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Report on the EVO facility and experimental data for the system codes benchmarking exercise.

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Data package on the EVO facility and experimental data for the system codes benchmarking exercise.

Abstract

The Oberhausen II (EVO II) facility is a 50MWe direct-cycle Helium turbine plant which was operated for more than 25000 hours by the utility EVO (Energie Versogung Oberhausen AG, Germany) between the years between 1974 and 1988.
The EVO II offers the opportunity to validate thermo hydraulic safety codes on a large-scale Brayton cycle using available measurements of the state parameters for steady state cases as well as for transients.

The following experiments were performed at EVOII: load following, loss of load, start-up and shut-down.

The aim of this report is to create a data base for validation of transient thermal hydraulic codes within a benchmark exercise.

The EVO II data pack consists of description of the principal cycle data of the Oberhausen helium turbine installation (the first helium turbine ever to be built), description of the various steady states assigned to the plant and two transient simulation analyses. The document is based upon literature recovered as a part on an on-going work in the frame of the European project RAPHAEL.

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
		Data of the EVO loop for benchmark exercise	Ayelet Walter Dr. W. Bernnat (Univ. Stuttgart - IKE Institute)	Walter Van Hove (Suez-Tractebel)	Carmen Angulo (Suez-Tractebel)	Edgard Bogusch (ANP GmbH)
0	10/04/2008					

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Abbreviations

EVO	Energie Versogung Oberhausen
GBP	Gas Bypass Valve
HHT	HTR with Helium Turbine
HICS	Helium Inventory Control System
HP	High Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IC	Inter-Cooler
LP	Low Pressure
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
PC	Pre-Cooler
PCU	Power Conversion Unit
PID	Proportional, integrator and differential
RX	Recuperator

1 EVO Description for Code Modeling

1.1 Introduction - Oberhausen II (EVO)

The Oberhausen II (EVO II) facility is a 50MWe direct-cycle Helium turbine plant which was operated for more than 25000 hours by the utility EVO (Energie Versogung Oberhausen AG) between the years between 1974 and 1988 ([1],[2]). The facility was part of a research and development project which the Federal Government of Western Germany initiated in 1968. The research was performed with international co-operation with the United States and Switzerland, and aimed at the development of helium turbo-machinery that could run on high temperature in a Brayton cycle [3]. Oberhausen II incorporated a gas-fired helium heater instead of a reactor, while all its other components were of the same design as the components of a power plant with nuclear heat source [4].

Although the design and construction of a closed-cycle turbine operated with air were at that time well-known, with the change to helium and the simultaneous need to meet the requirements of a nuclear power plant have caused difficulties in the operation of EVO II. Thus, the helium turbine, which was designed to produce 50MW_e, managed to produce only 30 MW_e. The efficiency of the plant reached only 23 %, instead of the calculated 34.5 % [5]. Since this large deficit was the result of many small ones, no successful reconditioning was possible without the redesign and construction a new turbo machine.

Numerous design specifications, drawings and experimental data have been obtained in the frame of the European HTR-E project, offering a unique opportunity to validate system codes on a large-scale helium Brayton cycle [6].

At Oberhausen II, four steady-state conditions and a several transient conditions have been described. Available measurements of temperatures, pressures and mass flows throughout the circuit have allowed for the simulation the four steady states (e.g., the design plant with 50MW_e, the operating plant with 30MW_e and two partial loads with 20MW_e and 13MW_e) as well as a load following transient. The scenario of the load following regards a change in the electrical power from 10.6MW to 7.6MW due to a decrease in the mass flow rate and due to a change in the helium inventory in the system.

1.2 General Plant Description

As it is depicted from **Figure 1.1**, the plant EVOII consisted of a direct helium Brayton cycle Power conversion unit (PCU) coupled to a gas heater [3]. The inlet temperature into the High Pressure turbine (HPT) was limited to 750°C. A two-shaft design was selected for the turbo-machinery. Thus, the HPT was designed to drive both High Pressure Compressor (HPC) and Low Pressure Compressor (LPC) on a common shaft running at a speed of 5500 rpm, and the low Pressure turbine (LPT) was connected to the generator on a separate shaft running at 3000 rpm. The shafts are interconnected via a gearbox. The recuperator (RX) of this plant is a high-efficiency baffled shell-and tube heat exchanger. With a surface which consisted of 17500 tubes it was designed to deliver 130 MW of heat. The Pre-cooler (PC) is a gas-to-water heat exchanger subdivided into a heating section and a cooling section. The inter-cooler (IC) is designed in a similar way but contains only a cooling section. It must be denoted that the leakages and bypass flows which account for the difference in mass flows across the circuit are not shown in the figure.

In normal load conditions, the circuit contains 1300 kg of helium.

Technical Data for EVO II (design) [5]:

Working medium	Helium
Terminal output	50 MW (30 MW achieved)
Hot gas temperature	750 °C
Pressure in front of the turbine	27 bar
Base pressure	10 bar
Helium flow	84.4 kg/s
Speed	5500/3000 rpm
Heating output	53.5 MW
Fuel utilization	65 %
Fuel	Coke oven gas
Cooling	District heat / cooling tower
Efficiency	34.5 % (23 % achieved)

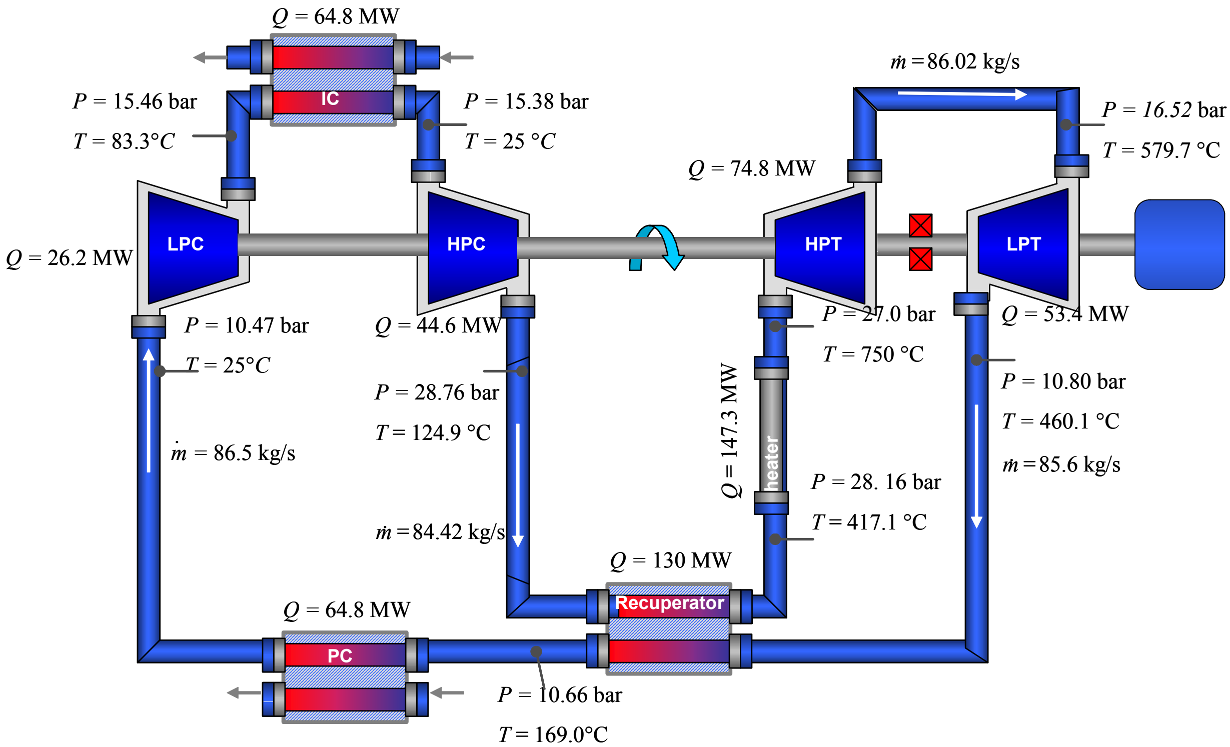


Figure 1.1: EVO II flow diagram (operating conditions).

<u>EVO II design performance - supplementary data:</u>

Heater power:	147.2MW
Pre-cooler (PC) power:	- 64.8 MW
Intercooler (IC) power:	-26.1 MW
Cold duct and hot duct cooling:	-2.6 MW
Leakages dissipated power:	-1.4 MW
Power available on the shaft:	52.3 MW

Turbo-machinery global friction: -1 MW

Alternator dissipation : -1.3 MW

Electrical power available : 50 MW

Referring to the cycle diagram of the EVO II plant (shown in **Figure 3.1**): the working fluid helium is compressed in the LPC (f), cooled in the intercooler (IC) (g), and then raised to maximum process pressure in the HPC (h). Then it is preheated in the recuperator (d), followed by final heating to the maximum process temperature in the coal fired helium heater (a). In the HPT (b), the working fluid is expanded and then it is further expanded in the LPT (c). In the PC (e), the helium is returned to its starting conditions. The PC is divided into two parts: the heating part (e'), which transfers heat from the working medium to the hot water of the heating network and the cooling part (e''), which transfer heat to the atmosphere. The turbo set is coupled to two shafts. The alternator runs by grid frequency. The HPT and the LPT and generator (i) shaft are coupled via the gearbox, k.

Figure 1.1 shows the circuit with the corresponding measured values (nominal operation conditions) which were observed during the plant operation. Compared with the heater thermal power of the design case, here only 135.6 MW_{th} was achieved. It can be seen that the variation in masse flow rates along the circuit are greater than in the design case of , due to leak flows and bypass flows which were greater than expected according to the design values. As it mentioned, the EVO II, which was designed to produce 50 MW_e only managed 30 MW_e [5]. This large deficit was caused by many factors. The turbo-set had a rather low output and the low speed of only 5500 rpm (which is adequate for air) resulted in very unfavorable hub to tip ratios for the compressors and the turbines, which led to poor isentropic efficiencies in the turbo-machines. In addition, the cycle pressure losses were excessive, especially the cooling and sealing mass flows as mentioned before, by a factor of four.

Despite of the deficiency in the performance of the plant, the EVO decided to accept the helium turbine from the manufacturer. This decision was made because helium-specific experiences could nevertheless be gained with the actual plant conditions, and because the plant could be operated as a co-generation plant satisfying the required district heat demand [3].

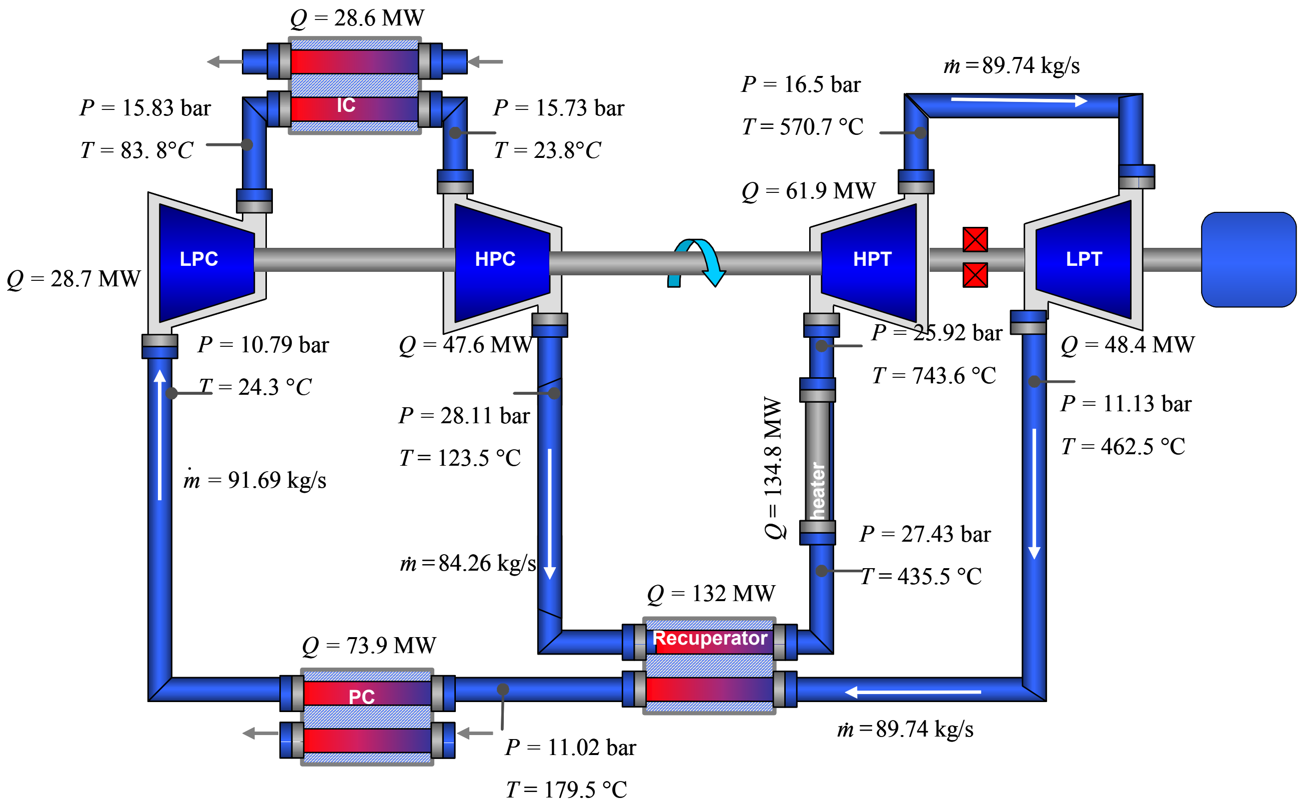


Figure 1.2: EVO II flow diagram (operating conditions).

The following table indicates the different factors which had the greatest influence on the reduced performance of the plan, as they were given by Bammert [7].

Table 1.1: Major factors which contributed to the EVO II decreased power output.

	Design	**Measured**	**ΔEfficiency on generator output**	**ΔPower on generator output**
HPT efficiency	88.3%	82.3%	- 2.29%	- 3.9 MW
LPT efficiency	90.0%	85.6%	- 1.43%	- 2.4 MW
HPC efficiency	85.5%	77.9%	-2.40%	- 4.0 MW
LPC efficiency	87.0%	82.6%	-0.95%	- 1.3 MW
Pressure losses	10.2%	12.8%	-1.37%	- 2.6 MW
Leakage + Cooling	1.78 kg/s	7.53 kg/s	-3.67%	- 5.3 MW
Turbo-machine input temperature HPT/LPC/HPC	750°C/ 25°C/ 25 °C	743.6°C/ 24.3°C/ 24 °C	-0.14%	- 0.4 MW
ΔT Recuperator	3.0°C	8.7°C	-0.5%	- 0.3 MW
Total			**-12.75%**	**- 20.2 MW**

It must be added that the retrieval of additional documents would allow for the extensions of the data pack for code validation and benchmarking. A contract recently signed by AREVA is on the way to EVO for countersignature. This contract will make data such as turbo-machines characteristics, valve characteristics and more information about transient analysis available for the partners.

2 Major Components and Piping

2.1 Loop Piping

2.2.1 Piping Layout

The main connecting pipes in the EVO II are introduced in the following figure (**Figure 2.1**).

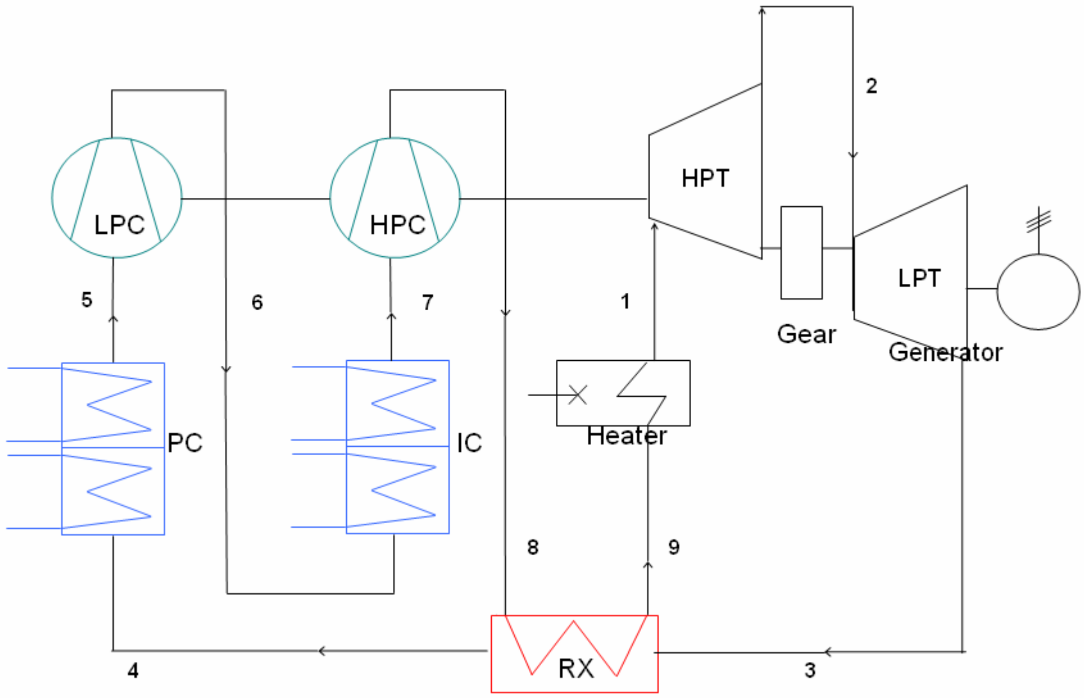


Figure 2.1: the EVO helium turbine – numbering of the main pipe lines.

Information about the pipe diameters is given in **Table 2.1**.

Table 2.1: EVO Main line characteristics.

Pipe #	Description	Diameter (m)
1	From heater to HPT	
2	From HPT to LPT	
3	From LPT to RX	1.4
4	From RX to PC	1
5	From PC to LPCM	0.9
6	From LPC to IC	0.9
7	From IC to HPC	0.8
8	From HPC to RX	0.6
9	From RX to heater	0.65

2.2 Major Plant Components

2.2.1 Recuperator

The main design parameters for the recuperator are given in the following table **Table 2.2**. A figure describing the RX is given in Appendix 1.

Table 2.2: Main design parameters of recuperator (RX).

Parameter	units	Design value
Number of baffles		30
Number of tubes		17430
Heat exchange area	m^2	18.54
Length (shell)	m	14,655
Volume (inlet, HP side)	m^3	8.65
Volume (outlet, HP side)	m^3	8.65
Volume (inlet, HP side)	m3	43.8
Volume (outlet, HP side)	m^3	38.1
Diameter (shell)	m	4.44
Diameter (bundle)	m	3.9
Tube wall thickness (internal)	mm	10
Tube wall thickness (external)	mm	12
Tube material		classic steel with elastic limit of 35.8

2.2.2 Precooler

The main design parameters for the PC are given in the following table **Table 2.3**. A figure describing the PC is given in Appendix 1.

Table 2.3: Main design parameters of the Pre-cooler (PC).

Parameter	units	Design value
Number of tubes (cold side)		1560
Number of tubes (hot side)		1248
Heat exchange area (cold side)	m^2	6000
Heat exchange area (hot side)	m^2	5000
Length (shell)	m	8.78
Volume (inlet)	m^3	24.5
Volume (outlet)	m^3	12.7
Diameter (shell)	m	3.6
Tube wall thickness (internal)	mm	10
Tube wall thickness (external)	mm	12
Tube and fin material		CuNi30Fe+Al

The main input parameters for the water side of the PC are given in **Table 2.4**.

Table 2.4: Design data for the water side of the Pre-cooler (PC).

Water parameters	units	Design value
Water inlet temperature (cold side)	°C	20
Water outlet temperature (cold side)	°C	40
Water inlet pressure (cold side)	bar	8
water mass-flow (cold side)	kg/s	159.72
Water inlet temperature (hot side)	°C	40
Water outlet temperature (hot side)	°C	120
Water inlet pressure (hot side)	Bar	12
water mass-flow (hot side)	kg/s	159.72

2.2.3 Intercooler

The main design parameters for the IC are given in the following table **Table 2.5**. A figure describing the IC is given in Appendix 1.

Table 2.5: Main design parameters of the Inter-cooler (IC).

Parameter	units	Design value
Number of tubes		2430
Heat exchange area	m^2	3900
Length (shell)	m	7.35
Volume (inlet)	m^3	19.3
Volume (outlet)	m^3	9.78
Diameter (shell)	m	3.3
Tube wall thickness (internal)	mm	10
Tube wall thickness (external)	mm	12
Tube and fin material		CuNi30Fe+Al

The main input parameters for the water side of the IC are given in **Table 2.6**.

Table 2.6: Design data for the water side of the intercooler

Water parameters	units	Design value
Water inlet temperature	°C	20
Water outlet temperature	°C	40
Water inlet pressure	bar	8
Water mass-flow	kg/s	311.94

2.2.4 Heater

The detailed description of the heater is demonstrated in a figure in Appendix 1. The gas-air mixture is burnt in the cyclone combustion chambers (a), from which the hot flue gases enter the radiant heater (b). From here it flows via the convection heaters, c, d and g to the air pre-heater, which is not shown in the drawing. The cold helium enters at f_1 and f_2. The helium entering at f_1 flows via g, and the connection pipes m. From h the helium flows through ducts (which are not shown) to I and from there via d to the outlet header k, which for strength reasons consists of two drums arranged side by side.

The heater conceived according to forced circulation principle has a mass flow rate at normal operating load of 84.42 kg/s. in the heater, the helium temperature is raised from 417°C to 753°C (at nominal operating conditions). For the tubes in the flue gas room a high alloy austenitic material with 40% nickel, 20.5% chromium and 8% cobalt (INCOLOY 807) was used. The end-heater consists of 110 parallel tubes with a diameter of 42.4 mm. the tube material is INCOLOY 807.

The protective screen consists of 200 parallel tubes made of INCOLOY 807 with a tube diameter which varies between 54.57mm and 63.5 mm.

The gas plenum is an independent unit with simple geometrical dimensions.

The pre-heater consists of 1016 parallel tubes with the following material specifications: at the inlet: 13CrMo44 and at the outlet: INCOLOY 807.

Referring to the demonstrative figure of the heater cross-section as it appears in Appendix 1, the following heating areas are known:

b	155 m^2
c	171 m^2
d	1270 m^2
e	42 m^2
g	4070 m^2

The total heating area is therefore 5780 m^2.

Various design data for the heater are represented in the next tables. These all address the figure below **(Figure 2.2)**.

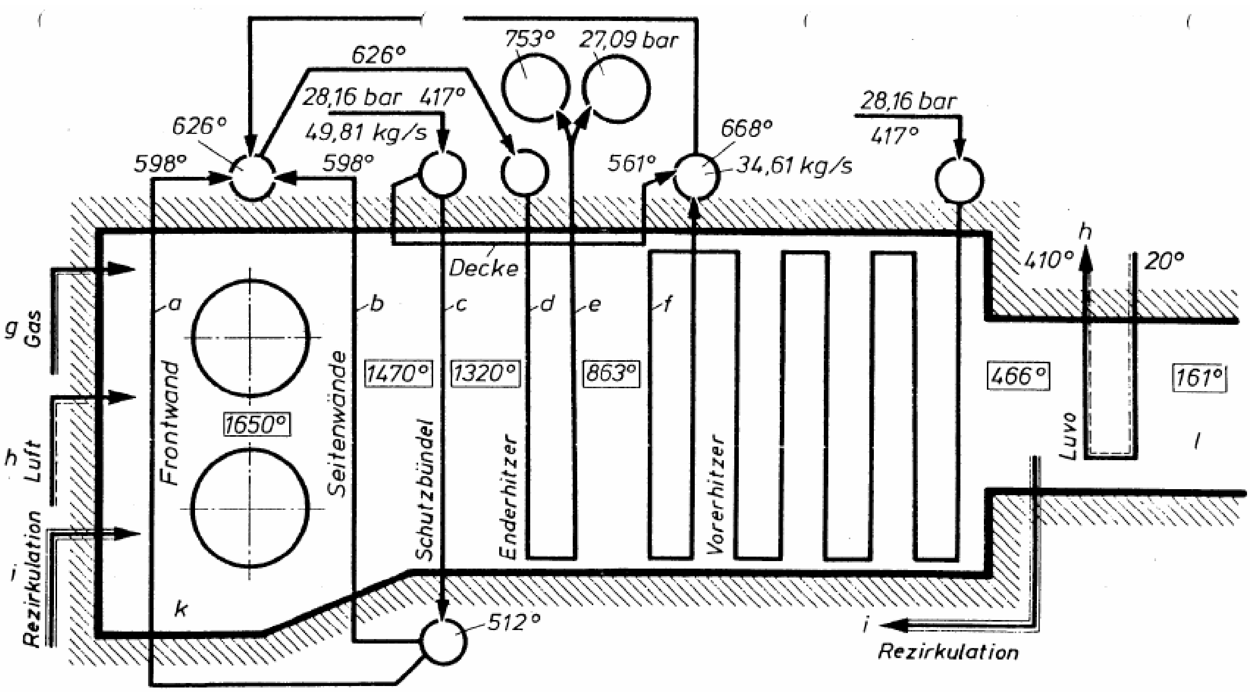


Figure 2.2: circuit diagram of the helium heater with un-cooled combustion chamber.

Table 2.7: gas volumes in the helium heater.

Location	Gas type	100% load - volume (nm^3)
g	Fuel gas	34485
h	Fuel air	144869
i	Recirculation	85500
k	Flue gas	261730
i	Exhaust gas	193025

Table 2.8: gas temperatures in the helium heater.

Flue gas	100% load - temperature in °C
In gas plenum	1650
Before protective screen	1470
Before end-heater	1320
After end-heater	863
Before air pre-heater	466
After air pre-heater	161

Table 2.9: tubes wall temperature in helium heater.

Tubes wall temperature t_w (m=middle, max=maximum)	Location	100% load - temperature in °C
Front wall Gas plenum	a	$t_{w,m}=751$
		$t_{w,max}=764$
Side wall Gas plenum	b	$t_{w,m}=789$
		$t_{w,max}=802$

Front wall Protective screen	c	$t_{w,m}$=750 $t_{w,max}$=771
Front wall End- heater	d	$t_{w,m}$=798 $t_{w,max}$=804
Back wall End- heater	e	$t_{w,m}$=804 $t_{w,max}$=808
Front wall Pre-heater	f	$t_{w,m}$=705 $t_{w,max}$=708

2.2.5 Turbo-machines

Turbo-machines characteristics at the design point are introduced in the following tables (**Table 10-Table 2.13**):

Table 2.10: LPT characteristics at the design point.

Parameter	units	Design value
Pin	16.47	bar
Pout	10.80	bar
Tin	579.7	°C
Tout	460.1	°C
Rotational speed	50.0	rps
Mass flow	86.02	kg/s
Isentropic efficiency	0.9	%

Table 2.11: LPC characteristics at the design point.

Parameter	units	Design value
Pin	10.49	bar
Pout	15.48	bar
Tin	25.0	°C
Tout	83.3	°C
Rotational speed	91.667	rps
Mass flow	86.53	kg/s
Isentropic efficiency	0.87	%

Table 2.12: HPC characteristics at the design point.

Parameter	units	Design value
Pin	15.38	bar
Pout	28.76	bar
Tin	25.0	°C
Tout	124.9	°C
Rotational speed	91.667	rps
Mass flow	86.02	kg/s
Isentropic efficiency	0.855	%

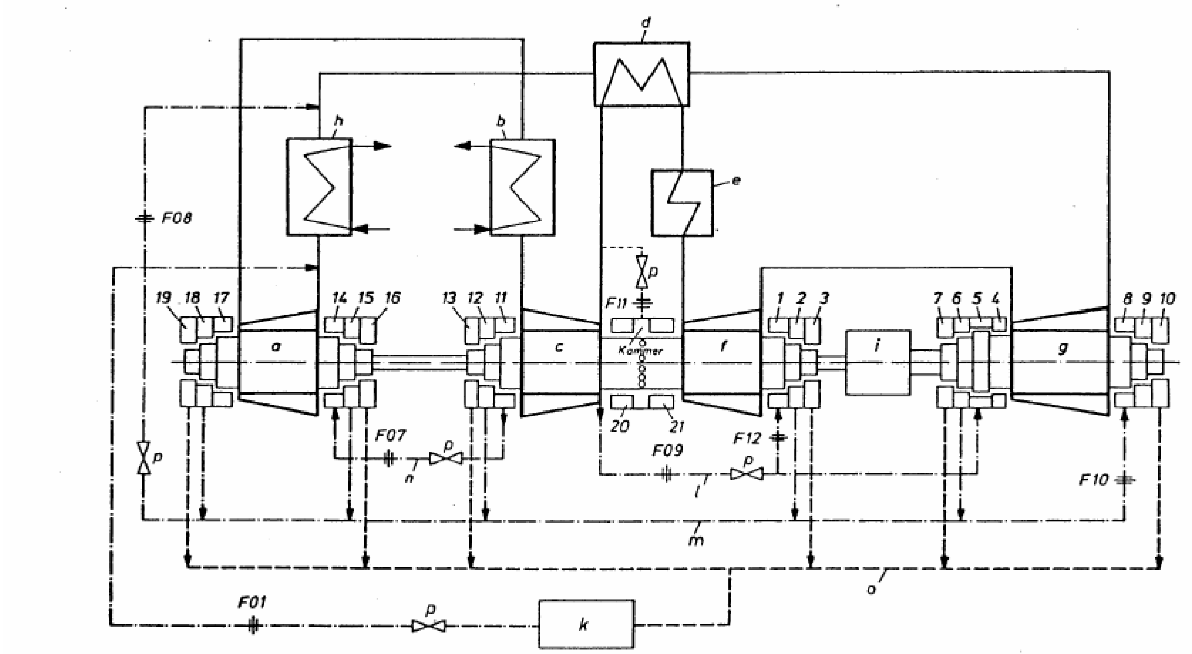
Table 2.13: HPT characteristics at the design point.

Parameter	units	Design value
Pin	27.0	bar
Pout	16.52	bar
Tin	750.0	k
Tout	579.7	k
Rotational speed	91.667	rps
Mass flow	84.42	kg/s
Isentropic efficiency	0.883	%

2.2.6 Leakage Flows and Re-injections

Actual leak flows paths in the EVO plant are from the HPC to the HPT to cool the flow entering the turbine and in addition re-injection of helium from the labyrinth seal of the LPT into the circuit occurred.

The measurement locations of the cooling flows and the re-injections flows which were identified in the EVO are demonstrated in **Figure 2.2**.



a LPC	g LPT	o Oil-helium-backflow	—— Helium flow in circuit
b IC	h PC	p Control valve	-·-·-· Labyrinth helium
c HPC	i Gearbox	f Throughput measuring points	----- Oil-helium-mix
d Recupertor	k Oil-helium separation	1-21 Labyrinth seals	.... External cooling gas flow
e Heater	l HP-runner		
f HPT	m LP-runner		

Figure 2.3: labyrinth seals system.

The corresponding mass flow rates at the measurement locations are exhibited in **Table 2.11** and **Table 2.12**.

Table 2.14: data for the secondary system measurements.

Location of measurement	Measure	13 MWe	20 MWe	30 MWe
Helium flow from oil-He separation F01	P (bar)	6.3	8.4	11.7
	T (°C)	20.0	22.5	14.0
	$\dot{m}$ (kg.s^{-1})	0.13	0.17	0.22
F07	P (bar)	6.5	8.8	12.3
	T (°C)	20.0	39.0	36.0
	$\dot{m}$ (kg.s^{-1})	0.03	0.06	0.08
LP-Labyrinth gas F08	P (bar)	6.5	8.6	11.8
	T (°C)	86.0	87.0	86.0
	$\dot{m}$ (kg.s^{-1})	0.46	0.97	1.58;1.61;1.64
HP-Labyrinth gas injection F09	P (bar)	13.2	19.2	28.0
	T (°C)	137.0	135.0	132.0
	$\dot{m}$ (kg.s^{-1})	1.47	2.22	3.03
HP- Labyrinth gas to HPT outlet side F12	P (bar)	8.1	11.8	16.8
	T (°C)	80.0	80.0	79.0
	$\dot{m}$ (kg.s^{-1})	0.43	0.61	0.82
LP- Labyrinth gas to LPT outlet side	P (bar)	6.5	8.6	11.8
	T (°C)	92.0	92.0	87.0
	$\dot{m}$ (kg.s^{-1})	*0.21*	*0.21*	0.22

Table 2.15: complete arrangement of the labyrinth and injection mass flows

	Mass flow	13 MWe	20 MWe	30 MWe
Helium flow from oil-He separation F01	$\dot{m}$ (kg.s^{-1})	0.10	0.18	0.22
LP-Labyrinth gas F08	$\dot{m}$ (kg.s^{-1})	0.44	0.96	1.58
HP-Labyrinth gas injection F09	$\dot{m}$ (kg.s^{-1})	-1.40	-2.22	-3.03
HP-extreme cooling F11	$\dot{m}$ (kg.s^{-1})	0.0	0.0	0.0
Labyrinth 1	$\dot{m}$ (kg.s^{-1})	0.25	0.40	0.50
Labyrinth 4	$\dot{m}$ (kg.s^{-1})	0.35	0.62	0.76
Labyrinth 8	$\dot{m}$ (kg.s^{-1})	0.26	0.16	0.20
Labyrinth 11	$\dot{m}$ (kg.s^{-1})	-0.04	-0.06	-0.07
Labyrinth 14	$\dot{m}$ (kg.s^{-1})	0.03	0.05	0.07
Labyrinth 17	$\dot{m}$ (kg.s^{-1})	-0.05	-0.08	-0.12
Labyrinth 20	$\dot{m}$ (kg.s^{-1})	-0.2.10	-3.10	-0.45
Labyrinth 21	$\dot{m}$ (kg.s^{-1})	0.36	0.44	0.70

Remarks: positive mass flow is injected into the circuit; negative mass flow in extracted from the circuit.

3 Experimental Data Description

3.1 Steady States

In addition to the design nominal point (50 MWe); the operational-nominal steady states of the EVO II are the following:

- The operating nominal point (30 MWe);
- Two operating partial loads (20MWe and 13MWe);
- One operating partial load corresponding to the nominal point of the load following transient.

The performance data for the reference case were viewed in numerous publications ([1], [8]). Calculations of the four nominal states are based upon the information which was first established in 1972. Calculations of the partial load of the plant are based on the description of the plant during its operation time [2].

Table 3.1 depicts the cycle main thermal-hydraulic parameters for the nominal cases listed above with reference to Bammert [7].

Table 3.1: EVO nominal operational cases: thermal-hydraulic parameters for 30 MWe, 20 MWe and 13 MWe (CEA contribution).

Component	Measure	13 MWe	20 MWe	30 MWe
LP Compressor	P_{in} (bar)	5.15	7.51	10.79
	T_{in} (°C)	24	24.8	24.3
	P_{out} (bar)	7.58	10.97	15.83
	T_{out} (°C)	85.7	85.1	83.8

HP Compressor	P_{in} (bar)	7.68	10.95	15.73
	T_{in} (°C)	24	24.3	23.8
	P_{out} (bar)	13.74	19.57	28.11
	T_{out}(°C)	124.7	124.1	123.5
Recuperator (HP side)	T_{in} (°C)	136.9	134.3	132.2
	P_{out} (bar)	13.46	19.23	27.63
	T_{out} (°C)	435.1	436.1	433.6
Heater	P_{in} (bar)	13.3	19.09	27.43
	P_{out} (bar)	12.68	18.22	26.22
	T_{out} (°C)	739.2	743.9	742.5
	$\dot{m}$ (kg.s^{-1})	41.1	58.5	84.2
HP Turbine	P_{in} (bar)	12.62	18.04	25.92
	T_{in} (°C)	740.2	745.1	743.6
	P_{out} (bar)	7.94	11.43	16.50
	T_{out} (°C)	562.8	570.4	570.7
LP Turbine	P_{out} (bar)	5.34	7.80	11.13
	T_{out} (°C)	448.6	461	462.5
Precooler	P_{in} (bar)	-	-	11.02
	T_{in} (°C)	177.2	178.3	179.5
Alternator	*Power (MWe)*	*12.9*	*20.1*	30.5

3.2 Transient Cases

Referring to **Figure 3.1**: the valve S_1 serves to feed helium from storage tanks into the piping upstream the LPC, and valve S_2 serves to extract helium from the piping downstream the HPC, respectively. The inlet valve, S_1, is used for power increase, and the outlet valve, S_2, is used for decreasing the load. In this manner the pressure level of the circulating working medium is controlled (so-called inventory control). The bypass valves, r_1 and r_2, serve for short-term power decrease and for maintaining the heating power at low electric power requirements.

3.2.1 Load Following Transient

Load following is a principle way to control the power output of the plant. By extracting helium from the main circuit and storing it, the pressure level in the circuit varies, and thus the power is affected and lessened. In the current transient participate both helium two tanks with a volume of 120 m^3 each and initial temperature of 12.3 °C. The initial pressures assigned to the tanks are 1075 kPa and 264 kPa for the first tank (1) and the second tank (2) respectively. The steady state conditions from which the transient starts are a plant mass flow rate of 51.9 kg/s, power output of 10.6 MW_e and maximum pressure of 1660 kPa. More specifications are given at **Table 3.2.**

Table 3.2: EVO nominal point of the load following transient (CEA contribution).

T (°C) HPT_{in}	**T (°C) HPT_{out}**	**T (°C) LPT_{out}**	**T (°C) HPC_{in}**	**T (°C) HPC_{out}**	**T (°C) LPC_{in}**	**T (°C) LPC_{out}**	**T(°C) PC_{in}**
745.5	575.2	467.6	20.4	84.2	21.8	120.9	180
P (bar) HPT_{in}	**P (bar) HPT_{out}**	**P (bar) LPT_{out}**	**P (bar) HPC_{in}**	**P (bar) HPC_{out}**	**P (bar) LPC_{in}**	**Power (MWe)**	**Q_m Heater (kg/s)**
15.5	9.8	6.6	16.2	6.5	9.4	10.6	51.9

The time events of the transient are the following:

- At time t= 0s: beginning of the transient.
- At time t= 231s: opening the valves the HPC outlet and tank 1.
- At time t= 515s: closing the valves connecting the HPC outlet and tank 1.
- At time t = 597s: opening the valves connecting the HPC outlet and tank 2.
- At time t= 1170s: closing the valves connecting the HPC outlet and tank 1.
- At time t= 1200s: end of the transient.

The system layout and control devices as depicted for the EVO II plant are shown in **Figure 3.1.**

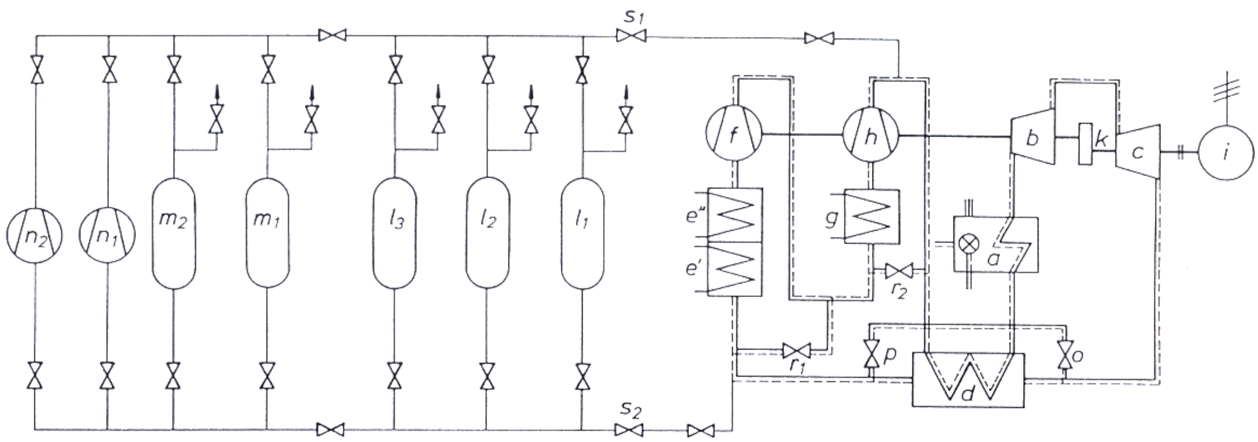


Figure 3.1: the EVO II system layout and control devices.

Available data for a comparison code-to-experience

The following thermal-hydraulic parameters are given as a function of time:

1. Mass flow rate in primary loop;
2. HPT Outlet pressure;

3. HPT Inlet pressure;
4. LPC Outlet pressure;
5. LPC Inlet pressure;
6. HPC Outlet pressure;
7. LPT Outlet pressure;
8. Generator electrical power;
9. Pressure in tank1;
10. Pressure in tank 2;
11. Temperature in tank 1;
12. Temperature in tank 2;

The corresponding excel files are given in Appendix 2 **(CEA contribution).**

Remarks:

- For this transient it is justified to apply scaled turbo-machines curves, as they maintain their nominal design point.
- The tank 1 and tank 2 seem to be cooled. However, the exact data for the cooling are not provided in the literature.

3.2.2 Loss of Load Transient

- At t = 0s: The generator is disconnected from the grid. In addition, the following actions take place:

1. The by-pass line r1 is being fully opened (this valve is located between HPC outlet and PC inlet, see **Figure 3.1**)

2. The by-pass line r_2 is being partially opened (this valve is located between the HPC outlet and the recuperator LP side inlet), in order to avoid thermal stresses at the recuperator inlet.
3. A shutdown of the heater

Available data for a comparison code-to-experience

The following thermal-hydraulic parameters are given as a function of time:

1. Turbo-machinery rotational speed;
2. Heater mass flow rate;
3. Heater inlet and outlet temperatures;
4. LPT outlet temperature;
5. HPT Inlet pressure;
6. LPT Outlet pressure;
7. Bypass valve outlet temperature;

The accuracy of the different parameters has been estimated: ~5°C, ~0.2b, ~2kg/s, ~2% for the turbo-machinery rotational speed.

The corresponding excel files are given in Appendix 3.

4 References

[1] Bammert, K., Krey, G. und Krapp, R., 1974. Die 50-MW-Heliumturbine Oberhausen, 19th Annual International Gas Turbine Conference and Products show, Schweizerische Bauzeitung, 92 Jahrgang, Heft 11, 14. März 1974, 235-240.

[2] Bammert, K, Johanning, J., and Weidner, E. 1983. Instrumentierung und Verfahren zur Messung des dynamischen Verhaltens der Heliumturbinenanlage Oberhausen. Atomkernenergie-Kerntechnik, 43 (4), 225-239.

[3] Weisbrodt, I.A., 1995. Summary report on technical experiences from high temperature helium turbo-machinery testing in Germany, Proceedings of Technical Committee meeting on Design and Development of gas-cooled reactor with closed cycle gas turbines, Beijing, China, 30 October – 2 November 1995, pp. 177-250.

[4] Bammert, K., September 1975. A general review of closed cycle gas turbines using fossil, nuclear and solar energy, Theimig-taschenbücher, ban 57, Verlag Karlthiemig, münchen.

[5] Frutschi, H. U., "Closed-cycle gas turbines operating experience and futurepotential", ASME, 2005.

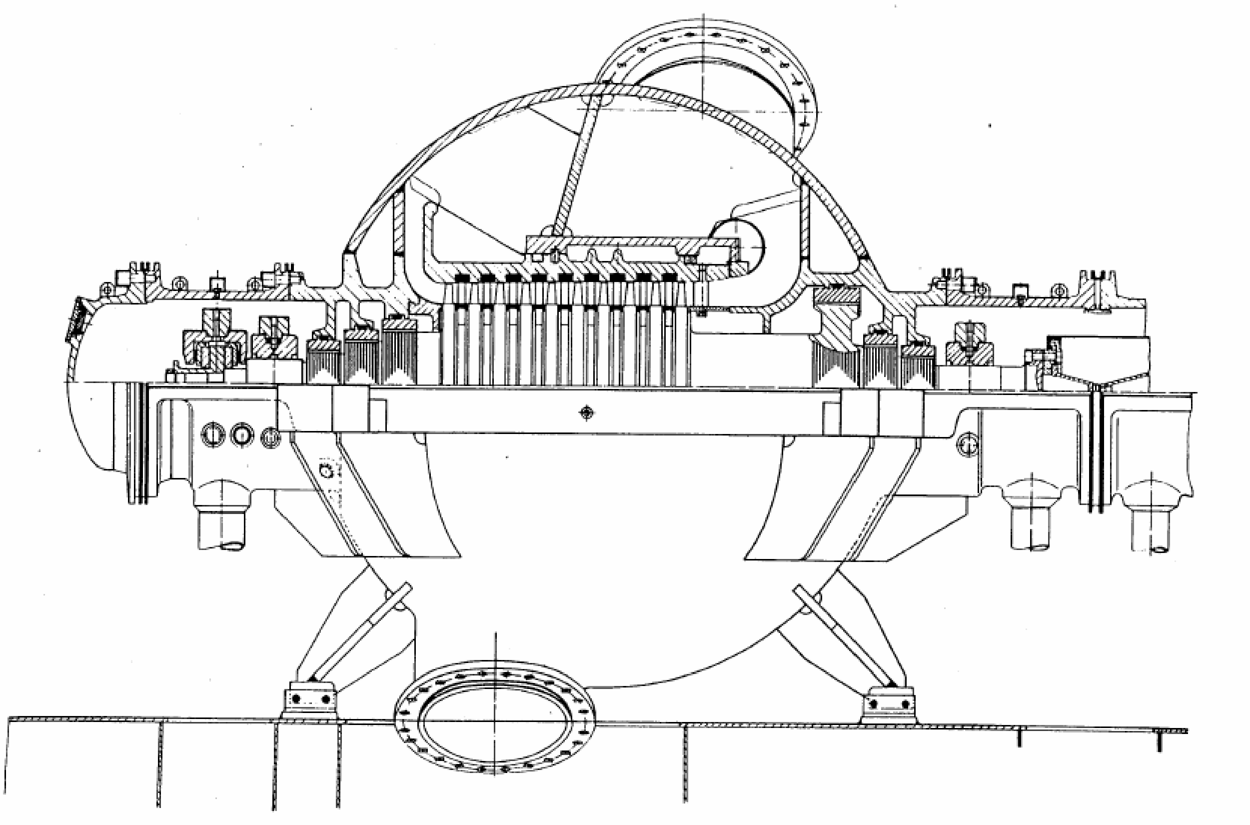
[6] Bentivoglio, F. and Geffraye, G., 2006. Validation of the CATHARE code against experimental data from Brayton cycle plants. Proceeding of HTR 06. October 1-4, 2006. Johannesbourg, South Africa.

[7] Bammert, K., 1988. Beitrag zur Dokumentation über die 50 MW-Heliumturbinenanlage ("Obheiz 2"). Draft technical report, Inst. für Strömungsmaschinen, Universität Hannover.

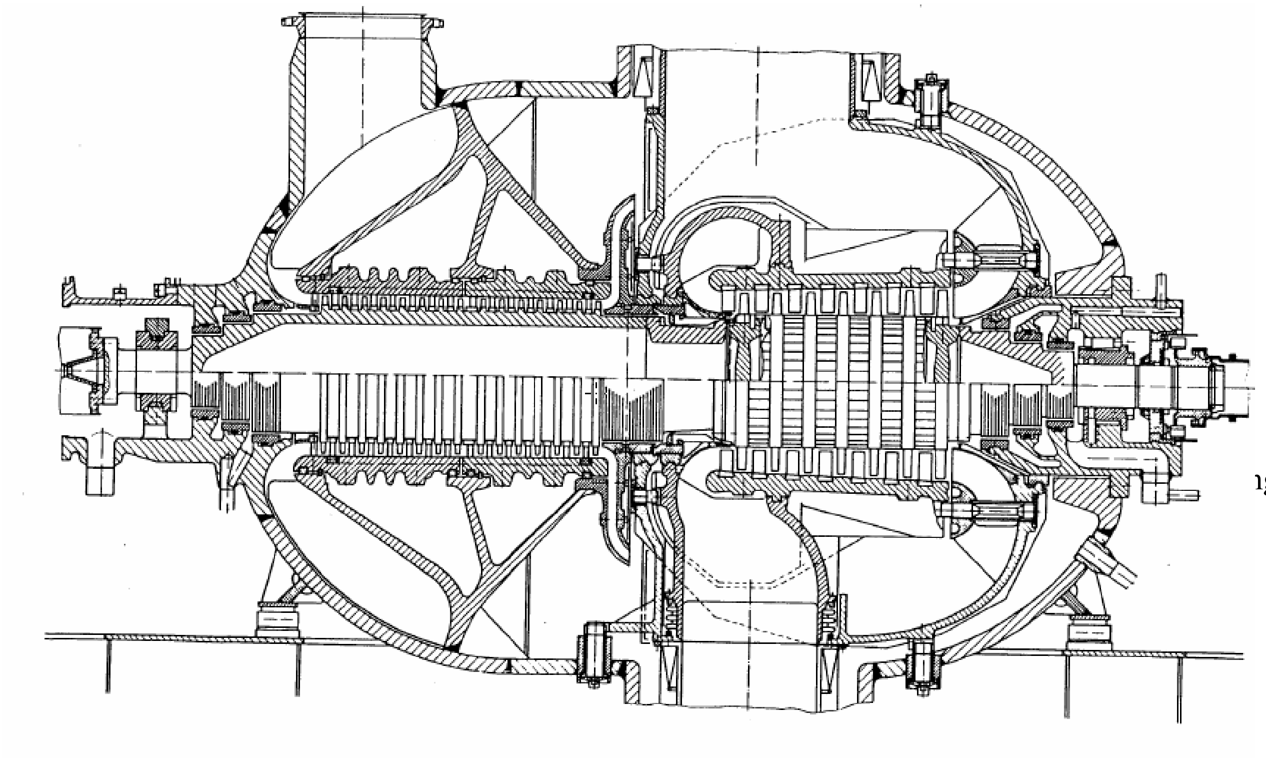
[8] Zenker, P., 1988. 10 Jahre Betriebserfahrung mit der Heliumturbinenanlage Oberhausen, VGB Kraftwerktechnik 68, heft 7, Juli 1988.

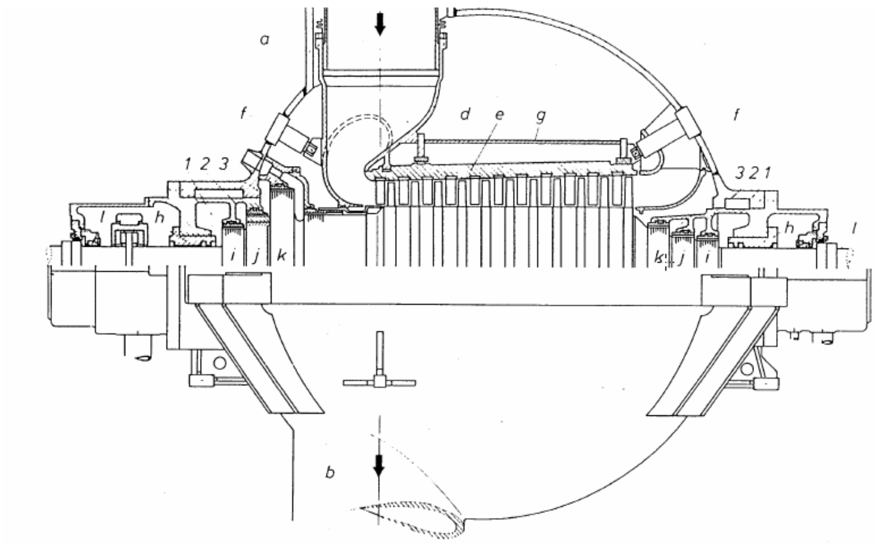
Appendix 1 – Major Components Figures

1. LPC



2. HPC and LPT





a Inlet nozzle

b Outlet nozzle

c Outer housing

d Inlet housing

e Stationary blade carrier

f Screw bolts

g Sheet plate envelope

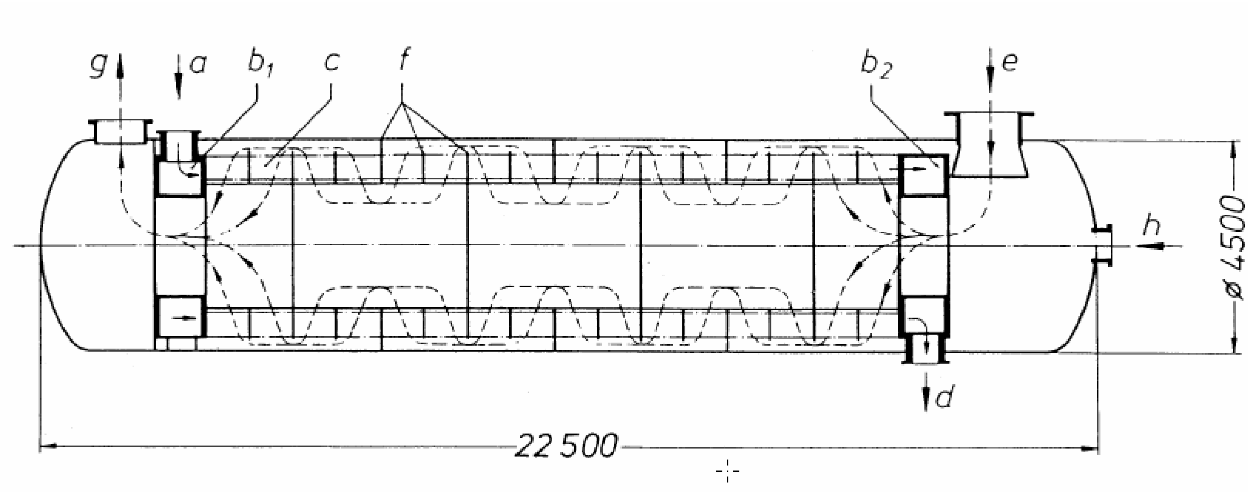
h Radial bearing

i,j,k 3-stage labyrinth seal

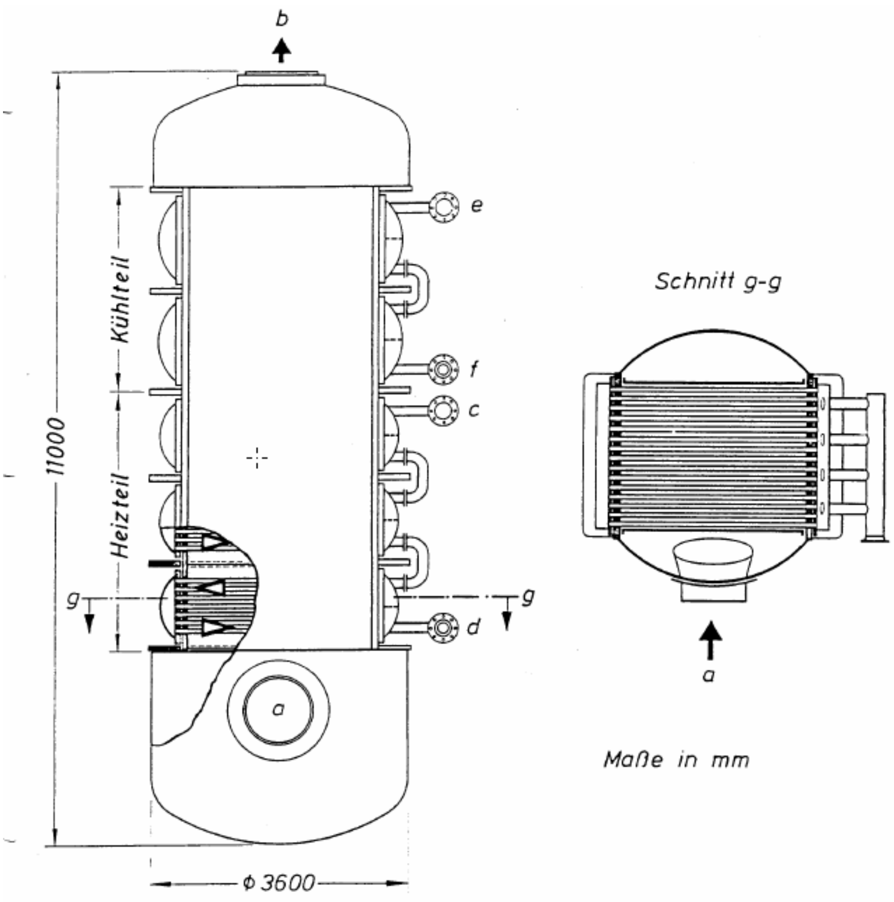
l Floating ring seal and still- stand seal

1,2,3 Labyrinth chambers

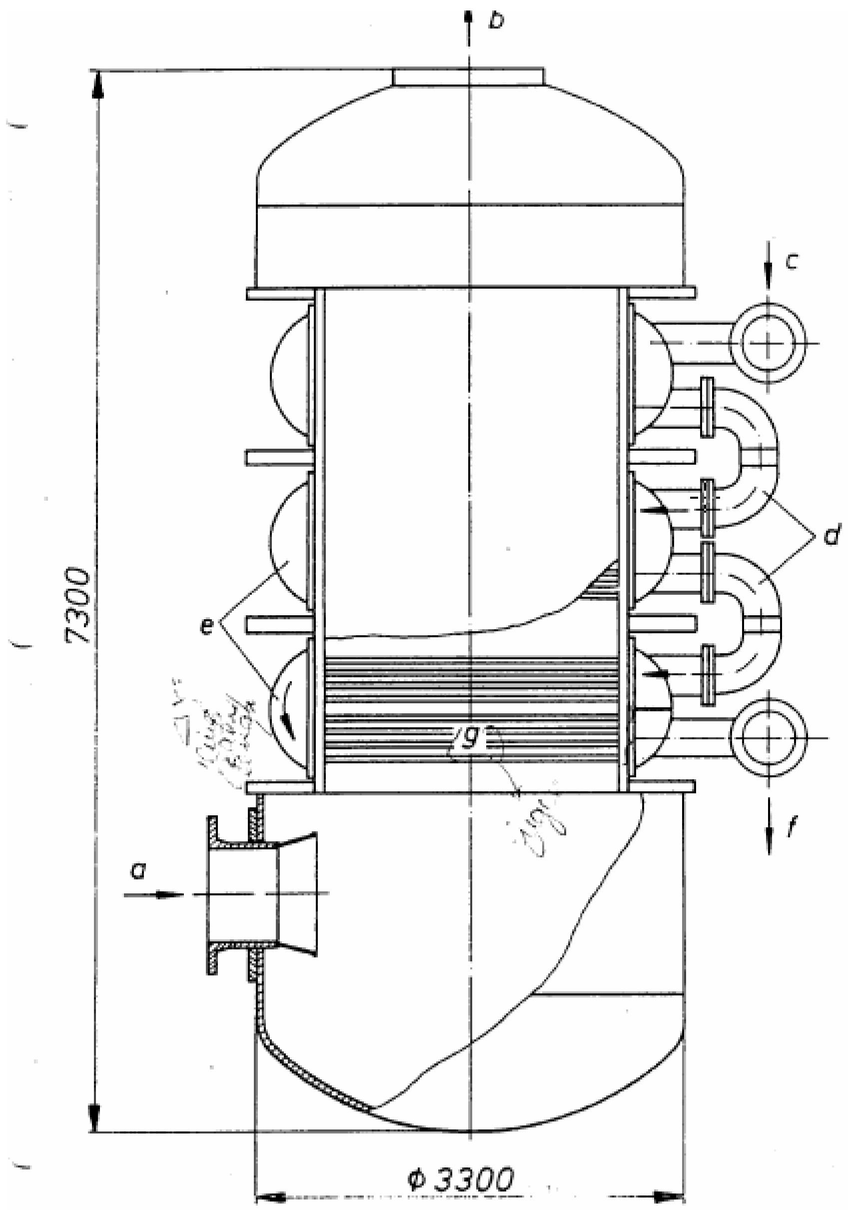
4. Recuperator



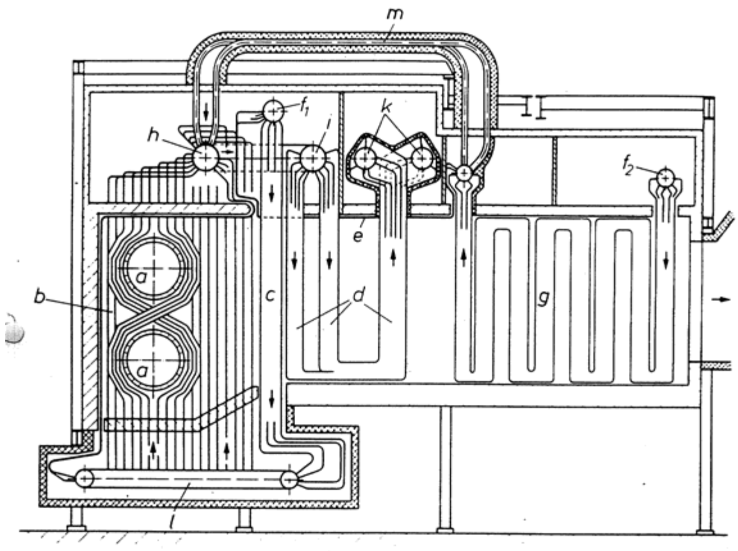
5. PC



6. IC



7. Heater



Gas heater

(a) combustion chamber,
(b) gas plenum,
(c) protective screen,
(d) end heater,
(e) cover heater,
(f1), (f2) inlet collectors,
(g) pre-heater,
(h) mixing collector,
(i) final heater inlet,
(k) final heater outlet,
(l) gas area distributor collecting tank,
(m) connecting tubes.

Appendix 2 –Load Following Transient

All the experimental data provided in this data pack have been derived from these 4 following Figures **(CEA contribution)**:

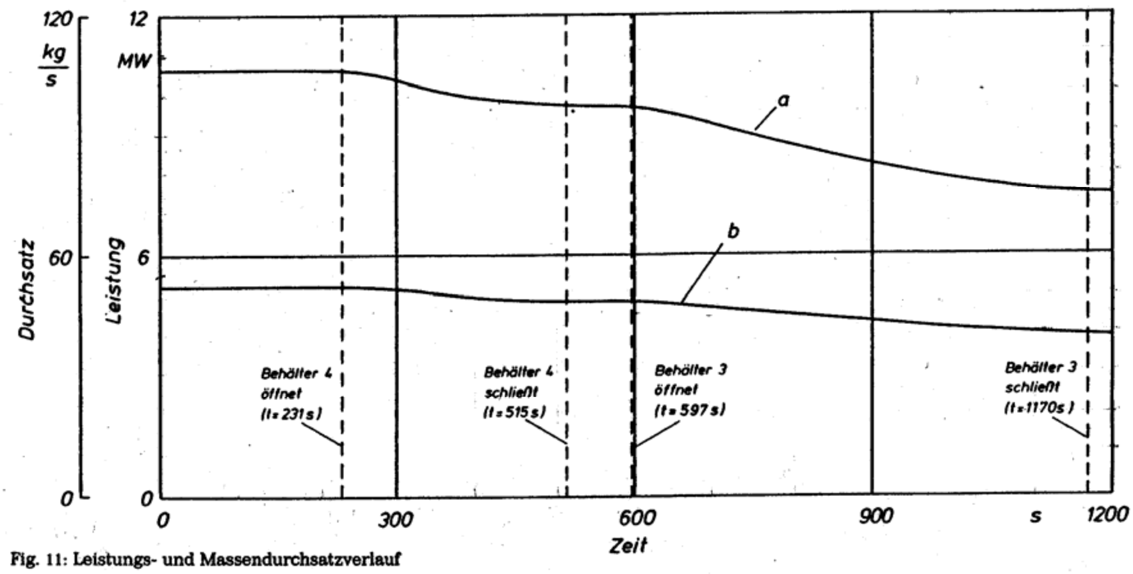


Fig. 11: Leistungs- und Massendurchsatzverlauf
a Leistung b Massendurchsatz

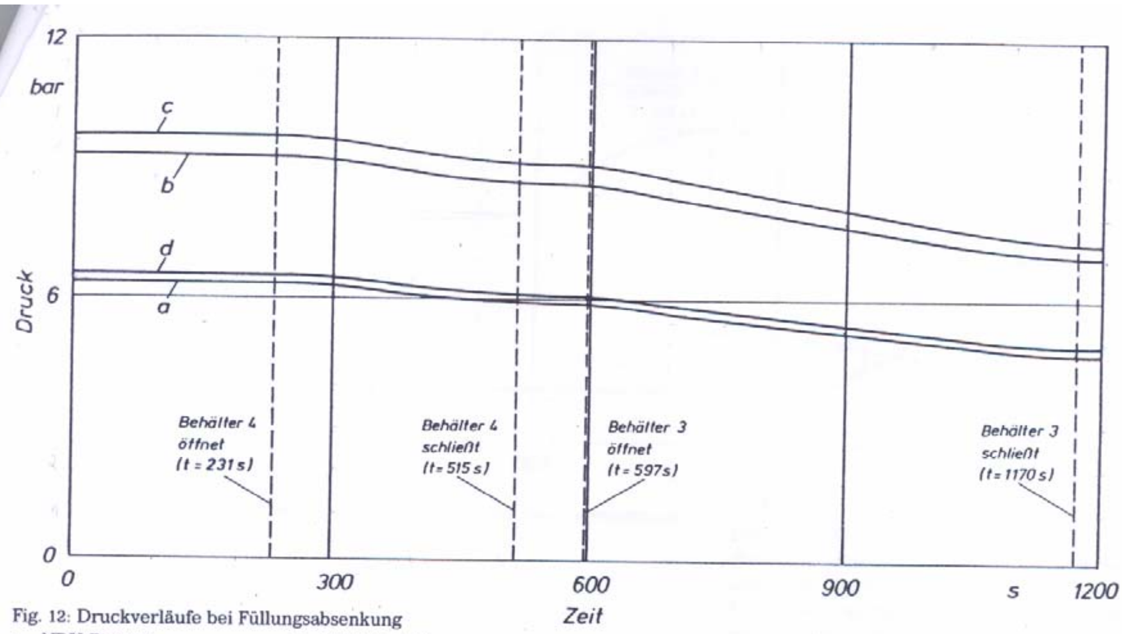


Fig. 12: Druckverläufe bei Füllungsabsenkung
a NDV-Eintritt
b NDV-Austritt
c HDT-Austritt
d NDT-Austritt

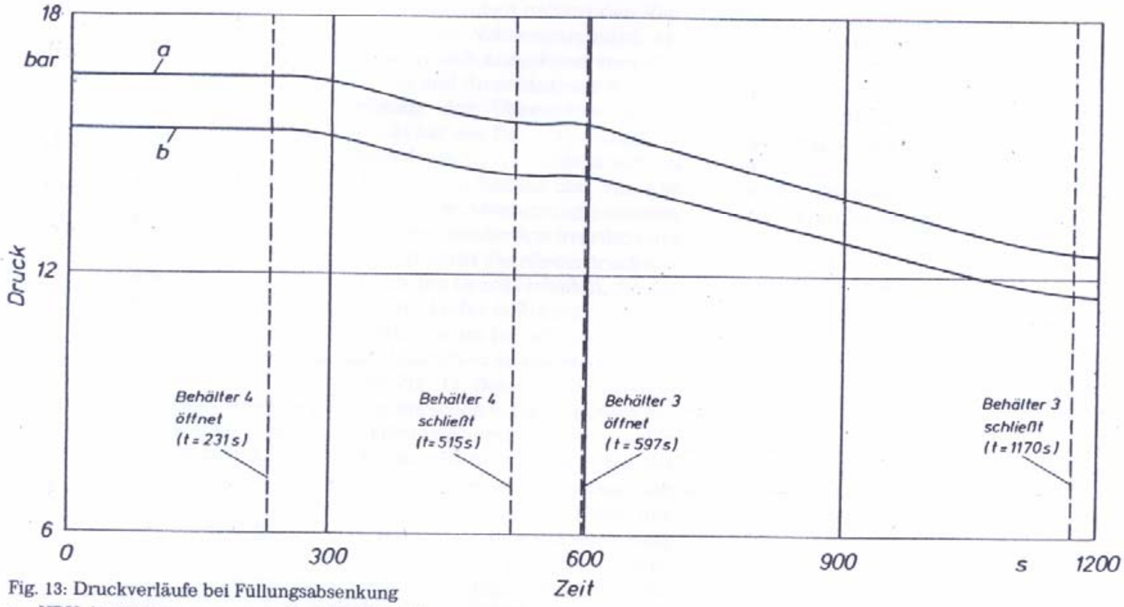
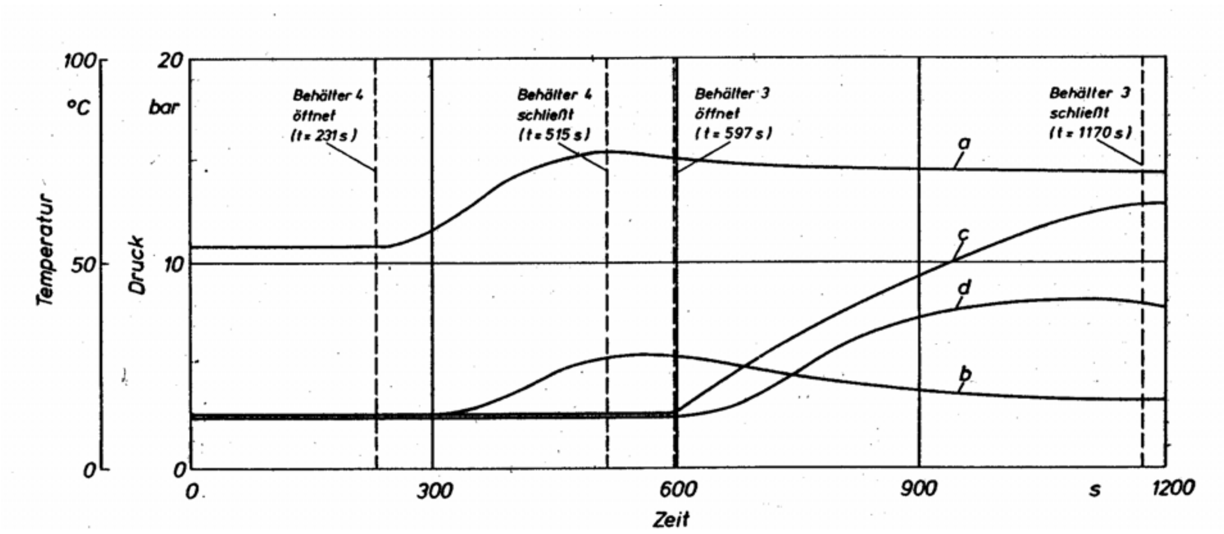
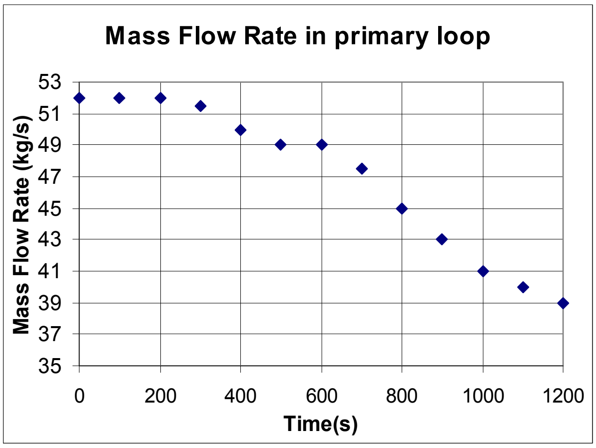
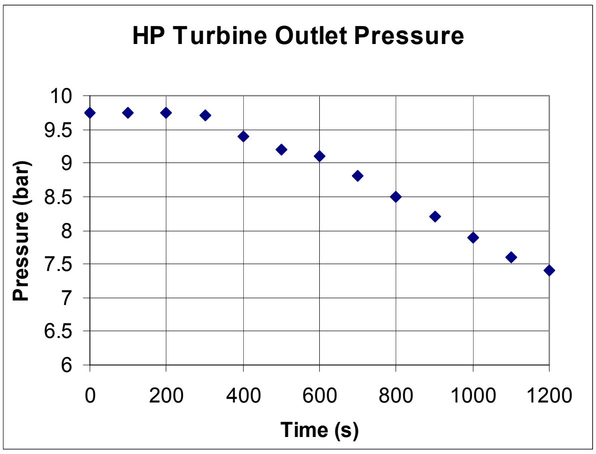
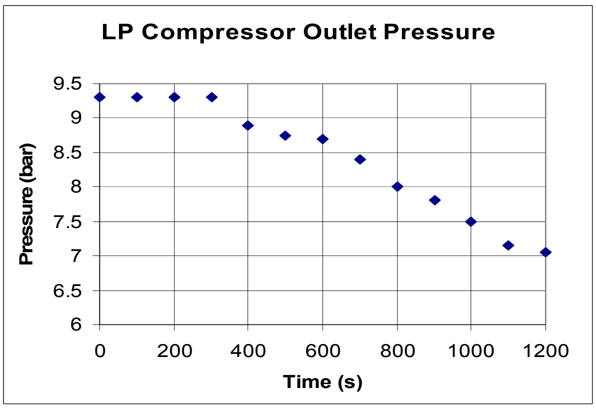


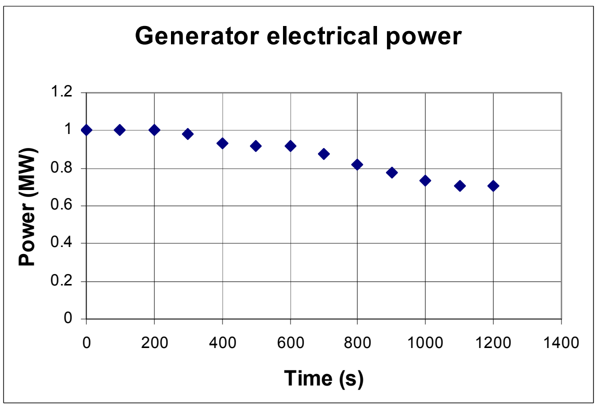
Fig. 13: Druckverläufe bei Füllungsabsenkung
a HDV-Austritt
b HDT-Eintritt

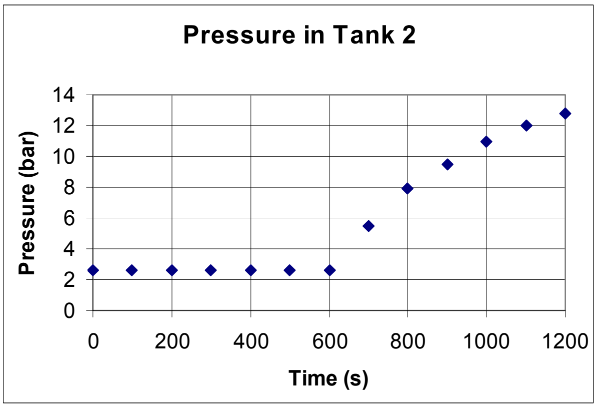

Temperatur
°C
Druck
bar
Behälter 4 öffnet (t = 231 s)
Behälter 4 schließt (t = 515 s)
Behälter 3 öffnet (t = 597 s)
Behälter 3 schließt (t = 1170 s)
a
b
c
d
Zeit
s

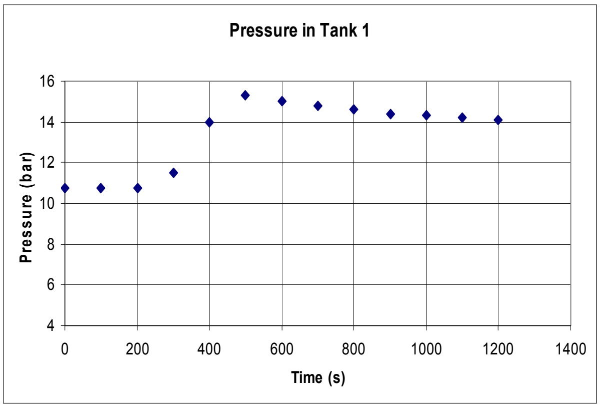

Mass Flow Rate in primary loop
Mass Flow Rate (kg/s)
Time(s)

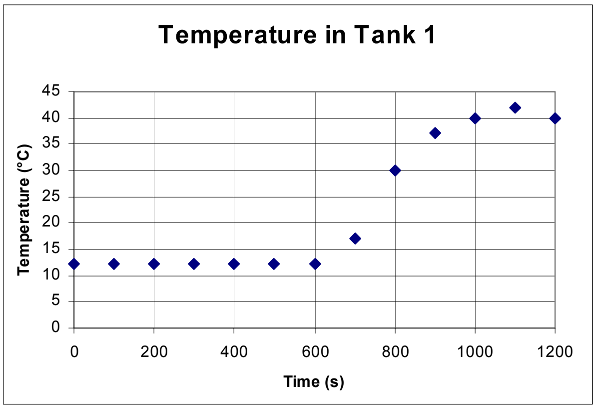

HP Turbine Outlet Pressure
Pressure (bar)
Time (s)

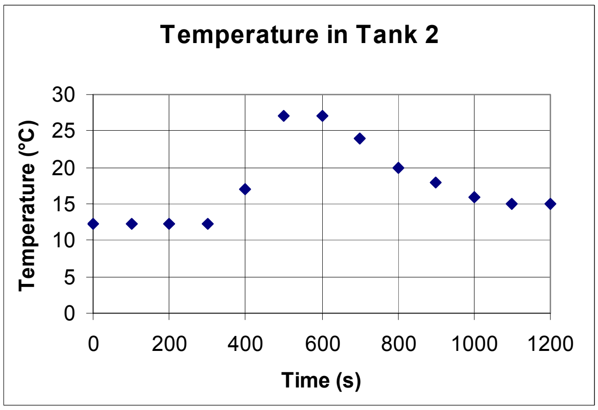

LP Compressor Outlet Pressure
Pressure (bar)
Time (s)

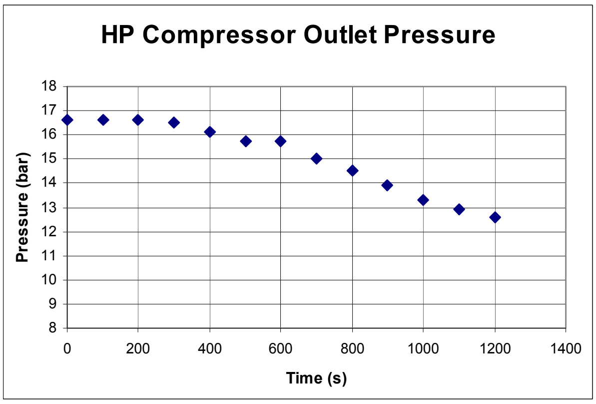

Generator electrical power
Power (MW)
Time (s)

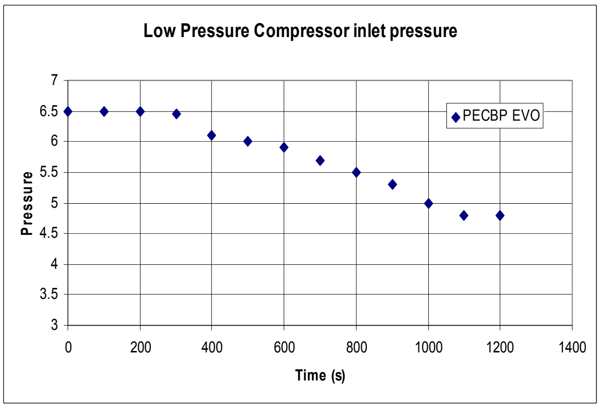

Pressure in Tank 2
Pressure (bar)
Time (s)

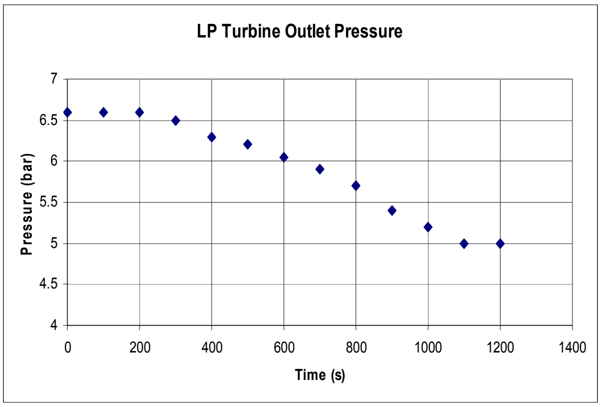

Pressure in Tank 1
Pressure (bar)
Time (s)

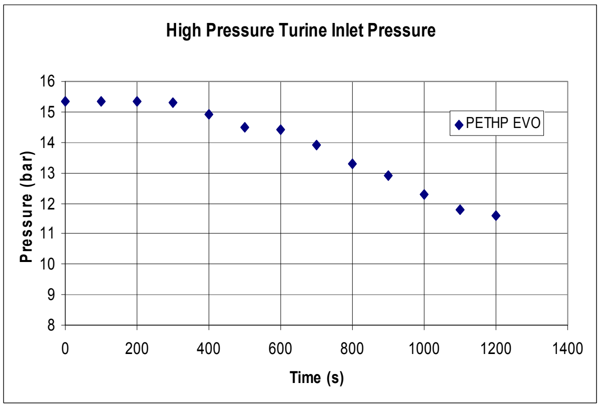

Temperature in Tank 1
Temperature (°C)
Time (s)


Temperature in Tank 2
Temperature (°C)
Time (s)


HP Compressor Outlet Pressure
Pressure (bar)
Time (s)


Low Pressure Compressor inlet pressure
Pressure
Time (s)
PECBP EVO





The corresponding excel files are as following:

Time (s)	flow rate (kg/s)	LPC Pin (bar)	LPC Pout (bar)	HPT Pout (bar)	LPT Pin (bar)	HPC Pout (bar)	HPT Pin (bar)
0	52	6.5	9.3	9.75	6.6	16.6	15.35
100	52	6.5	9.3	9.75	6.6	16.6	15.35
200	52	6.5	9.3	9.75	6.6	16.6	15.35
300	51.5	6.45	9.3	9.7	6.5	16.5	15.3
400	50	6.1	8.9	9.4	6.3	16.1	14.9
500	49	6	8.75	9.2	6.2	15.75	14.5
600	49	5.9	8.7	9.1	6.05	15.75	14.4
700	47.5	5.7	8.4	8.8	5.9	15	13.9
800	45	5.5	8	8.5	5.7	14.5	13.3
900	43	5.3	7.8	8.2	5.4	13.9	12.9
1000	41	5	7.5	7.9	5.2	13.3	12.3
1100	40	4.8	7.15	7.6	5	12.9	11.8
1200	39	4.8	7.05	7.4	5	12.6	11.6

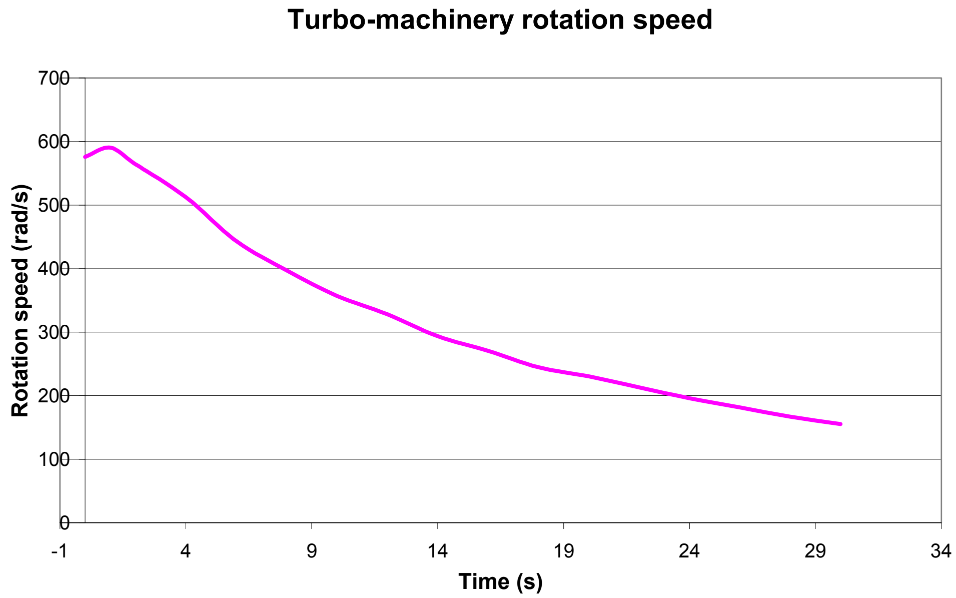
Time (s)	P tank1 (bar)	P tank2 (bar)	T tank1 (°C)	T tank2 (°C)	Generator Power (MWe)
0	10.75	2.64	12.3	12.3	10.6
100	10.75	2.64	12.3	12.3	10.6
200	10.75	2.64	12.3	12.3	10.6
300	11.5	2.64	12.3	12.3	10.4
400	14	2.64	17	12.3	9.9
500	15.3	2.64	27	12.3	9.7
600	15	2.64	27	12.3	9.7
700	14.8	5.5	24	17	9.3
800	14.6	7.9	20	30	8.7
900	14.4	9.5	18	37	8.2
1000	14.3	11	16	40	7.8
1100	14.2	12	15	42	7.5
1200	14.1	12.8	15	40	7.5

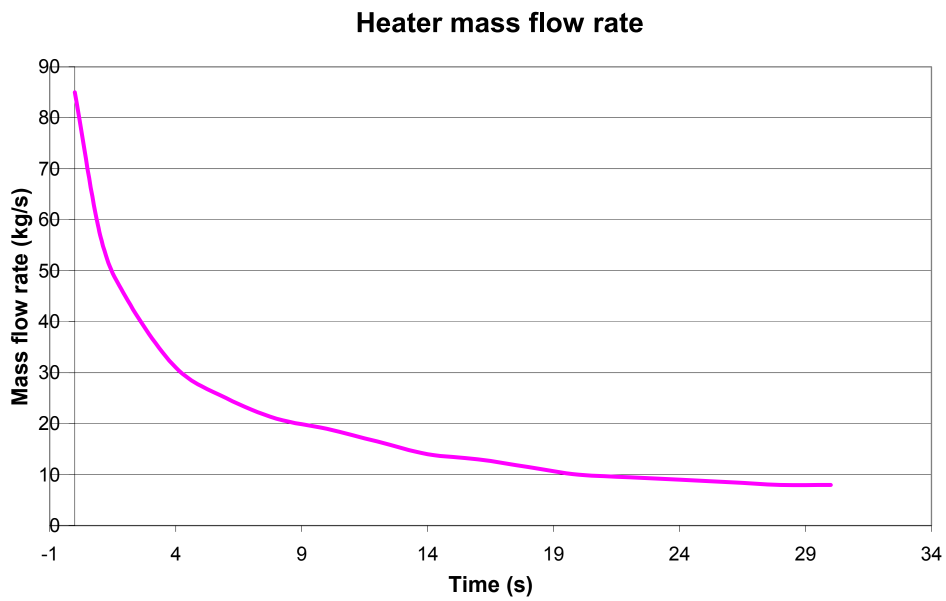
Appendix 3 – Loss of Load Transient

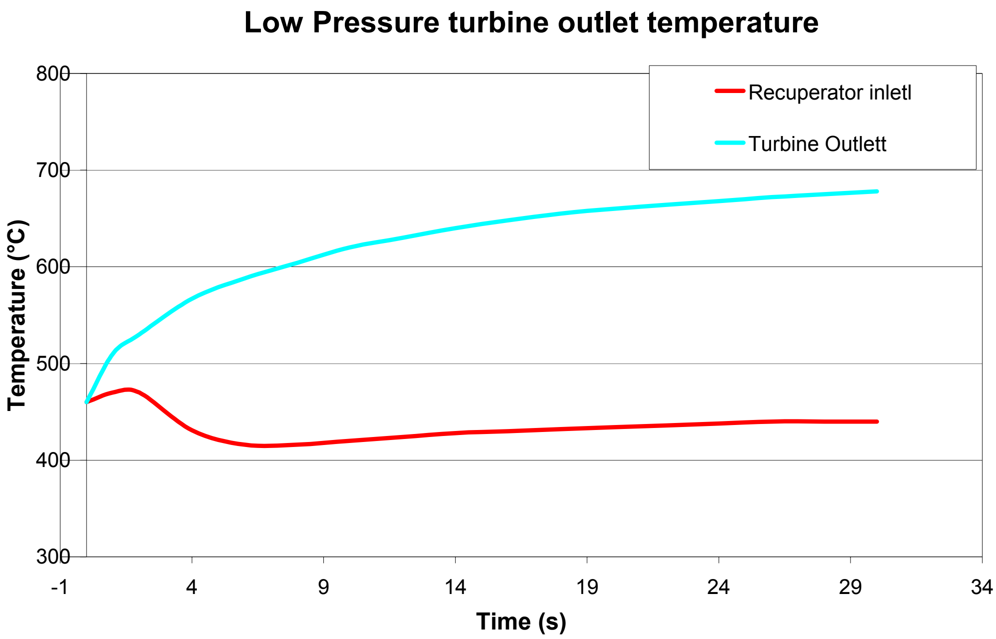
The excel files which correspond to the figures below are given as following **(CEA contribution)**:

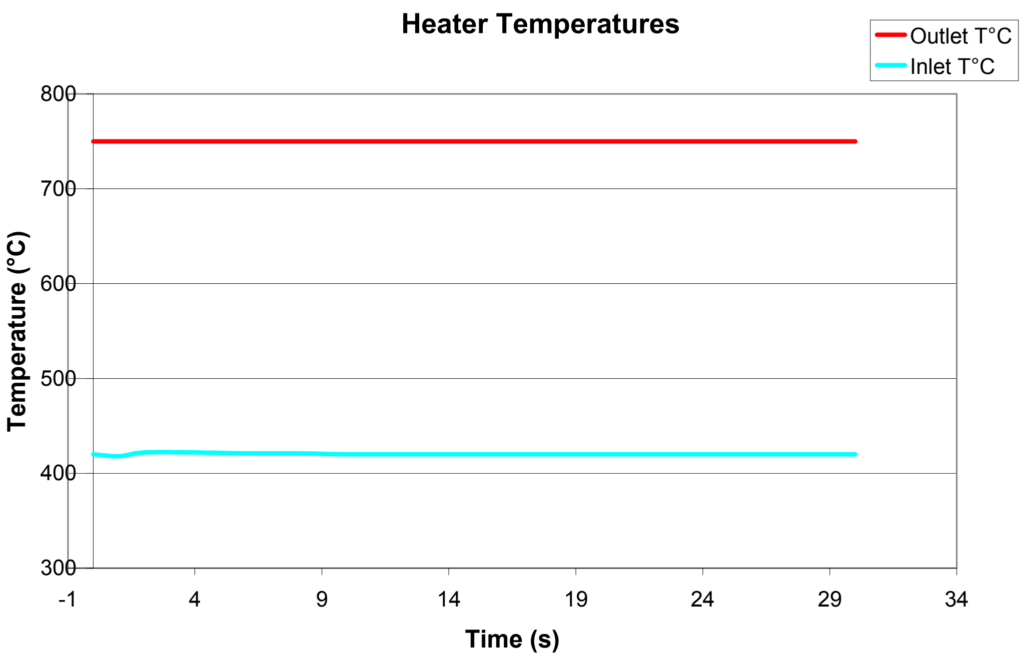
Time (s)	**ω Turbo-Machines (rad/s)**	**ωTurbo-Machines (rad/s)**	**heater mass flow rate (kg/s)**	**HPT Pin (bar)**	**LPT Pout (bar)**
0	1	575.941667	85	2700000	1080000
1	1.025	590.340208	57	2100000	1250000
2	0.98	564.422833	45	1950000	1300000
4	0.89	512.588083	31	1700000	1340000
6	0.77	443.475083	25	1600000	1390000
8	0.69	397.39975	21	1550000	1400000
10	0.62	357.083833	19	1510000	1410000
12	0.57	328.28675	16,5	1505000	1420000
14	0.51	293.73025	14	1500000	1430000
16	0.47	270.692583	13	1495000	1435000
18	0.425	244.775208	11,5	1490000	1440000
20	0.4	230.376667	10	1485000	1445000
22	0.37	213.098417	9,5	1485000	1450000
24	0.34	195.820167	9	1480000	1450000
26	0.315	181.421625	8,5	1480000	1450000
28	0.29	167.023083	8	1480000	1450000
30	0.27	155.50425	8	1480000	1450000

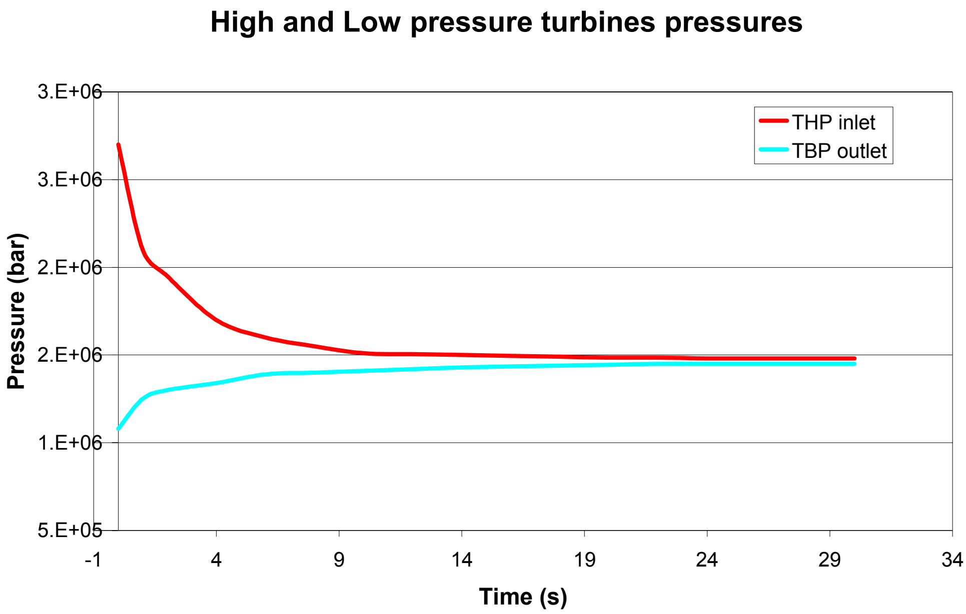
Time (s)	Tout Heater (°C)	Tin Heater (°C)	Byp. Valve T out (°C)	LPT Tout (°C)
0	750	420	460	460
1	750	418	470	510
2	750	422	470	530
4	750	422	431	567
6	750	421	416	588
8	750	421	416	604
10	750	420	420	620
12	750	420	424	630
14	750	420	428	640
16	750	420	430	648
18	750	420	432	655
20	750	420	434	660
22	750	420	436	664
24	750	420	438	668
26	750	420	440	672
28	750	420	440	675
30	750	420	440	678


Turbo-machinery rotation speed
Rotation speed (rad/s)
700
600
500
400
300
200
100
0
-1
4
9
14
19
24
29
34
Time (s)


Heater mass flow rate
Mass flow rate (kg/s)
90
80
70
60
50
40
30
20
10
0
-1
4
9
14
19
24
29
34
Time (s)


Low Pressure turbine outlet temperature
Recuperator inletl
Turbine Outlett
Temperature (°C)
800
700
600
500
400
300
-1
4
9
14
19
24
29
34
Time (s)


Heater Temperatures
Outlet T°C
Inlet T°C
Temperature (°C)
800
700
600
500
400
300
-1
4
9
14
19
24
29
34
Time (s)


High and Low pressure turbines pressures
THP inlet
TBP outlet
Pressure (bar)
3.E+06
3.E+06
2.E+06
2.E+06
1.E+06
5.E+05
-1
4
9
14
19
24
29
34
Time (s)