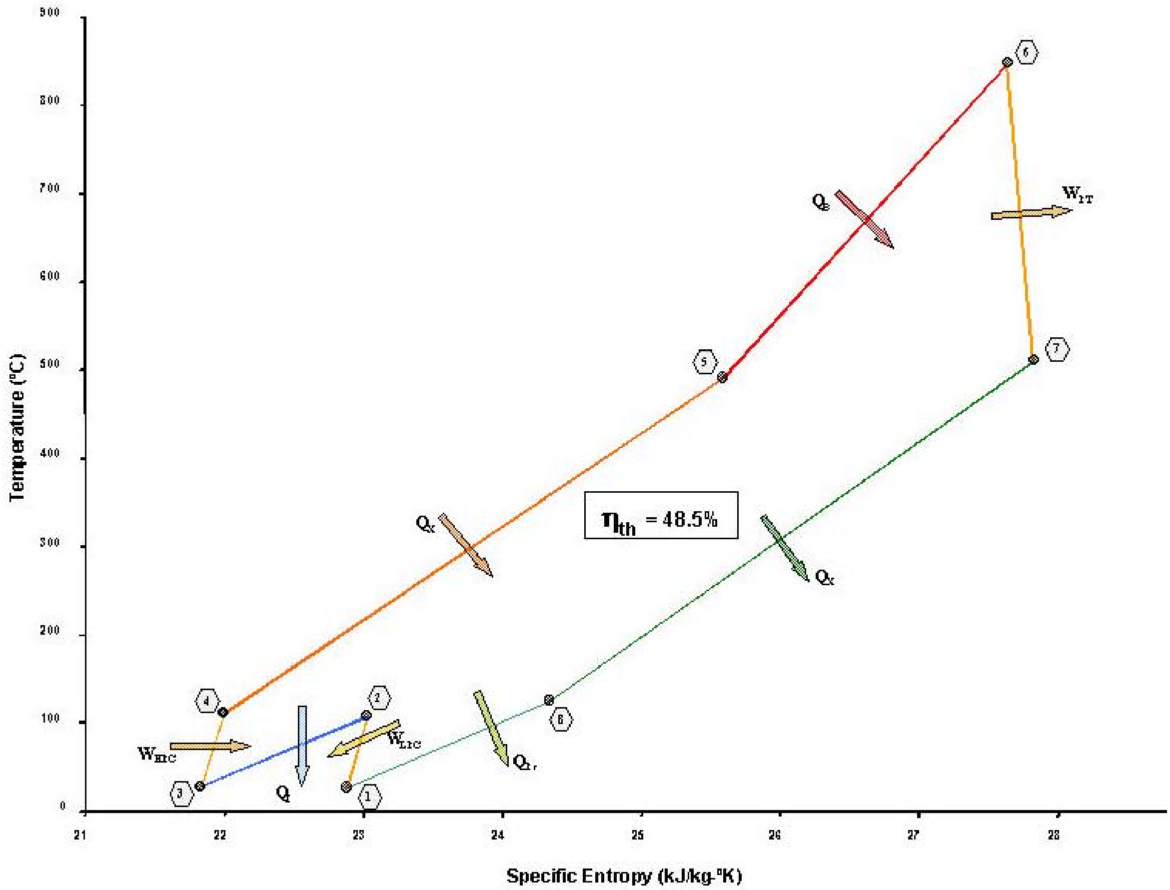

Figure 8: GT-MHR Thermal Cycle

The obtained Brayton cycle is based on the GT-MHR cycle input data given in Appendix A.

The resulting states 1 to 8 of the Brayton cycle are described below in Table 5.

Table 5: GT-MHR Brayton Cycle States

State	P (MPa)	T (ºC)	s (kJ/kg-ºK)	h (kJ/kg)	Flow (kg/s)
1	2.55	26.1	22.9	5.7	319.4
2	4.34	107.5	23.0	428.4	319.4
3	4.28	27.4	21.8	12.5	319.4
4	7.27	110.3	22.0	442.9	323.0
5	7.22	490.0	25.6	2414.6	316.0
6	7.07	848.0	27.6	4273.5	317.5
7	2.63	510.0	27.8	2518.4	317.5
8	2.59	125.0	24.3	519.3	317.5

5. ANALYSIS OF PBMR AND GT-MHR

5.1 DEVICE ANALYSIS

Table 6: PBMR and GT-MHR Device Analysis

Device	Power or Heat	GT-MHR	PBMR[(a)]
LP Compressor	W_{LPC} (MW)	-133.57	-79.12
HP Compressor	W_{HPC} (MW)	-136.03	-71.68
HP Compressor Turbine	W_{HPCT} (MW)	N/A	71.68
LP Compressor Turbine	W_{LPCT} (MW)	N/A	79.12
Power	W_{PT} (MW)	554.61	114.74
Reactor	Q_B (MW)	587.43	290.00
Regenerator	Q_X (MW)	0	0
Precooler	Q_{PR} (MW)	-162.28	-78.15
Intercooler	Q_I (MW)	-131.43	-79.12

(a) Bypass operation with 6.32 kg/s around the power turbine

5.2 CYCLE ANALYSIS

Table 7: PBMR and GT-MHR cycle analysis

Variable	Description	GT-MHR	PBMR[(a)]
T_max (ºC)	Maximum Cycle Temperature	848.0	900.0
T_min (ºC)	Minimum Cycle Temperature	26.1	30.0
Qdot_in (MW)	Heat added to the cycle	587.43	290.00
Qdot_out (MW)	Heat rejected by the cycle	293.71	157.27
Wdot_in (MW)	Power added to the cycle	269.59	150.80
Wdot_out (MW)	Power produced by the cycle	554.61	265.53
Qdot_net (MW)	Net heat added to the cycle	293.71	132.73
Wdor_net (MW)	Net power produced by the cycle	285.02	114.73
η_th (%)	Thermal efficiency of the cycle	48.52	39.56
η_Carnot (%)	Carnot ideal cycle efficiency	73.31	74.16
BWR (%)	Back work ratio	48.61	56.79

(a) Bypass operation with 6.32 kg/s around the power turbine

5.3 TURBINE MAIN FEATURES

Table 8: PBMR and GT-MHR Turbine Main Features

Name of Parameters	GT-MHR	PBMR(1)	PBMR(2)	PBMR(3)
Power (MWth)	560.3	116.74	79.15	71.63
Speed (rpm)	3000	3000	13800	15000
Helium Flow Rate (kg/s)	317.5	126.3	133	133
Bypass Flow (kg/s)	0	6.32	6.65	7.0
Inlet Temperature (ºC)	848	686.86	801.47	900
Inlet Pressure (MPa)	7.07	4.79	5.04	6.82
Inlet Pressure Losses (MPa)	0.007	---	---	---
Outlet Temperature (ºC)	510	508.92	686.86	801.47
Outlet Pressure (MPa)	2.63	2.68	3.28	5.03
Outlet Pressure Losses (MPa)	0.02	---	---	---
Blade System Efficiency (%)(4)	93	90	90	90
Number of Stages	12	13	3	3

(1) Power Turbine

(2) Low Pressure Compressor Turbine

(3) High Pressure Compressor Turbine

(4) Adiabatic

6. ANALYSIS OF HTR POWER CONVERSION UNIT

6.1 DESCRIPTION

The previous chapters have included a revision of the PCUs of two High Temperature Gas Reactors projects currently under way: the South-African PBMR and the Russian GT-MHR. These reviews will provide a basis for the design of the European HTR.

The PCU design for the HTR is still to be defined, but it can be generally be considered to include the same components seen in the PBMR and the GT-MHR.

The generic flow diagram of the HTR could be as follows:

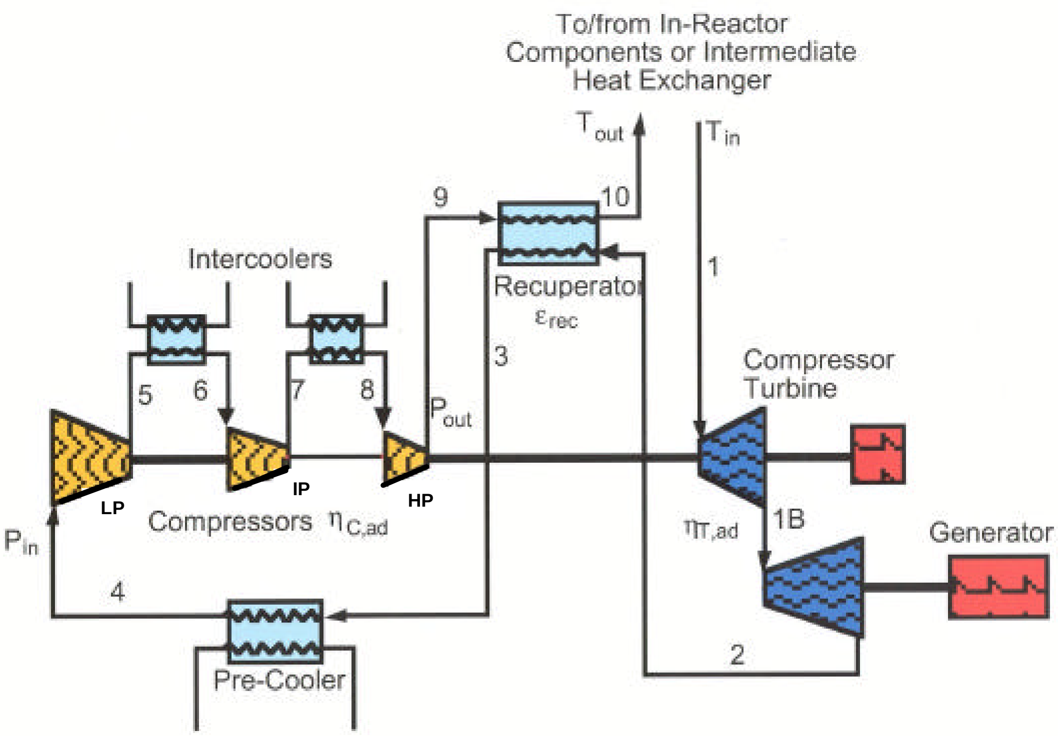

Figure 9: HTR Generic Flow Diagram

The generic cycle efficiency is given by:

$$\eta_{cycle} = \frac{\eta_{T,ad}\,\frac{T_{in}}{T_{min}}\left[1-\left(\frac{1}{\Pi_C}\right)^{\gamma-1/\gamma}\right]-\frac{3}{\eta_{C,ad}}\left(r_p^{\gamma-1/\gamma}-1\right)}{\frac{T_{in}}{T_{min}}-\varepsilon_{rec}\left\{\frac{T_{in}}{T_{min}}\left\{1-\eta_{T,ad}\left[1-\left(\frac{1}{\Pi_C}\right)^{\gamma-1/\gamma}\right]\right\}-1\right\}-\left(1-\varepsilon_{rec}\right)\left[\frac{r_p^{\gamma-1/\gamma}-1}{\eta_{C,ad}}+1\right]}$$

where,

$$\Pi_C = \left(1-\frac{\Delta P}{P_{out}}\right) r_p^{3} \quad \text{and} \quad r_p = \text{Compression ratio of each compressor}$$

6.2 INFLUENCE OF THE KEY FACTORS

In order to design the PCU of the HTR, it is important to analyse the key factors with a direct influence on cycle efficiency, since they condition the design.

The key factors are set out below:

- **T_{in}** : Turbine inlet temperature. In the case of PBMR, it corresponds to the HP turbo-compressor turbine inlet temperature. In the case of GT-MHR, it corresponds to the power turbine inlet temperature

- ε_{rec} : Recuperator effectiveness. Very important for the overall cycle efficiency since it benefits from the energy of the turbine exhaust to heat the gas returning to the reactor. The recuperator sees the maximum pressure difference in the cycle, so its effectiveness depends mainly on the leaks, and thus on the sealing materials.

- **P_{out}** : HP compressor discharge pressure, the maximum pressure in the cycle

- $\eta_{T,ad}$: adiabatic efficiency of the gas turbines

- $\eta_{C,ad}$: adiabatic efficiency of the compressors

- **$\Delta P/P$** : system pressure drop ratio, that is, the pressure difference between the HP compressor discharge pressure and the LP compressor inlet pressure; $\Delta P = p_{out} - p_{in}$

The aforementioned key factors significantly affect both the main equipment (e.g. turbines, compressors and heat recuperators), which constitute the power conversion system, and the Brayton cycle gross efficiency in a plant based on high temperature modular helium reactor technology. All of these key factors actuate as independent thermodynamic variables, and can be controlled by the plant designer with the only limitation of technological progress. This progress encompasses the expected improvements in the characteristics of the new materials and the design of turbo-machinery and heat recuperators operating under high pressure and temperature conditions.

The dependence between the main PCU equipment and the different key factors is shown below:

Equipment	Key Factor
Turbine and Compressor	T_i ; η_{tad} ; η_{cad}
Heat Recuperator	T_i ; P_{out} ; ε_{rec}
Overall PCS: Brayton Cycle Gross Efficiency	$\Pi_C = \Delta P/P_{out}$

A possible estimation of the projection of the key factors in the near future, considering the development of new materials and components, is set out below:

Table 9:Projection of the Key Factors in the Near Future

Variable	Description	Current State-of-the-art value	Near term technology value[(a)]
T_{in}	Turbine Inlet Temperature	850ºC	1200ºC
e_{rec}	Recuperator Effectiveness	95% @ ~510ºC	96% @ ~ 800ºC
P_{out}	HP Compressor Discharge Pressure	7 MPa	15 MPa
$h_{T,ad}$	Gas Turbines Adiabatic Efficiency	93%	94%
$h_{C,ad}$	Compressors Adiabatic Efficiency	89%	92%
DP/P_{out}[(b)]	System Pressure Drop Ratio	0.07	0.04

(a) 10 to 20 years in the future

(b) $\Delta P = p_{out} - p_{in}$; where p_{in} is the LP compressor inlet pressure

A study of the sensitivity of the cycle efficiency considering the various key factors and considering the previous near-term future estimate of its maximum values produces the following graph:

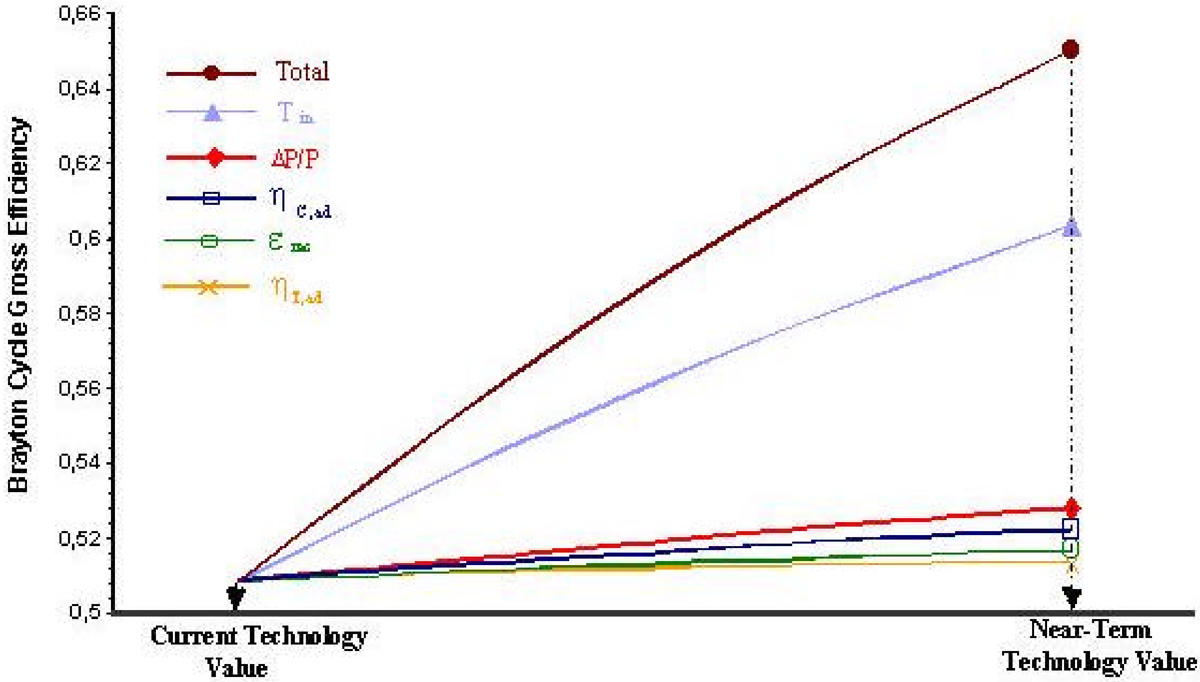

Figure 10:
Sensitivity Analysis of Cycle Efficiency as a Function of Key Factors

The key factor with a greatest influence on the cycle efficiency in the near future is the turbine inlet temperature (T_{in}).This factor could show a significant increase, although it shall be basically limited by the turbine materials. The rest of the key factors are equally important because even small increases of their highest values allow an increase in cycle efficiency. Considering the key factors are lineally independent, the total increase in cycle efficiency can be obtained from the sum of their efficiency increases. An increase of around 10-12% in the total efficiency of the cycle is expected in the next 10-20 years.

6.3 BRAYTON CYCLE EFFICIENCY

The direct Brayton cycle efficiency is theoretically dependent on the fractional pressure drop, which is the ratio of pressure drop to system pressure, ΔP/P. He-cooled high temperature reactor components are expected to have relatively high-pressure losses because of the high volumetric flow rates. This can be compensated by an increase in the system pressure. The maximum pressure considered in nuclear designs to date is ~7 MPa, a value which is limited to the capability of large, non-insulated, high temperature pressure vessels.

The pressure capability can be increased with the use of internal insulation. It is likely that the in-reactor components will establish the pressure limit, but the power conversion system should be able to achieve the same pressure capabilities as current nuclear pressure vessels and piping components (~15 MPa).

Figure 11 shows the estimated gross cycle efficiency for each of the two cases as a function of **?**$_{C}$ under the assumption of a lowest He cycle temperature of 35°C. The optimum cycle efficiencies for the current and near term technology parameter values are 51% and 64%, which correspond to **?**$_{C}$ values of 2.38 and 2.43, respectively. Also shown in the figure for each case is the in-reactor return temperature, $\mathbf{T_{out}}$, as a function of **?**$_{C}$. The values of T_{out} which correspond to the optimised **?**$_{C}$ values are 522°C and 759°C for the current and near term technology parameter values, respectively. Since **?**$_{cycle}$ shows virtually no variation with **?**$_{C}$ between the optimised **?**$_{C}$ value and **?**$_{C}$ of ~3, it is possible to change **?**$_{C}$ in this range to lower $\mathbf{T_{out}}$, if required by material considerations, while at the same time maintaining a high cycle efficiency.

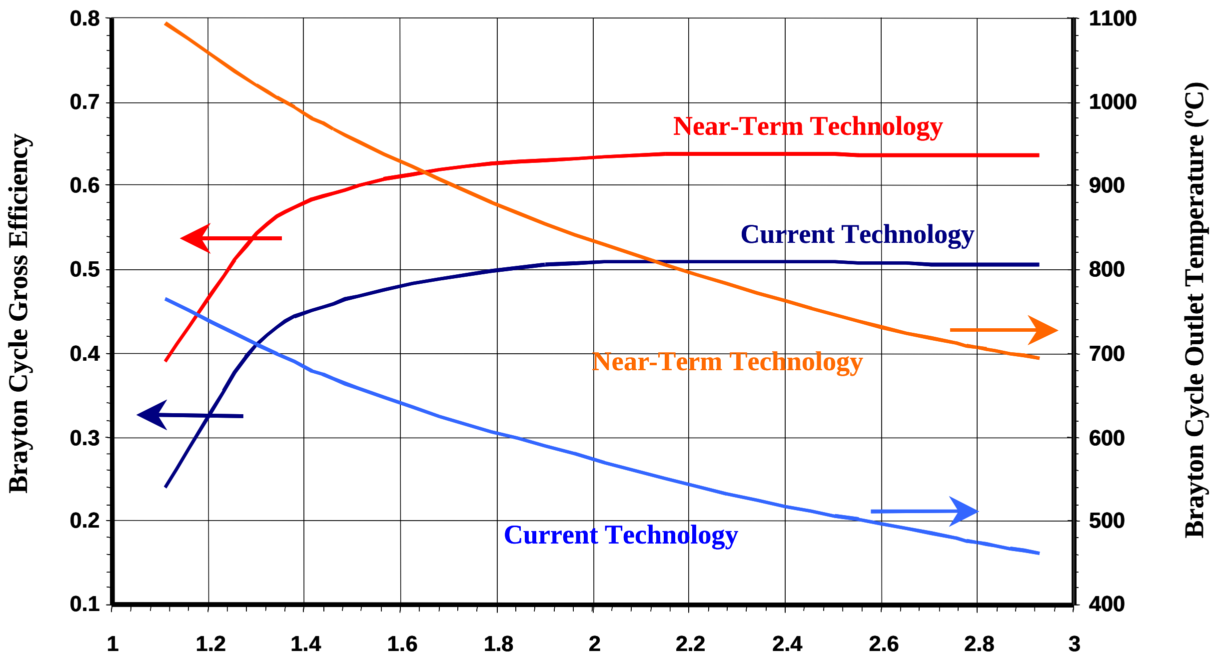

Fig. 11. Brayton Cycle Gross Efficiency and Outlet Temperature as a Function of Compression Ratio for Current and Near-Term Technology Cases

6.4 DEVELOPMENT OF GAS TURBINES AND COMPRESSORS

6.4.1 Materials for Blades and Discs

The major issues associated with the design of large helium turbines and compressors are material limitations of the high temperature blades and discs, dynamic stability of large flexible rotor assemblies and the dynamic loading capability of magnetic bearings.

The selection of metal alloys for high temperature turbine blades and discs is limited by resistance to creep and fatigue crack growth at high temperature with trace impurities (such as carbon) in the helium coolant. Current available materials include cast mono-crystal nickel (e.g. IN-100) and special wrought materials. The useable lifetimes of uncooled turbine components fabricated from these materials is expected to be between 50-60,000 hrs. Therefore, planned blade/disk replacement will be required during the life of the plant. Based on this work, it is suggested that 850^{o}C is the maximum temperature that could be achieved with uncooled metallic blades/disks. Cooling of blades/disks with cold bypass helium could enable higher inlet temperatures, but with diminishing improvements to cycle efficiency. For example, an increase in turbine inlet temperature from 850^{o}C to 950^{o}C results in a ~3.0 point ideal efficiency increase, but cold bypass flow of 2% of total flow reduces the increase to only 2.0 points.

A wide variety of ceramic materials is being investigated for monolithic radial and axial turbines ("blisks", for "blades and disks"), for ceramic blades inserted into metal disks and for combustion chambers. The overwhelmingly favoured material at the time of writing is silicon nitride. (Yoshimo et al. [1995] wrote, "Silicon-nitride nozzles should exceed feasible temperature limits [for a .1500 C-class gas turbine 1 without cooling]".)

Many other more complex high-temperature non-metallic materials show promise but have not yet been generally adopted. Two of these are whisker-toughened ceramics, and carbon fibres in a graphite matrix (so-called "carbon-carbon"). The latter actually increases in strength with an increase in temperature up to close to the stoichiometric level of combustion of turbine fuels in air. No way has yet been found to prevent carbon-carbon from being changed to carbon dioxide at high temperatures. One would think that by operating slightly rich fuel there would be no oxygen to combine with the carbon, but to ensure this situation would require a complex control system.

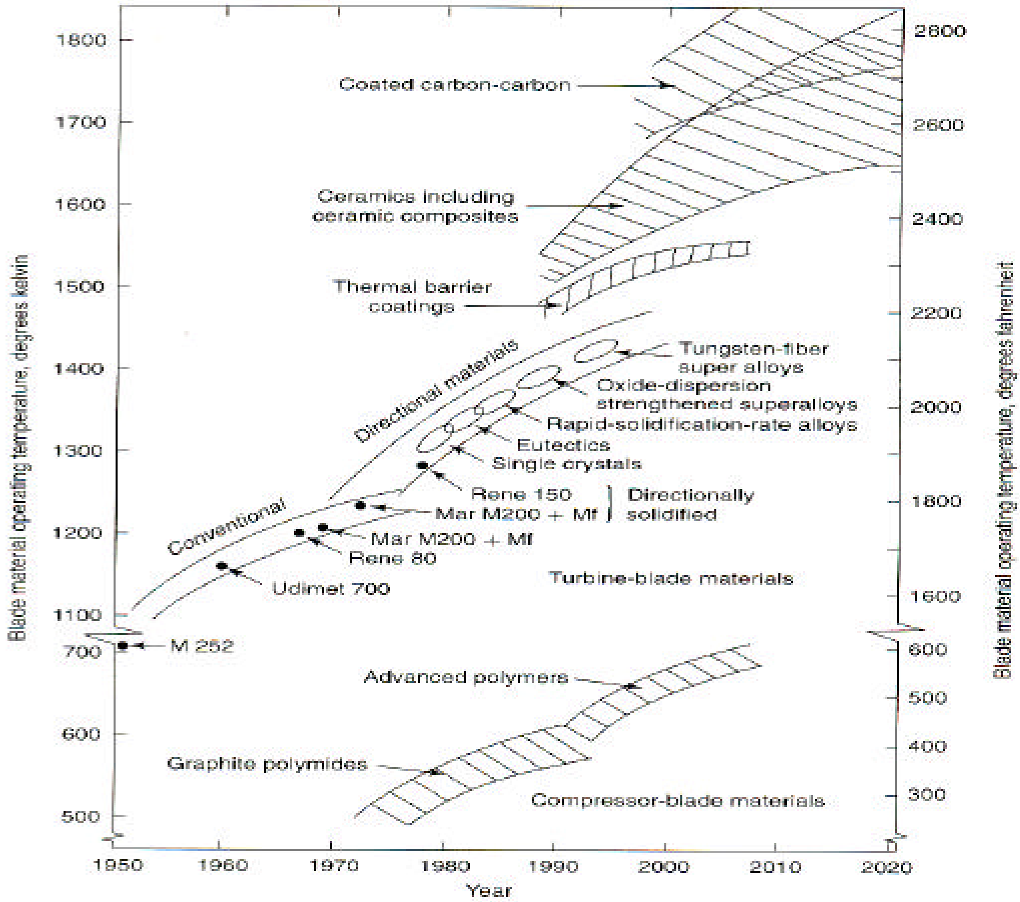

Figure 12: Material Applications

The collection of information in the chart above shows both the materials used up to date from around 1940 and a future forecasting based on NASA sources. (“High-temperature polymer matrix composites”, Aeropropulsion ’87, issue 3049, Cleveland, OH)

6.4.2 Adiabatic Efficiency

Helium turbine and compressor adiabatic efficiencies are only indirectly related to the turbine inlet temperature and are more directly dependent on the volumetric flow and rotational speeds. It is common practice to mechanically connect the turbine and compressor (e.g. through a common shaft) to limit runaway speeds in the event of a loss of load. This limits optimisation of the compressor efficiency, which would perform better at high rotational speeds to compensate for lower volumetric flows.

Splitting the turbine and compressor into two shafts as in the PBMR power conversion system design will give better compressor performance but require development of fast-acting control techniques to protect against rapid load fluctuations.

As a general rule, it is easier to achieve higher adiabatic efficiencies with larger turbine and compressor sizes. Based on turbine aerodynamic sizing calculations, turbine and compressor adiabatic efficiencies of 94% and 92%, respectively, should be achievable for sizes of ~400 MWe after allowing for blade, entrance and exit losses. Increasing the turbine size shifts the development burden to the bearing system for load support and maintenance of rotor dynamic stability. Because of the large number of turbine and compressor stages and the slender aspect ratio of the generator, large helium turbo-compressors tend to be long and flexible. When comparing helium gas turbines with current developments for combustion turbines (such as those used for combined cycle power plants) it is found that because of the high specific heat of helium (approximately 4.4 times more than the typical for flue gases), helium turbines and compressors have a relatively low adiabatic head per stage, and very high enthalpy drop from the inlet to outlet (approximately 6.6 times the corresponding figure for typical flue gases), hence a large number of stages is required for helium turbo-machinery.

The operating speed will be well into the critical speed range. Operation of large turbines above critical speeds is only possible with magnetic bearings, which can actively control stiffness and damping characteristics to adjust the critical speed relative to the operating speed. Such rotors are estimated to weigh up to 100 tonnes and would require between 4-6 radial bearings. The largest rotor suspended to date on magnetic bearings is 23 tonnes and uses 5 active magnetic radial bearings.

7. CONCLUSIONS

- Helium closed-cycle gas turbines appear to be the best technology for HTR based plants

- The overall compression ratio for given cycle parameters can be optimised for maximum cycle efficiency but can also be adjusted to reduce the in-reactor inlet temperature if required for material considerations

- The effect on the gross cycle efficiency of slightly increasing the overall compression ratio past its optimised value is relatively small and can be done to reduce the in-reactor inlet temperature with minimal cycle efficiency penalty

- Based on current technology, this power conversion technique can achieve a short-term gross thermal efficiency of 50%. With technological developments related to turbine and recuperator materials and increases in turbine size, it could be possible to achieve in the medium term (10 to 20 years) a gross thermal efficiency of ~60% on a time scale commensurate with fusion reactor development

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6. *The Design of High-Efficiency Turbomachinery and Gas Turbines*. David Gordon Wilson and Theodosios Korakianitis

7. *Steam and Gas Turbines*. A. Kostyuk and V. Frolov

8. All direct gas-turbine cycle calculations have been performed with Thermodynamic Software Test™

APPENDIX A

GT-MHR AND PBMR BRAYTON CYCLE INPUT DATA

Input data used in this study have been obtained from a wide bibliography. It is important to note that the available information published is not complete.

Variable	Description	GT-MHR	PBMR
T_max (ºC)	Maximum Cycle Temperature	848.0	900.0
T_min (ºC)	Minimum Cycle Temperature	26.1	30.0
P_max (MPa)	Maximum Pressure at HP Compressor Outlet	7.3	7.0
r_{HP}	HP Compressor Pressure Ratio	1.7	1.8
r_{LP}	LP Compressor Pressure Ratio	1.7	1.8
Main Flow (kg/s)	Helium Flow Leaving the Reactor	317.5	140
Bypass Flow (kg/s)	Bypass Flow around the Main Gas Turbine	N/A	6.32
η_T (%)	Gas Turbine Adiabatic Efficiency	93%	90%
η_HPC (%)	HP Compressor Adiabatic Efficiency	87%	90%
η_LPC (%)	LP Compressor Adiabatic Efficiency	88%	90%
ε_{rec} (%)	Recuperator Efficiency	95%	/95%