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D5.2 LFR BOP Main components definition: definition and sizing of the main components, including sensitivity analysis of both BOP configurations

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Document Summary

This document includes the heat and mass balance calculations for the water-steam cycle of ALFRED plant and its integration with the two technologies assessed in ANSELMUS Deliverable D5.1: a molten salts thermal storage system and a High Temperature Steam Electrolysis hydrogen production system. Several designs are proposed for different degrees of electric and thermal productions, analyzing the main performance parameters and providing the sizing parameters of the main equipment that form each configuration.

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List of Acronyms

ACC	Air Cooled Condenser
ALFRED	Advanced Lead-cooled Fast Reactor European Demonstrator
ANSELMUS	Advanced Nuclear Safety Evaluation of Liquid Metal Using Systems
BOP	Balance of Plant
CSP	Concentrating Solar Power
DA	Deaerator
DCA	Drain Cooler Approach
FP	Full Power
FW	Feedwater
FWH	Feedwater Heater
FWTCH	Feedwater Temperature Control Heater
GSC	Gland Steam Condenser
HHV	Higher Heating Value
HLM	Heavy Liquid Metal
HPT	High Pressure Turbine
HTS	Heat Transfer System
HTSE	High Temperature Steam Electrolysis
LFR	Lead Fast Reactor
LPT	Low Pressure Turbine
NPP	Nuclear Power Plant
PCE	PEACE Component (THERMOFLEX nomenclature)
RH	Relative Humidity
RPM	Revolutions per minute
SG	Steam Generator
SGS	Steam Generation Systems
SOEC	Solid Oxide Electrolysis Cell
STG	Steam Turbine Generator
TES	Thermal Energy Storage

List of Acronyms

TTD	Terminal Temperature Difference
V-RES	Variable Renewable Energy Sources

1 Introduction

ANSELMUS Deliverable D5.1 [4] assessed the feasibility and the potential of integrating two different technologies of cogeneration / thermal storage with ALFRED reactor to achieve load-following performances while maintaining the reactor at high power levels minimizing power excursions. Several configurations were presented and analysed in a qualitative way.

Following this analysis, the present report selects a technological configuration proposal for both options (molten salts thermal storage and hydrogen production), and performs several heat and mass balance calculations by simulating the systems' performances under different sizing options using Thermoflex software by Thermoflow Inc. PEACE module included in Thermoflex allows to estimate the preliminary sizing of the equipment.

The heat and mass balances present the most relevant operating parameters, including overall efficiencies, thermal and electric power inputs and outputs, and the main process thermodynamic properties of the working fluids. The main components that form each of the technological solutions proposed are sized in a preliminary approach for several designs. This is important considering the initial stage of the project, so that different possibilities are left opened for future decision taking. The performances of the proposed systems along with the sizing of the main equipment shall be used as input data for the ongoing techno-economic analysis to be performed in the scope of Task 5.1 of the project.

Firstly, the configuration and heat and mass balance of the nominal steam-water cycle of ALFRED reactor is proposed, without considering cogeneration or thermal energy storage of the plant. This is a useful starting point for the ongoing chapters and gives a perspective to compare the normal operation that the plan would have without load-following capability. Chapters 5 and 6 asses the configuration, thermal balances of the plant, and sizing of main equipment for the molten salts thermal energy storage and the hydrogen production systems, respectively.

The Appendices include all the supporting information of the mentioned chapters.

2 Input data

For this deliverable purpose, ALFRED demonstrator is used as the reference reactor. It is intended as an European demonstrator of LFR technology, and to reduce the lack of validation and operating experience, a staged operation approach will be implemented, by increasing progressively its thermal power, and consequently, the temperature and pressure of the generated steam: stage 1 – low temperature, stage 2 – medium temperature, stage 3 – high temperature [3].

The investigation on Energy Storage and Cogeneration integration is limited to the plant commercial exploitation so the third stage is taken as the reference for this report. Indeed, it is the one that shall be attractive from an economic viewpoint and representative for commercial size LFR plant efficiency. The following input data [ID] have been considered, as follows:

[ID 1] The main parameters of the final commissioning stage of ALFRED reactor as shown in Table 1 [2].

Table 1 - Main parameters of the ALFRED reactor

Design data (nominal conditions)	**Units**	**Stage 3**
Thermal power	MWth	300
Primary System (Lead)		
Core inlet temperature	°C	400
Core outlet temperature	°C	520
Secondary System (Water / Steam)		
Mass flow rate	kg/s	192.6
Feedwater inlet temperature	°C	335
Steam outlet temperature	°C	450
SG outlet pressure	bar(a)	180

[ID 2] The minimum feedwater temperature at the Steam Generators inlet of ALFRED reactor is 335 °C, to ensure a minimum margin above lead freezing temperature (327 °C). This strongly limits the lower bound for the SG outlet pressure to ensure a minimum degree of under-cooling at the SG inlet (greater than 15 °C, corresponding to a saturation pressure of about 150 bar). Feedwater inlet temperature variation of ±5 °C at partial loads constraints is acceptable [3].

[ID 3] The following ambient conditions shall be considered (Table 2). The design conditions shall be used to specify equipment. The extreme conditions values should be taken into account only for operational limits [3].

Table 2 - Ambient conditions

Design Condition	
Nominal (yearly average)	12 °C at 60% RH
Summertime (maximum)	32 °C at 60% RH
Wintertime conditions (minimum)	-13 °C at 100% RH
Extreme Condition (verification only)	
Summertime extreme conditions	37 °C at 60% RH
Wintertime extreme conditions	-25 °C at 100% RH

[ID 4] The BOP design shall comply with Mioveni industrial water availability, currently set to 28 kg/s (goal) but extendable up to 56 kg/s (maximum) [3].

[ID 5] Target Steam Turbine Generator (STG) power ramp rate is ±15% FP / min. Minimum requirement is ±10% FP/min [3].

3 Calculation software

The heat and mass balance schematics and calculations as well as the sizing and design of the main components of each configuration have been performed with Thermoflow software.

Thermoflow is a well-known developer of thermal engineering for power and cogeneration industries that allows the user to accurately compute the thermodynamic performance of the plant and create detailed, physical preliminary designs for all significant components and piping.

In particular, it is used the general purpose program of the software, called THERMOFLEX. This is a fully flexible program with graphic user interface which the user creates a thermal system network by selecting, dragging, dropping and connecting icons representing over two hundred different components. The program covers both design and off-design simulation.

This program is used in combination with the PEACE module, which gives access to a set of more sophisticated engineered components. This combination allows the user to estimate the overall dimensions, weights and costs of each item of major equipment.

4 LFR Heat balance

A general Heat and Mass Balance is presented for the Steam and Power Conversion System of the plant. The selected configuration shall be the origin of the Heat and Mass Balance sensitivity analysis of the technological options for thermal storage and cogeneration, included in the following chapters.

4.1 General configuration definition

The final configuration of the Steam and Power Conversions systems of ALFRED plant shall be based on the following approach. This arrangement is the outcome of an iterative process in which the main parameters and equipment of the secondary side of the plant have been modified in order to obtain a solution that gives the highest plant gross electric power and electric efficiencies that can be achieved for the thermal power of ALFRED demonstrator and Steam Generators (SG) inlet and outlet fluid conditions.

The main steam produced in the Steam Generators located in the reactor vessel is superheated steam at 450 °C and 180 bar(a). A conventional single reheat Rankine cycle with regenerative preheating is selected, shown in Appendix A, along with the heat and mass balance parameters.

The Steam Turbine (ST) Group is a single shaft turbine at a rotating speed of 3000 rpm, formed by two sections, the High Pressure Turbine (HPT) and the Low Pressure Turbine (LPT), having each of them a single flow casing (see Figure 1).

The high pressure turbine (HPT) section is composed of three groups, expanding the incoming main steam to the reheat pressure, at slightly superheated conditions to avoid moisture at HPT exhaust (cold reheat steam).

A Moisture Separator shall be installed at the HPT exhaust for lower load plant operations although during nominal operation no moisture shall be removed, as the cold reheat steam is over saturation conditions. ST internal moisture separators have been included in the fourth and fifth LPT groups exhausts in order to remove part of the liquid water from the wet steam flow and increase the overall efficiency of the ST Group.

The reheating cycle is formed by two stages. In the first stage the cold reheat steam is heated by the exhaust of the second HPT group. Then, in the second stage of the Reheater, the reheating stream is heated by main steam from a splitter right before the HPT inlet valves. The reheating pressure is set to 36 bar, and the hot reheat is superheated steam at 355 °C.

The low pressure turbine (LPT) section is composed of six groups, expanding the incoming hot reheat steam up to wet steam conditions between 0.85 and 0.90 of steam title at the exhaust condenser, driven by backpressure. A steam extraction is performed at each LPT group exhaust to feed the Deaerator (DA) and the four successive low pressure condensate preheaters.

The inlet pressure of both sections (HPT and LPT) is controlled by throttle control valve(s), whereas there is not pressure control in the rest of the turbine groups. All feedwater heaters (FWH) operate with natural non-controlled extractions excepting the last one (FWH8) used to ensure 335 °C at the reactor inlet.

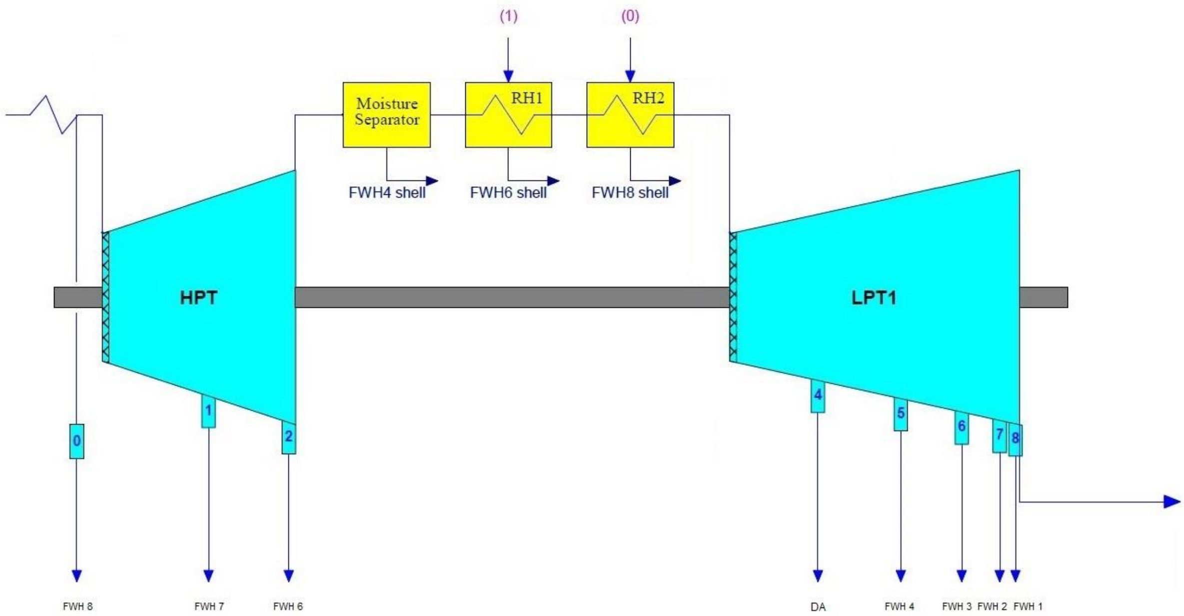


Figure 1 – ST Group, Moisture Separator and Reheater schematic

The sealing steam used to seal the HPT stop and throttle valves stems and the turbine shaft leakages, which comes from the HPT inlet itself, shall be conducted towards the Gland Steam Condenser (GSC) and condensed to recover its heat by slightly preheating the condensate water at the Condensate Pumps outlet. The resulting saturated liquid is directed to the condenser inlet stream.

The condenser will be a dry Air-cooled Condenser (ACC) in order to largely reduce the need of water of the cycle. The condensing pressure, which serves as driving force for the steam through the ST Group, is set to 0.1 bar. The ACC inlet temperature difference (ITD) between the inlet steam (turbine exhaust) and the inlet cooling air is around 15 °C to maximize cycle efficiency. Its design is done considering the summertime design conditions provided in [ID 3], that is 32 °C and 60% RH, which are the most unfavorable ones.

This equipment shall be specified with a A-Frame tube bundle configuration, as shown in Figure 2, where the steam coming from the last turbine group enters the condenser through a large header on top of the tube bundles, and goes down as it is condensed by the air flow that circulates through the outside, driven by a fan located in the bottom part of the structure. The equipment is arranged in cells connected in both, parallel and series forming modules.

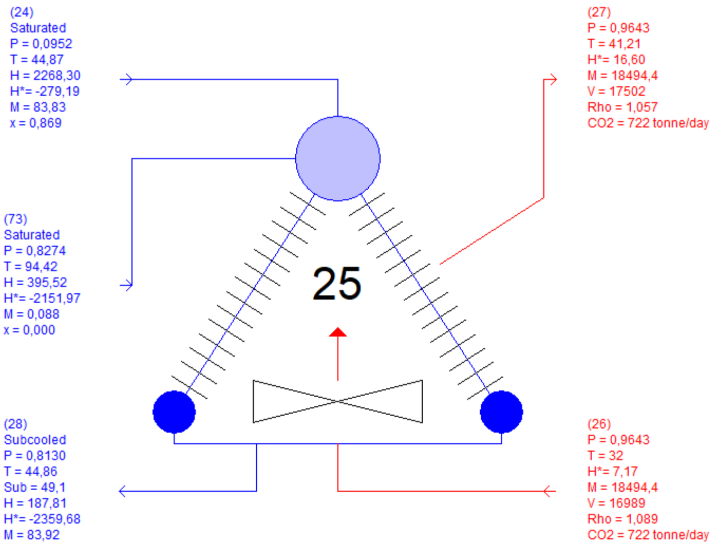


Figure 2 – Air-Cooled Condenser operation schematic

The condensate pumps take the condensate water from the ACC tank and pump it towards the deaerator passing through a series of LP preheaters. Then, the Feedwater Pumps suck from the deaerator to provide water to the SGs passing through a series of HP preheaters. All preheaters are fed by steam extractions and exhaust of the HPT, and the condensed water in the shell side of these heat exchangers is redirected to previous steps of preheating, in cascade mode, to take advantage of the higher enthalpy conditions. FWH1 drain is pumping forward to the condensate line because it is not possible to send directly to the ACC tank.

Figure 1 shows the Turbine bleeding connections with the FWH) and DA. This is the configuration which offers a higher cycle efficiency. The main characteristics of the FWH preheating sequence are shown below, from the Condensate Pumps outlet, to the SG inlet:

- FWH1:
  - Outlet temperature: 77 °C
  - TTD: 3 °C
  - Steam source: 5th LPT group exhaust
  - Desuperheating section: No
  - Drain type: Pump forward
  - DCA: No Drain Cooler
- FWH2:
  - Outlet temperature: 108 °C
  - TTD: 3 °C
  - Steam source: 4th LPT group exhaust
  - Desuperheating section: No
  - Drain type: Cascade drain to FWH1
  - DCA: 5 °C
- FWH3:
  - Outlet temperature: 139 °C
  - TTD: 3 °C
  - Steam source: 3rd LPT group exhaust
  - Desuperheating section: No

- Drain type: Cascade drain to FWH2
- DCA: 5 °C
- FWH4:
  - Outlet temperature: 170 °C
  - TTD: 3 °C
  - Steam source: 2nd LPT group exhaust
  - Desuperheating section: No
  - Drain type: Cascade drain to FWH3
  - DCA: 5 °C
- DA:
  - Outlet temperature: 208 °C
  - Steam source: 1st LPT group exhaust
  - Drain type: Pump forward (Feedwater Pumps)
- FWH6:
  - Outlet temperature: 242 °C
  - Steam source: HPT exhaust
  - Desuperheating section: No
  - Drain type: Cascade drain to DA
  - DCA: 5 °C
- FWH7:
  - Outlet temperature: 286 °C
  - TTD: 3 °C
  - Steam source: 2nd HPT group exhaust
  - Desuperheating section: Yes
  - Drain type: Cascade drain to FWH6
  - DCA: 5 °C
- FWH8 (FWTCH):
  - Outlet temperature: 335 °C
  - TTD: 0 °C
  - Steam source: Main Steam
  - Desuperheating section: Yes
  - Drain type: Cascade drain to FWH7
  - DCA: 5 °C

The FWH8 is an extra heater called Feedwater Temperature Control Heater (FWTCH) fed with main steam and located upstream the SG inlets to maintain, during any transient or mode of operation, a feedwater temperature of 335 °C, as required in [ID 2].

Between the high pressure FWH and the low pressure FWH the Deaerator is located, which supplies water with a low oxygen and carbon dioxide concentration to protect the SGs from corrosion. This is a direct contact heater. The Feedwater Pumps pump the fluid towards the high pressure preheaters, working in a 2x100% configuration.

A 100% turbine bypass system is included, allowing direct transfer of main steam from the steam generator to the condenser, giving the plant total power variability during possible thermal load transients. There is desuperheating feature in the bypass valves using cold water coming from the condensate pumps to condition the steam before dumping to ACC duct.

The main equipment of the water-steam cycle systems (T) for which a preliminary sizing is presented in this report are the following ones, with the designated identification in the heat and mass balances shown in Appendix A and Appendix B, as well as in the sizing parameters shown in Appendix C:

- Steam Turbine: ST Assembly (1)
- Air-cooled Condenser: Air-cooled Condenser (PCE) (25)
- Deaerator (FWH-5): Deaerator (42)
- Feedwater Heater (FWH-2): Feedwater Heater (PCE) (36)
- Feedwater Heater (FWH-3): Feedwater Heater (PCE) (38)
- Feedwater Heater (FWH-4): Feedwater Heater (PCE) (40)
- Feedwater Heater (FWH-6): Feedwater Heater (PCE) (46)
- Feedwater Heater (FWH-7): Feedwater Heater (PCE) (49)
- Feedwater Heater (FWH-8): Feedwater Heater (PCE) (51)
- Feedwater Heater (FWH-1): Feedwater Heater w/ Pump (PCE) (33)
- 1st Reheater: General HX (10)
- 2nd Reheater: General HX (12)
- Condensate Pumps Pump (PCE) (30)
- Feedwater Pumps Pump (PCE) (44)

4.2 Nominal load heat balance

The heat balance for the nominal operation of the ALFRED plant is presented in Appendix A, including the main streams thermodynamic parameters: mass flow rate - m (kg/s), temperature - T (°C), pressure - p (bar) and enthalpy - h (kJ/kg).

The main performance outputs are outlined:

- Gross power: 128.5 MW
- Net power: 118.9 MW
- Gross electric efficiency: 42.85 %
- Net electric efficiency: 39.63 %

These results refer to the summertime ambient conditions [ID 3], and will be the reference for the following chapters. Nevertheless, as the ambient conditions have a high influence on the performance of the cycle, due to the variation of the condensing pressure with the ambient temperature, it is included the heat and mass balance of the cycle for yearly average conditions of 12 °C, 60% RH, wintertime conditions of -13 °C, 100% RH [ID 3], and also for 18 °C, 60% RH ambient conditions. These three additional balances are calculated using the design obtained for the summertime conditions.

Table 3 gathers the main performance results obtained:

Table 3 – Nominal load heat balance performance results

Variable	Unit	32°C, 60% RH	18°C, 60% RH	12°C, 60% RH	-13°C, 100% RH
Plant gross power	kW-e	128542	131501	131579	131649
Plant net power	kW-e	118897	120892	121732	123551
Gross efficiency	%	42.85	43.83	43.86	43.88
Net efficiency	%	39.63	40.30	40.58	41.18

It has to be noted that a minimum condensing pressure in the Air-Cooled Condenser of 45 mbar has been established, as being a common limit for this kind of equipment. This implies that the gross electric power and gross electric efficiencies are similar once the minimum condensing pressure is reached. On the other hand, as the electric consumption of the ACC decreases with lower temperatures, the plant net power and net electric efficiency increase.

For more information, Appendix A includes the ST Assembly (1) Mollier Chart for the four above mentioned ambient conditions.

This Heat and Mass Balance will be the nominal case for the hydrogen production analysis, whereas the molten salts thermal storage heat balance will be modified following the different design options explained in Chapter 5. Anyway, the selected design criteria (e.g. number of preheaters, reheat pressure, turbine exhaust pressure, etc.) will be maintained for all cases.

The sizing parameters of the main equipment of the water-steam cycle in case that no cogeneration/thermal storage is installed, are obtained with THERMOFLEX software and shown in Table C- 1, in Appendix C.

5 Molten salts thermal storage

Following the description of the molten salts thermal energy storage solution assessed in ANSELMUS Deliverable D5.1 [4], this chapter develops the final configuration, defines its main equipment, and provides the Heat and Mass Balances for different sizing designs.

5.1 Selected configuration

The conceptual design of the Thermal Energy Storage (TES) using molten salts as heat transfer fluid is formed by the following systems:

- Storage System, formed by the hot and cold molten salt tanks
- Loading System, to charge the hot molten salt tank
- Unloading System, to discharge the hot molten salt tank.

The hot salts produced in the Loading System using the heat of the main steam produced in the SGs, are stored in the hot salts storage tank of the Storage System during the Loading Operating Mode. Then, during the Unloading Operating Mode, the hot salts are used to produce an extra steam in the Unloading System, and stored back in the cold salts storage tank. The interaction between these systems was explained in previous deliverable [4]. See Appendix B heat and mass balances for Loading and Unloading operating modes to visualize the described configuration.

The following Sections explain the main functions to be performed by these systems and define their main components to be sized in this preliminary stage.

5.1.1 Storage System

The main function of this system is to store the hot and the cold salts in the most thermally efficient way and transfer them to the Loading and Unloading Systems when required by the plant control room.

To do this, two independent storage tanks shall be installed, one dedicated to store the hot salts and the other one the cold salts (see Appendix B heat and mass balances for Loading and Unloading operating modes) , which have a minimum operating temperature of 290 °C. The tanks are vertical cylinders made up of carbon steel and insulated in order to minimize the heat loss through the walls and ceiling. The tanks are maintained at atmospheric pressure by means of atmospheric vents.

The material selected to construct the tanks is carbon steel because the operating temperatures that it can withstand are enough for the required application (400 °C). Using other alloy or stainless steels would increase the operating temperatures but this shall increase considerably the cost of the tanks and the heat exchangers, and the maximum source temperature is only 50 °C, over the mentioned temperature.

Each of these tanks has additional equipment to be installed for the correct operation of the system:

- Salts circulation pumps: these are vertical pumps submerged in the tanks with outboard electric motors with variable speed drives supported by an independent platform outside the tanks. In the present report, these equipment are included in the Loading and Unloading Systems.
- Tempering pumps used during startups and transients of the plant.
- Electric heaters are installed at the bottom part of both tanks in order to maintain under any circumstances the salts over their freezing point, keeping the fluid over the minimum operating

temperature. They shall be placed under a minimum molten salts volume that is defined for operability reasons.
- Salts distribution rings are used to receive and distribute the molten salts in each of the tanks. Usually, they are located at the bottom of the tank and are fed by a vertical collector of the same diameter.
- Other auxiliary and safety minor equipment such as overpressure protection devices, vents and drainage systems.
- Instrumentation & Control systems to monitor and control the main operating parameters.

The main equipment of this system for which a preliminary sizing is presented in this report are the following ones, with the designated identification in the heat and mass balances shown in Appendix B, as well as in the sizing parameters shown in Appendix C:

- Cold molten salt tank: Storage Tank (65)
- Hot molten salt tank: Storage Tank (66)

5.1.2 Loading System

The main function of the Loading System is to heat up the cold salts stored in the cold salts tank up to the operating temperature of the hot salts while condensing the main steam used as heat source.

The main steam is cooled from superheated steam to saturated steam in a Desuperheater heat exchanger (Shell-Tube General HX (PCE) (83)). The steam shall go to the saturation state through the tubes of the heat exchanger while the molten salts flow through the shell side because the operating pressure will be very high, close to the main steam pressure.

The steam is condensed back to liquid in the Condenser (Shell-Tube Condensing HX (PCE) (86)), using the cold molten salts. This equipment has to operate as well as high pressure, so that the saturation temperature of the steam is high enough to heat the salts.

Then, the liquid is pumped back to the water-steam cycle by the loading FW pump (General Pump (82)), and the heated salts are stored in the hot reservoir. The following interface conditions between the Loading System and the water-steam cycle have been selected as the most appropriate ones in terms of efficiency, and have been defined under engineering criteria, taking into account the thermodynamic constraints on both fluids:

- Steam Inlet: 450 °C / 180 bar (Main Steam)
- Feedwater Outlet: 285 °C / 187 bar (FWH#7 Outlet)
- Molten Salts Inlet: 290 °C (Cold Salts)
- Molten Salts Outlet: 400 °C (Hot Salts)

However, the interfaces parameters shown will slightly vary with respect to the heat and mass balance calculations shown in the following sections.

The main equipment of this system for which a preliminary sizing is presented in this report are the following ones, with the designated identification in the heat and mass balances shown in Appendix B, as well as in the sizing parameters shown in Appendix C:

- Condenser: Shell-Tube Condensing HX (PCE) (86)
- Desuperheater: Shell-Tube General HX (PCE) (83)

- Loading FW Pump: General Pump (82)
- Cold Tank Pumps: Pump (PCE) (55)

5.1.3 Unloading System

The main function of the Unloading System is to produce steam to be introduced as an extra stream into the LPT by using the heat stored in the hot salts.

This function is performed by a train of heat exchangers, arranged from the hottest salts to the coolest ones in the following way, in series connection: Superheater, Evaporator and Economizer. This is equivalent to the so-called Steam Generation System (SGS) that is commonly used in Concentrating Solar Plants (CSP).

The Economizer (Shell-Tube Economizer (PCE) (80)) is a shell-tube type heat exchanger where the liquid water flows through the tube side and the molten salts through the shell side. The entrance of the cold fluid (water) is controlled by a temperature controller that is fed by the outlet of the Economizer tube side, in order to ensure that the inlet temperature is always over 290 °C, so that the minimum operating temperature of the molten salts is always respected. To do this operation, a recirculation pump is used (General Pump (62)).

In the kettle type Evaporator (Shell-Tube Evaporating HX (PCE) (75)), the salts flow through the tube side and the water is evaporating the shell side. A blowdown is included.

The last step in the water-steam side is the Superheater (Shell-Tube Superheater (PCE) (69)), which heats up the saturated steam produced in the Evaporator up to superheating conditions. At its exit, there is a depressurizing valve that adjust the steam pressure from the Evaporator operating pressure to the inlet pressure of the LPT, in an isenthalpic process, thus, lowering the temperature of the steam up to the inlet temperature of the LPT (around 355 °C).

The following interface conditions between the Unloading System and the water-steam cycle have been selected as the most appropriate ones, under engineering criteria, taking into account the thermodynamic constraints on both fluids:

- Feedwater Inlet: 242 °C / 187 bar (FWH#6 Outlet)
- Steam Outlet: 355 °C / 36 bar (LPT inlet)
- Molten Salts Inlet: 400 °C (Hot Salts)
- Molten Salts Outlet: 290 °C (Cold Salts)

Again, as in the Loading System, the interfaces parameters shown will slightly vary with respect to the heat and mass balance calculations shown in the following Sections.

The main equipment of this system for which a preliminary sizing is presented in this report are the following ones, with the designated identification in the heat and mass balances shown in Appendix B, as well as in the sizing parameters shown in Appendix C:

- Economizer: Shell-Tube Economizer (PCE) (80)
- Evaporator: Shell-Tube Evaporating HX (PCE) (75)
- Superheater: Shell-Tube Superheater (PCE) (69)
- Recirculation Pump: General Pump (62)
- Hot Tank Pumps: Pump (PCE) (67)

5.2 Case studies

Four groups of equipment are defined for the conceptual design of the plant. For each of them, an identification letter is assigned for its ongoing identification.

- Water-Steam Cycle (T): formed by the equipment shown in Section 4.1.
- Storage System (S): formed by the equipment shown in Section 5.1.1.
- Loading System (L): formed by the equipment shown in Section 5.1.2.
- Unloading System (U): formed by the equipment shown in Section 5.1.3.

The Storage System, which includes the hot and cold salts tanks, do not intervene in the calculation of the heat and mass balances, as the design of these equipment depend on the time variable, which is not included in the computation. Thus, in all the performance simulations the tanks are considered as fluid sources and fluid sinks of infinite capacity.

However, three different sizing options are given for Storage System, as shown in Table 4, for the total molten salts inventory:

Table 4 – Storage System design case studies

Design ID	Total salts inventory [Tn]
S1	12000
S2	15000
S3	20000

For each of the other three groups of equipment which intervene in the performance calculations: Water-Steam Cycle (T), Loading System (L) and Unloading System (U), several design options are proposed, and for each design, several partial load heat and mass balances are shown. In turn, the preliminary sizing of the main equipment is given.

The design of the Water-steam Cycle (T) is dependent on the design of the Unloading System (U) because the turbine cycle has to be able to admit all the extra steam generated in the Unloading System.

The main variable that will determine the design of the Water-steam Cycle (T) and the Unloading System (U) is the maximum unloading steam mass flow rate, $m_{Steam,Unload,MAX}$. This is the maximum steam mass flow rate produced in the Unloading System and sent to the LPT to produce extra electric power, expressed in kg/s. Three values for this variable are selected to obtain the three designs of the Water-steam cycle and Unloading System, shown in Table 5. These are calculated as percentages of the nominal LPT steam mass flow rate, $m_{Steam,LPT,Nominal}$, which is 115 kg/s, as shown in the nominal heat load balance for 32C, 60% RH (see Appendix A).

Following this criteria, as shown in Table 5, there are three different sizing designs for the Water-Steam Cycle equipment group (T):

- T1, smallest design, admitting an extra LPT steam mass flow rate of 28.7 kg/s,
- T2, medium design, admitting an extra LPT steam mass flow rate of 57.5 kg/s,
- T3, biggest design, admitting an extra LPT steam mass flow rate of 114.9 kg/s;

And three corresponding different sizing designs for the Unloading System equipment group (U):

- U1, smallest design, generating a steam mass flow rate of 28.7 kg/s,
- U2, medium design generating a steam mass flow rate of 57.5 kg/s,
- U3, biggest design, generating a steam mass flow rate of 114.9 kg/s.

Table 5 – Water-Steam Cycle and Unloading System design case studies

Design ID	% of $m_{Steam,LPT,Nominal}$	$m_{Steam,Unload,MAX}$ [kg/s]
T1U1-BaseCase	25%	28.7
T2U2-BaseCase	50%	57.5
T3U3-BaseCase	100%	114.9

Apart from knowing the operation and performance of the system for its nominal mode of operation, it is also interesting to know the performance of that same design for partial loads, in order to assess the operating flexibility of each design. For each design, three partial loads are defined in Table 6, as a fraction of the nominal unloading steam mass flow rate of each design.

Table 6 – Unloading operation partial loads

Partial Load ID	% of $m_{Steam,Unload,MAX}$	$m_{Steam,Unload}$ [kg/s]
T1U1-BaseCase	100%	28.7
T1U1-Case1	75%	21.5
T1U1-Case2	50%	14.4
T1U1-Case3	25%	7.2
T2U2-BaseCase	100%	57.5
T2U2-Case1	75%	43.1
T2U2-Case2	50%	28.7
T2U2-Case3	25%	14.4
T3U3-BaseCase	100%	114.9
T3U3-Case1	75%	86.2
T3U3-Case2	50%	57.5
T3U3-Case3	25%	28.7

In case of the Loading System (L), the equipment design is determined by the maximum loading steam mass flow rate, $m_{Steam,Load,MAX}$. This is the steam derived from the main steam outlet of the Steam Generators and used to heat up the molten salts, expressed in kg/s. Two values for this variable are selected to obtain the different possible designs of the Loading System. These are calculated as percentages of the nominal HPT steam mass flow rate, $m_{Steam,HPT,Nominal}$, which is 152 kg/s, as shown in the nominal heat load balance (see Appendix A).

Following this criteria, as shown in Table 7, there are two different sizing designs for the Loading System equipment group (L):

- L1, smallest design, using a loading steam mass flow rate of 60.9 kg/s to heat the molten salts,
- L2, biggest design, using a loading steam mass flow rate of 121.8 kg/s to heat the molten salts.

Both Loading System (L) designs have to be combined with the previous three designs of the Water-steam Cycle (T) as the performance will vary for each combination. This is shown in Table 7.

Table 7 – Loading System design case studies

Design ID	% of $m_{Steam,HPT,Nominal}$	$m_{Steam,Load,MAX}$ [kg/s]
T1L1-BaseCase	40%	60.9
T2L1-BaseCase	40%	60.9
T3L1-BaseCase	40%	60.9
T1L2-BaseCase	80%	121.8
T2L2-BaseCase	80%	121.8
T3L2-BaseCase	80%	121.8

In the same way as in the Unloading mode, the performance of these designs are tested for partial loads operation in order to assess the operating flexibility of each design. For each design, two partial loads are defined in Table 8, as a fraction of the nominal loading steam mass flow rate defined for each design.

Table 8 – Loading operation partial loads

Partial Load ID	% of $m_{Steam,Load,MAX}$	$m_{Steam,Load}$ [kg/s]
T1L1-BaseCase	100%	60.9
T1L1-Case1	75%	45.7
T1L1-Case2	50%	30.4
T2L1-BaseCase	100%	60.9
T2L1-Case1	75%	45.7
T2L1-Case2	50%	30.4
T3L1-BaseCase	100%	60.9
T3L1-Case1	75%	45.7
T3L1-Case2	50%	30.4
T1L2-BaseCase	100%	121.8
T1L2-Case1	75%	91.3
T1L2-Case2	50%	60.9
T2L2-BaseCase	100%	121.8
T2L2-Case1	75%	91.3
T2L2-Case2	50%	60.9
T3L2-BaseCase	100%	121.8
T3L2-Case1	75%	91.3

Table 8 – Loading operation partial loads

Partial Load ID	% of $m_{Steam,Load,MAX}$	$m_{Steam,Load}$ [kg/s]
T3L2-Case2	50%	60.9

In this case, very low loads cannot be achieved for the same design, because it is not possible to achieve a condensing pressure in the Condenser (Shell-Tube Condensing HX (PCE) (86)) high enough to have a saturation temperature in the shell side high enough to heat up the salts to the desired values, before entering in the Desuperheater (Shell-Tube General HX (PCE) (83)). Thus, the lowest partial load calculated for these designs is the 50%, as shown in the previous Table.

The results of the proposed designs, including different partial loads are introduced in Section 5.3, whereas the sizing of the equipment that form each of the defined groups can be found in Section 5.4.

5.3 Heat and mass balance results

The different sets of heat and mass balances for the defined case studies are presented including the main streams thermodynamic parameters for different loading and unloading operating loads:

- Mass flow rate (m) [kg/s]
- Temperature (T) [°C]
- Pressure (p) [bar,a]
- Enthalpy (h) [kJ/kg]

The main performance outputs of the regenerative water-steam Rankine cycle and the Loading System and Unloading System are outlined for each case studies defined. These shall include:

- Reactor thermal power [kWth]
- Plant gross power [kWe]
- Extra steam mass flow [kg/s]
- Molten salts mass flow [kg/s]
- Hot salts thermal input [kWth]
- Cold salts thermal output [kWth]
- Unloading/Loading Gross efficiency [%]

All the heat and mass balances presented are calculated, conservatively, for summertime ambient conditions [ID 3]:

- Ambient temperature: 32 °C
- Ambient relative humidity: 60 %

The defined heat and mass balances and the summary results tables are listed and shown, respectively, in Appendix B.

In order to obtain the overall performance of the plant, the different loading designs are combined with their corresponding unloading designs. Table 9 compares the overall performance of the plant for the different combinations available, for their Base Cases. For each loading design, it is considered that the plant works during one hour, for which the plant stores certain amount of energy in the form of hot molten salts. Then, for the corresponding unloading design, the time that the plant can operate with the previously stored energy is calculated by dividing the stored energy in the loading time by unloading thermal power. For each case an overall efficiency is calculated in the following way, where Q_e is the electric power delivered to the grid, $Q_{Reactor}$ is the thermal power delivered by ALFRED reactor and t is the time the plant works in loading/unloading mode:

$$\eta_{Overall} = \frac{Qe_{Load} \cdot t_{Load} + Qe_{Unload} \cdot t_{Unload}}{Q_{Reactor} \cdot (t_{Load} + t_{Unload})}$$

Table 9 – Molten salts Thermal Energy Storage overall performance

Loading Design	Loading thermal power [MW-th]	Plant net power [MW-e]	% of Nominal net power [%]	Unloading Design	Unloading thermal power [MW-th]	Plant net power [MW-e]	% of Nominal net power [%]	Unloading /Loading time ratio	Overall Eff. [%]
T1L1-BaseCase	83.9	80.6	67.8	T1U1-BaseCase	58.5	136.0	114.4	1.44	37.74
T1L2-BaseCase	168.0	41.5	34.9	T1U1-BaseCase	58.5	136.0	114.4	2.87	37.19
T2L1-BaseCase	83.9	73.6	61.9	T2U2-BaseCase	116.8	153.6	129.1	0.72	35.68
T2L2-BaseCase	166.7	35.0	29.5	T2U2-BaseCase	116.8	153.6	129.1	1.43	34.91
T3L1-BaseCase	83.9	68.3	57.4	T3U3-BaseCase	231.9	187.1	157.4	0.36	33.28
T3L2-BaseCase	166.7	30.1	25.3	T3U3-BaseCase	231.9	187.1	157.4	0.72	31.93

Following the previous Table, an example of operation of the plant is illustrated for the combination of Turbine equipment sizing T2, Loading equipment sizing L1 and Unloading equipment sizing U2. For this sizing the plant could work at full loading operation during one hour, giving an electric power of 73.6 MW-e (61.9 % of nominal net power) and being able to store 83.9 MW·h of thermal energy. Using this stored energy, the plant would be able to turn into the unloading operating mode and work during 0.72 hours (around 43 minutes) giving to the grid an electric power of 153.6 MW-e (129.1 % of nominal power). This working cycle would have an overall process efficiency of 35.68 %.

As mentioned before, the time that the plant could be loading thermal energy would depend on the storage capacity of the molten salts tanks, which shall be analysed under an economic-financial basis.

5.4 Sizing results

Preliminary sizing parameters are given for the different design case studies presented in Section 5.2, for each group of equipment: Water-Steam Cycle (T), Loading System (L) and Unloading System (U). The results are listed and shown in Appendix C, arranged in tables for each design group of equipment. The preliminary sizing of the equipment is performed using PEACE module, included in Thermoflex software.

The design selection among the different analyzed case studies shall be based on the techno-economic analysis to be performed in Deliverable D5.3.

In case of the Storage System (S), Table 10 shows the tanks dimensions for each of the sizing options presented in Section 5.2, for the molten salts total inventory. For each design total capacity, it is calculated the maximum loading or unloading times for each of the molten salts mass flow rates calculated in the heat and mass balances presented in the previous Section (see Appendix B), for the Base Cases.

Table 10 – Storage main equipment sizing

Parameter	Unit	Storage S1	Storage S2	Storage S3
Dimensions				
Height	m	14.2	14.2	14.2
Diameter	m	24.2	27.1	31.3
Total Volume	m3	6543	8179	10905
Total salts	Tn	12000	15000	20000
Available salts	Tn	10560	13200	17600
Loading time				
L1-BaseCase	h	5.7	9.5	19.1
L2-BaseCase	h	2.9	4.8	9.6
Unloading time				
U1-BaseCase	h	8.5	14.1	28.3
U2-BaseCase	h	4.2	7.1	14.2
U3-BaseCase	h	2.1	3.6	7.1

It is considered that both tanks (hot and cold salts) have the same dimensions, for design simplicity and optimization. In order to calculate the total volume of each of the tanks, there are some operational margins that have to be applied: 3% margin for safety space, 6% margin for the stagnant salts space in the bottom of the tanks and a 3% margin for the salts stored in the piping and Loading and Unloading Systems equipment. Applying these margins, the available salts to be loaded or unloaded represent the 88% of the total salts inventory.

Some other considerations have to be taken into account for the tank dimensions calculation. The volume calculation is performed for the hot salts density at 400 °C, which is taken as 1834 kg/m^3, giving conservative results. Following good practices learnt from CSP projects, the maximum height of the tanks is considered 14.2 m, because going further can result in over costs due to constructive problems.

The molten salts storage tanks sizing strongly depends on the economic assessment of the whole plant, taking into account the performance regimes of the plant regarding the hours spent in each of the main operating modes defined for the plant operation (nominal, loading and unloading).

6 Hydrogen production

Following the description of the hydrogen production by electrolysis solution assessed in ANSELMUS Deliverable D5.1 [4], this chapter develops the final configuration, defines its main equipment, and provides the Heat and Mass Balances for different sizing designs.

6.1 Selected configuration

The conceptual design of the Hydrogen Production (HP) using High Temperature Steam Electrolysis (HTSE) is formed by two main systems:

- Heat Transfer System
- HTSE System

The Heat Transfer System uses steam from the water-steam cycle of the plant to heat up a heat transfer fluid while the steam is condensed and driven back to the water-steam cycle of the plant (described in Section 4 and shown in Appendix A), at its corresponding point. The selected heat transfer fluid is the thermal oil Therminol-66 [3], which circulates through an intermediate circuit that is used as a safety and buffer system between the NPP and the HTSE facility. Further information about this configuration can be found in previous deliverable ANSELMUS D5.1 [4].

The following Sections explain the main functions to be performed by these systems and define their main components to be sized in this preliminary stage.

6.1.1 Heat Transfer System

The main function of the Heat Transfer System is to transfer the heat from the steam derived from the water-steam cycle systems to the process stream of the HTSE System.

Therminol-66 is the most popular high-temperature, liquid-phase heat transfer fluid that offers long life operation at high temperatures and resists solids formation and system fouling, providing more reliable operation and potential cost savings. It is a clear, pale yellow liquid composed by modified terphenyl, and operates at temperatures between -3 °C and 345 °C [5].

The heat source for the HTSE is preferable to be saturated steam, with a pressure high enough to have a saturation temperature suitable for the heat transfer processes ahead. The selected point of the water-steam cycle is the outlet of the Moisture Separator located at the HPT exhaust, so that this steam mass flow is already expanded in the turbine, and its saturation conditions are guaranteed.

In a first set of heat exchangers, the steam coming from the plant is condensed in a steam Condenser and then cooled down in a Sub-Cooler before returning back the liquid water into the water-steam cycle. The selected point for the water return is the inlet of the Deaerator, before being pumped by the Feedwater Pumps.

The described interface conditions between the water-steam cycle, the Heat Transfer System and then HTSE Modules are specified below:

- Steam Inlet: 247 °C / 37 bar (Moisture Separator Outlet)
- Feedwater Outlet: 200 °C / 18 bar (FWH#4 Outlet)
- Hot Thermal oil: 239.5 °C
- Cold Thermal oil: 162.8 °C

- HTSE Water Inlet: 152.5 °C / 5.9 (HTSE Water Outlet, see Table 11)
- HTSE Steam Outlet: 154.8 °C / 5.4 (HTSE Steam Inlet, see Table 11)

The thermal oil is heated up close to the saturation temperature of the feeding steam (239.5 °C, as the Terminal Temperature Difference of the Condenser is set to 3 °C). Afterwards, it passes through the HTSE Evaporator, where it transfers part of its heat to produce the HTSE process steam out of the incoming HTSE process liquid. The thermal oil cold temperature (162.8 °C) is determined by the shell-side saturation temperature of the Evaporator plus the design pinch point temperature, set to 8 °C. The HTSE steam flow rate to be produced shall depend on how many HTSE modules have to be fed, and this will determine the thermal oil flow rate and the water-steam cycle derived steam flow rate.

The main equipment of this system for which a preliminary sizing is presented in this report are the following ones, with the designated identification in the heat and mass balances shown in Appendix D:

- Condenser: Shell-Tube Condensing HX (PCE) (60)
- Sub-Cooler: Shell-Tube General HX (PCE) (71)
- HTSE Evaporator: Shell-Tube Evaporating HX (PCE) (56)
- HTS Pump: General Pump (PCE) (59)

6.1.2 HTSE System

The High Temperature Steam Electrolysis (HTSE) System is considered as a closed Skid package which is provided in standardized modules. The operation description of this system is provided in ANSELMUS deliverable D5.1 [4].

This technology is under development by different universities and companies, but it is still not under commercial deployment. Following the design provided by ANSALDO Nucleare about the possible ALFRED-HTSE architecture options [3], a research of the state of the art for this technology has been performed. A recent study made by the Idaho National Laboratory called “High-Temperature Steam Electrolysis Process Performance and Cost Estimates” published in March 2022 [6] offers the most complete, reliable and public reference to be used for this analysis.

The main interfaces of this Skid are depicted in Figure 3 and their interactions are described in ANSELMUS Deliverable D5.1 [4].

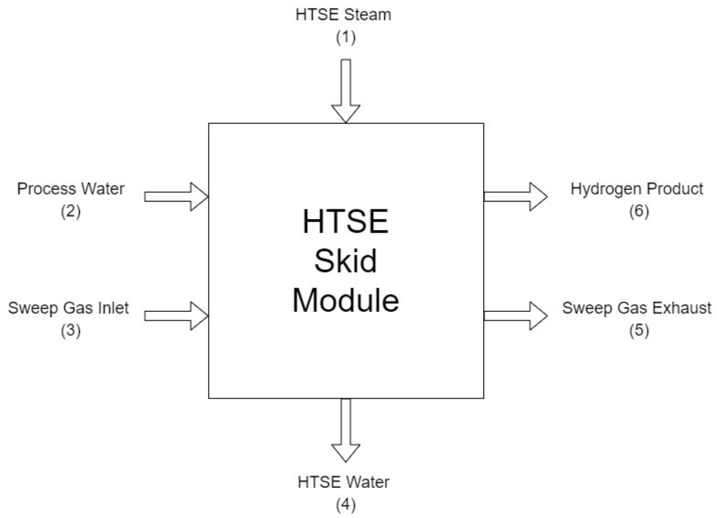


Figure 3 – HTSE Skid Module schematic

As it is shown, six main streams are defined as the interface fluid connections of the HTSE skid. Following the mentioned reference [6], these interfaces are defined for a single module of HTSE in Table 11:

Table 11 – HTSE Skid Module interfaces

Stream	ID	Flow direction	Fluid [mole fraction]	Mass flow [kg/s]	Pressure [bar,a]	Temperature [°C]
HTSE Steam	1	Inlet	Saturated Steam	2.21	5.40	154.8
Process Water	2	Inlet	Subcooled Water	1.82	5.17	10.0
Sweep Gas Inlet	3	Inlet	21% O_2 - 79% N_2	4.59	1.01	20.0
HTSE Water	4	Outlet	Subcooled Water	2.21	5.90	152.5
Sweep Gas Exhaust	5	Outlet	40% O_2 - 60% N_2	6.20	1.01	98.3
Hydrogen Product	6	Outlet	100% H_2	0.20	20.0	15.0

An additional non-fluidic interface is the total AC electric power supply for the HTSE module. This value is taken as being 26.9 MW-e [6]. This value includes the DC power that feeds the stack power input as well as the AC power for the AC power rectifier, pumps, compressors and topping heaters of the Skid.

As it can be observed in the previous Table, the hydrogen product is 100% pure hydrogen delivered at 20 bar,a and 15 °C.

6.2 Case studies

The heat and mass balance calculations for the configuration described above is based on the number of HTSE Skid Modules that shall be fed by the steam produced in the water-steam cycle of the plant and the electric power derived from the Steam Turbine electric generator.

For the selected reference HTSE Skid Module, the total AC electric consumption of each module is 26.9 MW, so this shall be the limiting factor for the HTSE sizing. For a nominal net power of the water-steam cycle presented in Section 4.2 of 118.9 MW, the maximum number of HTSE Skid Modules that can be fed by the electric generator of the plant is four, assuming that the loss of gross electric power produced due to the delivered thermal energy into the HTSE will not be higher than 8 MW-e, as it is demonstrated in the following Section.

Therefore, four designs shall be assessed for the Hydrogen production cogeneration option, based on the number of HTSE Skid Modules that are included and the corresponding thermal and electric inputs to be supplied by the cycle, as shown in Table 12.

Following this criteria, there are four different sizing designs for the Hydrogen equipment group (H):

- H1, with one HTSE Skid Module,
- H2, with two HTSE Skid Modules,
- H3, with three HTSE Skid Modules,
- H4, with four HTSE Skid Modules.

These four Hydrogen equipment group designs (H) have to be combined with the nominal design of the Water-steam Cycle (T) shown in section 4.2 (for the summertime ambient conditions) as the performance will vary for each combination. This is shown in Table 12.

Table 12 – Hydrogen production design case studies

Design ID	Number of HTSE Skid Modules	HTSE process steam flow [kg/s]	HTSE Electric Power [MW-e]
TH1	1	2.21	26.9
TH2	2	4.43	53.8
TH3	3	6.64	80.7
TH4	4	8.85	108

Each design for the hydrogen production facility is integrated to the nominal design of the water-steam cycle (identified as T) described in Section 4, for which the heat and mass balance is included in Appendix A, and the sizing of its equipment is shown in Table C- 1 of Appendix C.

Due to the modular nature of this configuration for the HTSE hydrogen production process, the partial loads performance for each of the designs do not differ in a significant way from the performance of the rest of the designs working with the same number of modules. This is, the performance of TH4 design with just three HTSE Skid Modules in operation do not differ from the performance of design TH3 operating at full capacity, with its three HTSE Skid Modules in operation. The HTSE Skid Modules are considered to work at full steady-state load, so no partial load calculations are shown for the proposed designs. Transient operation could by admitted by the Solid Oxide Electrolysis Cell (SOEC) stacks, so partial loads or even reverse operation could be considered in future steps of the project.

The heat and mass balances for each of these design cases are presented in the following Section, whereas the sizing of the main equipment is included in Section 6.4.

6.3 Heat and mass balance results

The heat and mass balances for the defined case studies are presented including the main streams thermodynamic parameters:

- Mass flow rate (m) [kg/s]
- Temperature (T) [°C]
- Pressure (p) [bar,a]
- Enthalpy (h) [kJ/kg]

The main performance outputs of the regenerative water-steam Rankine cycle, the Heat Transfer System and HTSE Skid Module are outlined for each case studies defined. These shall include:

- Reactor thermal power [kWth]
- Cycle gross power [kWe]
- Grid power [kWe]
- HTSE steam mass flow [kg/s]
- Thermal oil mass flow [kg/s]
- Heat from HTSE [kWth]
- Heat to HTSE [kWth]
- HTSE AC electric power [kWe]
- Cycle Net Efficiency [%]

As for previous Chapter for the molten salts thermal storage option, all the heat and mass balances presented are calculated, conservatively, for summertime ambient conditions [ID 3]:

- Ambient temperature: 32 °C
- Ambient relative humidity: 60 %

The defined heat and mass balances are listed and shown in 0.

Table 13 summarizes the results obtained using THERMOFLEX software for each of the defined designs, where the HTSE Skid Modules interface parameters have been included. The overall efficiency $\eta_{Overall}$ is calculated in the following way, where Qe_{Grid} is the electric power delivered to the grid; Q_{H2} is the thermal power stored in form of gas, considering the Higher Heating Value (HHV) of hydrogen, which is 141.9 MW/kg; $Q_{Reactor}$ is the thermal power delivered by ALFRED reactor; $Q_{HTSE\ Process\ water}$ is the thermal power of the HTSE module inlet process water current; and $Q_{HTSE\ Sweep\ Gas\ Inlet}$ is the thermal power of the HTSE module inlet sweep gas current:

$$\eta_{Overall} = \frac{Qe_{Grid} + Q_{H2}}{Q_{Reactor} + Q_{HTSE\ Process\ water} + Q_{HTSE\ Sweep\ Gas\ Inlet}}$$

Table 13 – Hydrogen production performance results

Variable	Unit	TH1	TH2	TH3	TH4
Number of HTSE Skid Modules	-	1	2	3	4
Cycle gross power	kW-e	127146	125490	123836	122175
Grid power	kW-e	89453	60904	32361	3806
Water-Steam Cycle derived mass flow	kg/s	2.41	4.83	7.24	9.65
HTSE steam mass flow	kg/s	2.21	4.43	6.64	8.85

Table 13 – Hydrogen production performance results

Variable	Unit	TH1	TH2	TH3	TH4
Thermal oil mass flow	kg/s	27.57	55.27	82.84	110.4
Heat from HTSE	kW-th	1421	2848.4	4269	5690
Heat to HTSE	kW-th	6079	12186	18265	24344
HTSE AC electric power	kW-e	26900	53800	80700	107600
Cycle Net Efficiency	%	40.34	41.35	42.35	43.35
Hydrogen production	kg/s	0.203	0.406	0.609	0.812
Hydrogen thermal power (HHV)	kW-th	28815	57631	86446	115261
HTSE Process water	kW-th	77.2	154.4	231.5	308.7
HTSE Sweep Gas Inlet	kW-th	92.3	184.7	277.0	369.3
HTSE Efficiency	%	90.82	90.79	90.80	90.81
Overall Efficiency	%	39.40	39.47	39.54	39.60

6.4 Sizing results

Preliminary sizing parameters are given for the different design case studies presented in Section 6.2, for the equipment forming the Heat Transfer System. As mentioned before, the HTSE Skid Modules shall be supplied as a fixed and complete skid, formed by all the equipment and sub-systems considered by the manufacturer. The interfaces of the Skid shall be the ones defined in Table 11.

The results of the sizing for the hydrogen production systems are listed and shown in Appendix E, arranged in tables for each design. The sizing for the water-steam cycle main equipment is shown in Table C- 1 of Appendix C.

The design selection among the different analysed case studies shall be based on the techno-economic analysis to be performed in Deliverable D5.3.

7 Conclusions

The two analyzed technologies, molten salt thermal storage and hydrogen production, can be integrated with the water-steam regenerative cycle proposed for ALFRED reactor. It is firstly assessed the performance of the cycle for nominal operation, with no load-following, without hydrogen production or thermal energy storage. For summertime ambient conditions (32 °C, 60% RH), this cycle delivers a full load net electric power of 118.9 MW-e with a net efficiency of 39.6%, which is in line with other lead fast cooled reactors under design phase. During yearly average ambient conditions (12 °C, 60% RH, nominal conditions), the cycle performance could increase up to a net electric production of 121.7 MW-e and 40.58 % net efficiency, due to the reduction of the condensing pressure in the Air-Cooled Condenser.

The molten salts thermal energy storage solution is a commercially developed technology. The equipment of the water-steam cycle, including the steam turbine generator, has to be oversized with respect to its nominal operation to admit the extra steam generated when using the hot salts storage, in a proportional way with the unloading capacity. For the different proposed designs, the plant net power can increase up to 136.0 MW-e (T1U1 design), 153.6 MW-e (T2U2) or 187.1 MW-e (T3U3), with decreasing net efficiencies: 37.9%, 36.8% and 35.2%, respectively. As the intervening flow rates, thermal and power capacities of each design increase, the equipment associated is logically bigger, and thus, more expensive.

Regarding the biggest loading design option (T3L2), the plant with a thermal storage power capacity of 166.7 MW-th (see Table 9) must decrease its delivered electric power to the grid to a minimum of 30.1 MW-e. For the smallest loading design option (T1L1), the plant with 84.0 MW-th of thermal storage power will have to decrease to 80.6 MW-e the electric production. During loading operating mode, the more thermal power is stored in form of hot salts, the higher is the efficiency of the cycle, as less reactor thermal power is converted into electric power, which is a more inefficient process.

The overall efficiencies of the molten salts thermal storage for ALFRED plant are between 32% (T3L2 loading design and T3U3 unloading design) and 38% (T1L1 loading design and T1U1 unloading design), corresponding to the biggest design option for Turbine, Loading and Unloading equipment, and to the smallest one, respectively. Table 9 shows the plant overall performance for different Loading and Unloading designs. For passing from power terms to energy terms, several storage capacities are proposed for different salts tanks dimensions (S1, S2 and S3), offering different loading and unloading total operating times (see Table 10).

The results herein presented offer a wide variety of performance options for the plant with load-following capability in the hour-to-hour base, in terms of maximum and minimum electric power and corresponding thermal storage power and cycle efficiencies. The selection of the most suitable options shall be based on the techno-economic analysis of the plant to be performed in future steps of the project. This analysis should include the annual operation, in which it shall be analyzed different loading and unloading times and partial loads, yielding different sizing options for the hot and cold salts storage tanks.

Regarding the hydrogen production option for ALFRED plant, the integration of the HTSE system based on the INL reference [6] is analyzed in a modular way. One to four modules of the HTSE Skid are proposed to be fed by the water-steam cycle of the plant.

The thermal input obtained from the saturated steam at the exhaust of the HPT is small compared to the electric input. Thus, the gross electric power of the plant is affected in a very slightly way, going from a gross electric production of 127.1 MW-e when feeding one HTSE Skid module to 122.2 MW-e when feeding four modules (Table 13). The electric power required by the HTSE (26.9 MW-e) is the limiting factor in the integration with the cycle, as the electric power delivered to the grid highly decreases to feed each module. The overall efficiency of the whole process is maintained around 39.5%.

At this stage of the project , the HTSE Skid modules are modeled considering that they work in steady state conditions, so the only partial loads admitted by this configuration is the connection of one, two, three or four modules, with no intermediate operating points between these ones. Thus, the load-following capacity is limited to the steps corresponding to the HTSE modules in operation. In future steps of the project, when suppliers of this kind of technology are involved, transient conditions, partial loads or even reverse operation could be considered.

The most relevant operating and performance parameters associated to the defined configurations for both proposed technological solutions are herein depicted for several design options, in a preliminary basis. The main equipment is listed and defined, giving the main operating and associated constructive parameters for the techno-economic analysis to be performed in the Sub-Task 5.1.2 of the project.

8 References

[1] ANSELMUS Proposal 1011061185 document. HORIZON-EURATOM-2021-NRT-01-02, October 2021.

[2] “ALFRED Balance of Plant. General Considerations”, ALFRED project: Advanced Lead-cooled Fast Reactor European Demonstrator. EAI Ref Z72-053-F-M-00001 Ed1, December 2020.

[3] “WP ANN input data.zip”, ANSALDO Nucleare input data documents, 17th January 2023.

[4] ANSELMUS Deliverable, D5.1 LFR BOP Configurations analysis: definition of the final system configuration, equipment specifications and balance of plant, 13th March 2023.

[5] Therminol 66 Heat Transfer Fluid | Therminol | Eastman. (s. f.). https://www.therminol.com/product/71093438?pn=Therminol-66-Heat-Transfer-Fluid

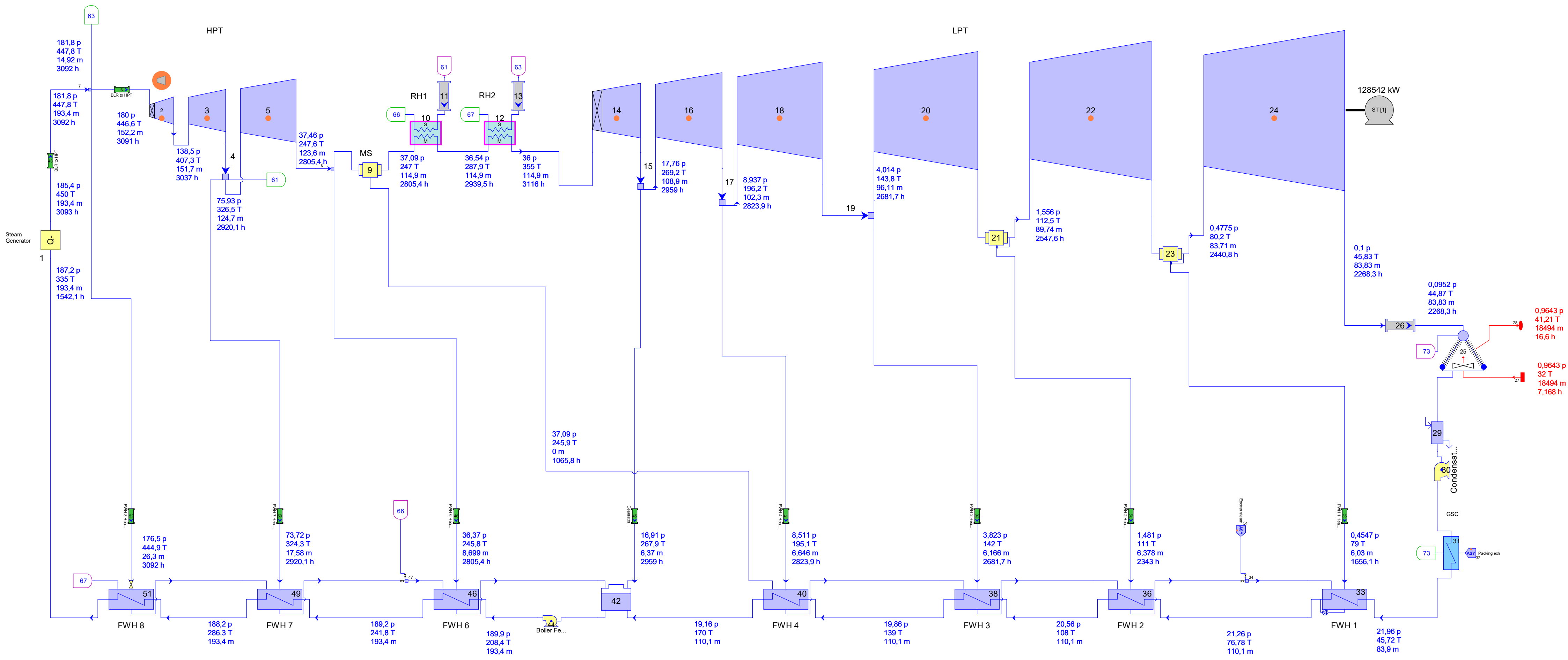
[6] Wendt, D., & Knighton, L. (2022). High Temperature Steam Electrolysis Process Performance and Cost Estimates. Idaho National Laboratory https://doi.org/10.2172/1867883

Appendix A Nominal load heat and mass balance

In this Appendix the following schematics can be found, belonging to the nominal load heat balance (Chapter 4):

- Heat and mass balance for design conditions (32 °C, 60% RH)
- Steam Turbine Mollier Chart for design conditions (32 °C, 60% RH)
- Heat and mass balance for mild conditions (18 °C, 60% RH)
- Steam Turbine Mollier Chart for mild conditions (18 °C, 60% RH)
- Heat and mass balance for nominal conditions (12 °C, 60% RH)
- Steam Turbine Mollier Chart for nominal conditions (12 °C, 60% RH)
- Heat and mass balance for wintertime conditions (-13 °C, 100% RH)
- Steam Turbine Mollier Chart for wintertime conditions (-13 °C, 100% RH)

bar | C
kg/s | kJ/kg



Plant gross power	128542 kW
Plant net power	118897 kW
Gross efficiency	42,85 %
Net efficiency	39,63 %

Site: Ambient temperature	32 C
Site: Ambient relative humidity	60 %

LFR Water-Steam Cycle
Nominal Mode - 32C, 60% RH
T

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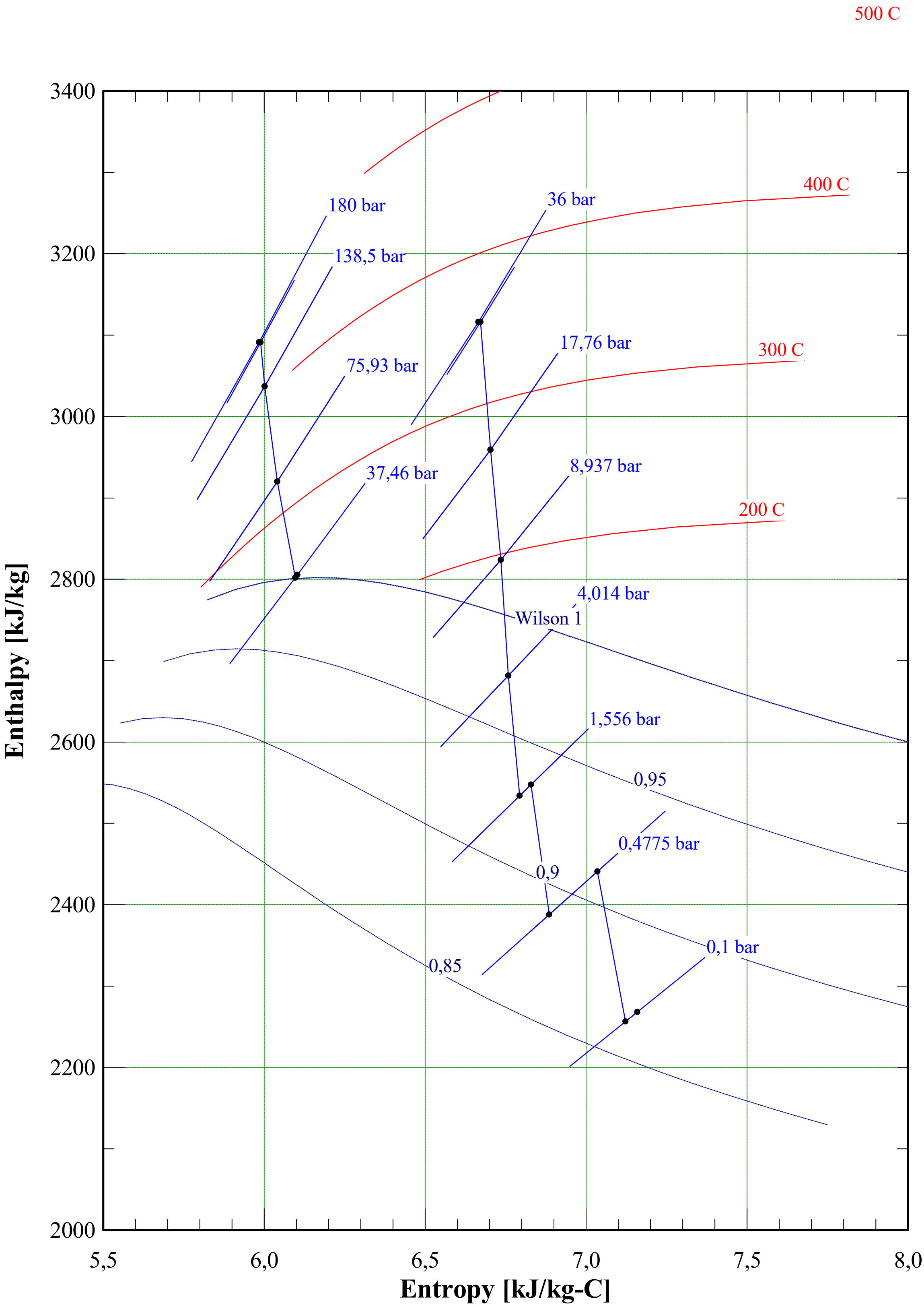
ST Mollier Chart: ST Assembly



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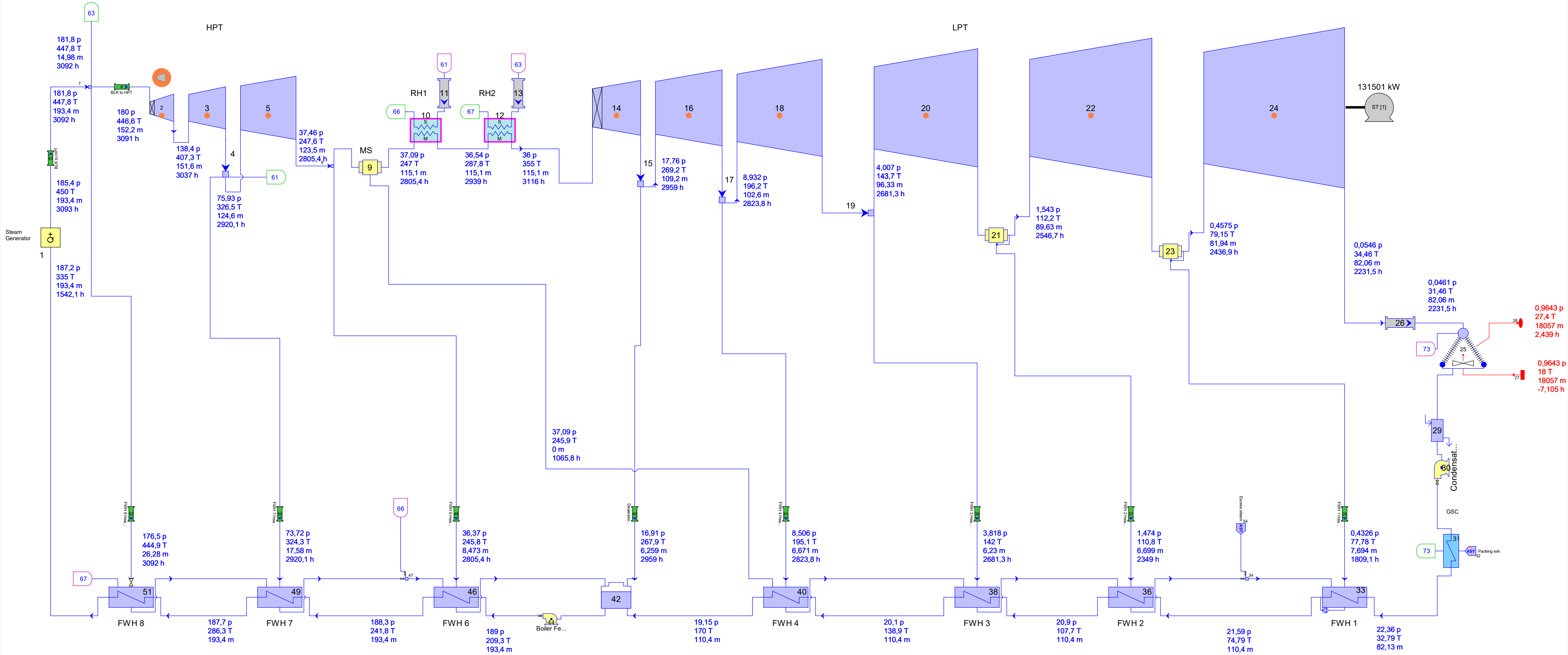
bar	C
kg/s	kJ/kg



Plant gross power	131501 kW
Plant net power	120892 kW
Gross efficiency	43,83 %
Net efficiency	40,3 %

Site: Ambient temperature	18 C
Site: Ambient relative humidity	60 %

LFR Water-Steam cycle
Nominal Mode - 18C, 60% RH
T

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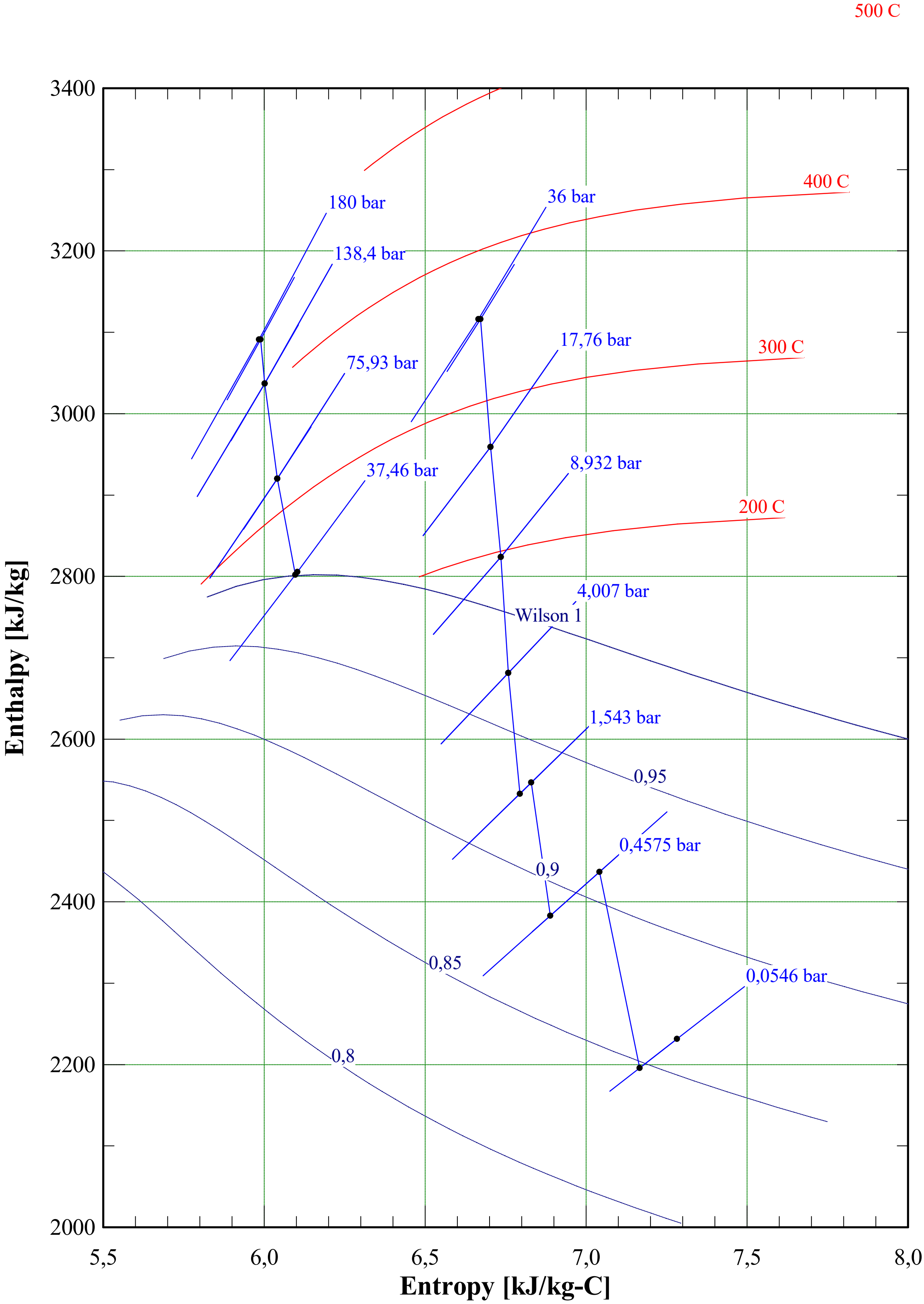
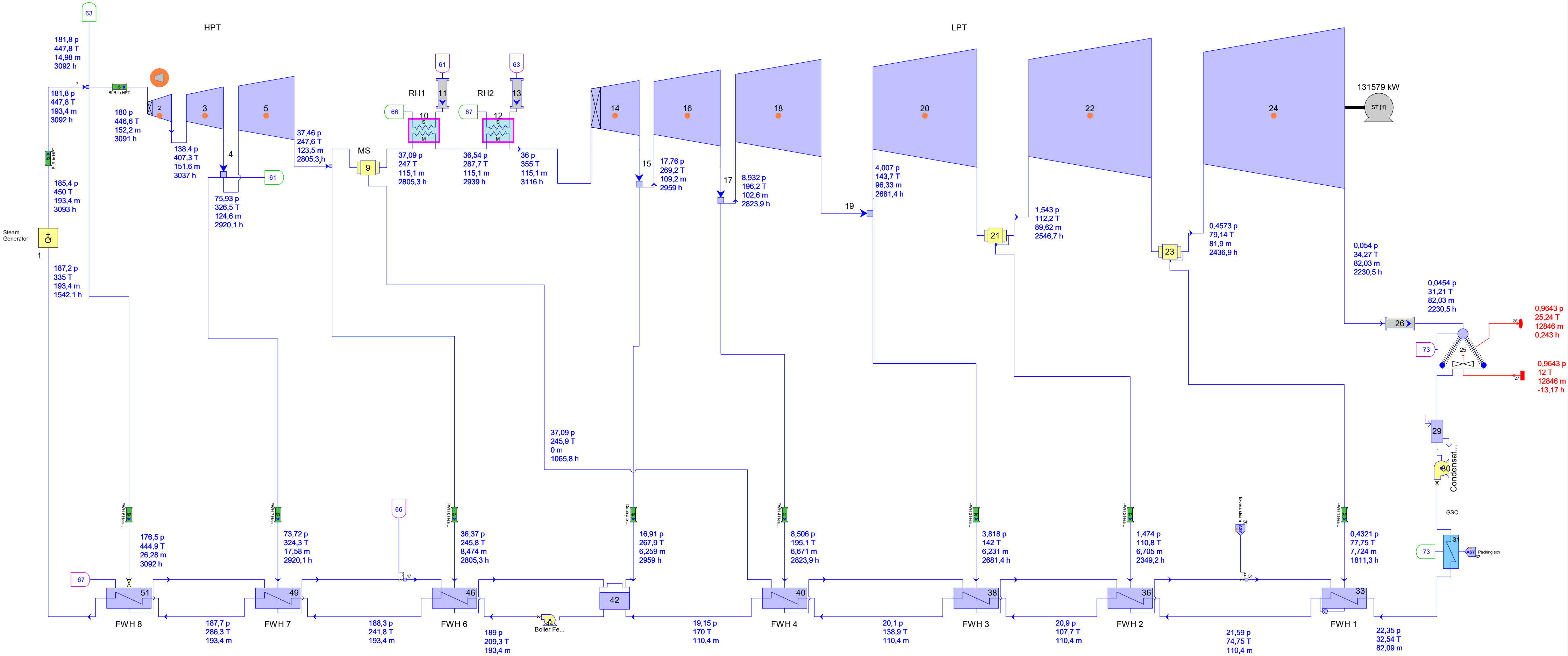
ST Mollier Chart: ST Assembly



bar	C
kg/s	kJ/kg



Plant gross power	131579 kW
Plant net power	121732 kW
Gross efficiency	43,86 %
Net efficiency	40,58 %

Site: Ambient temperature	12 C
Site: Ambient relative humidity	60 %

LFR Water-Steam cycle
Nominal Mode - 12C, 60% RH
T

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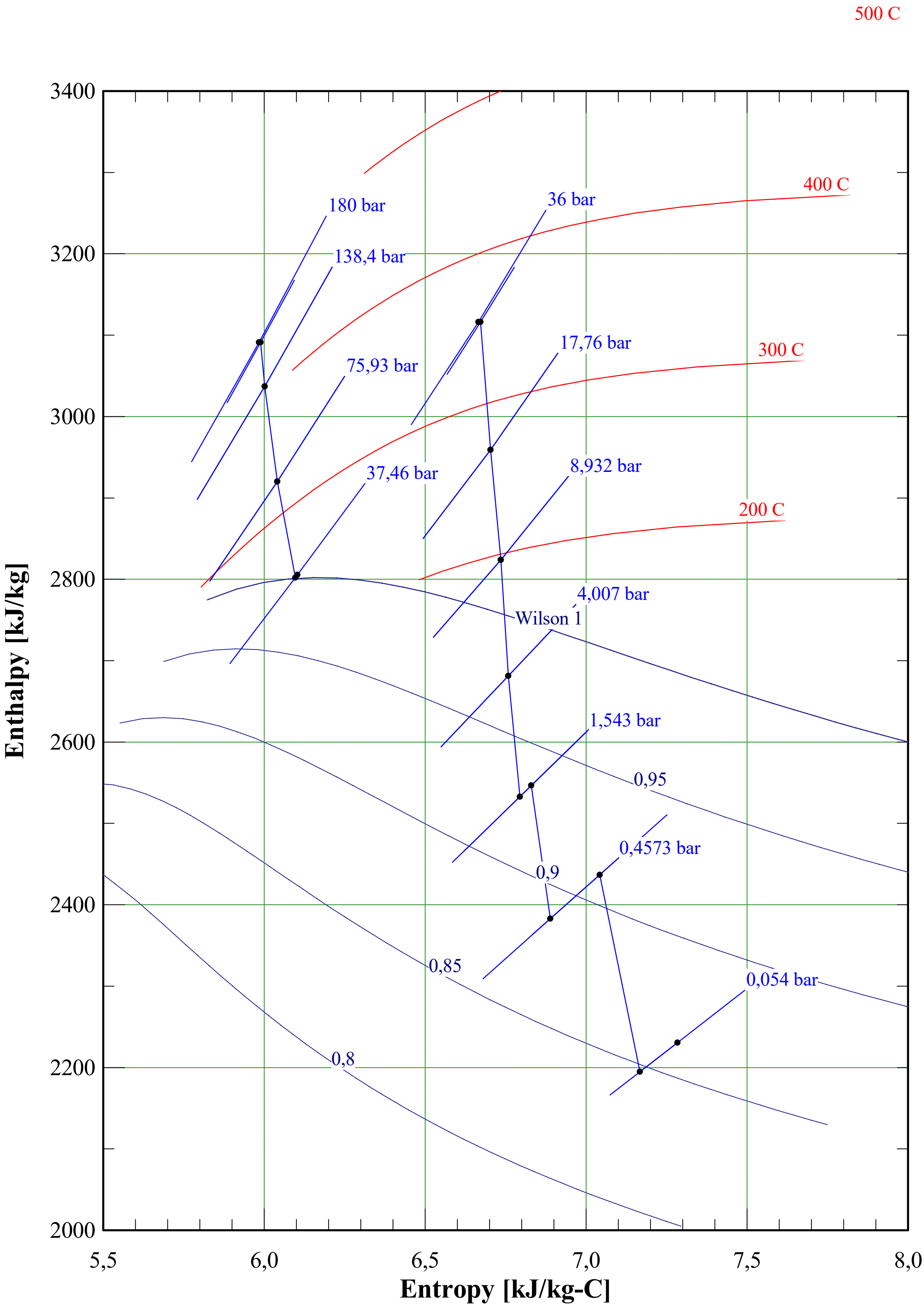
ST Mollier Chart: ST Assembly



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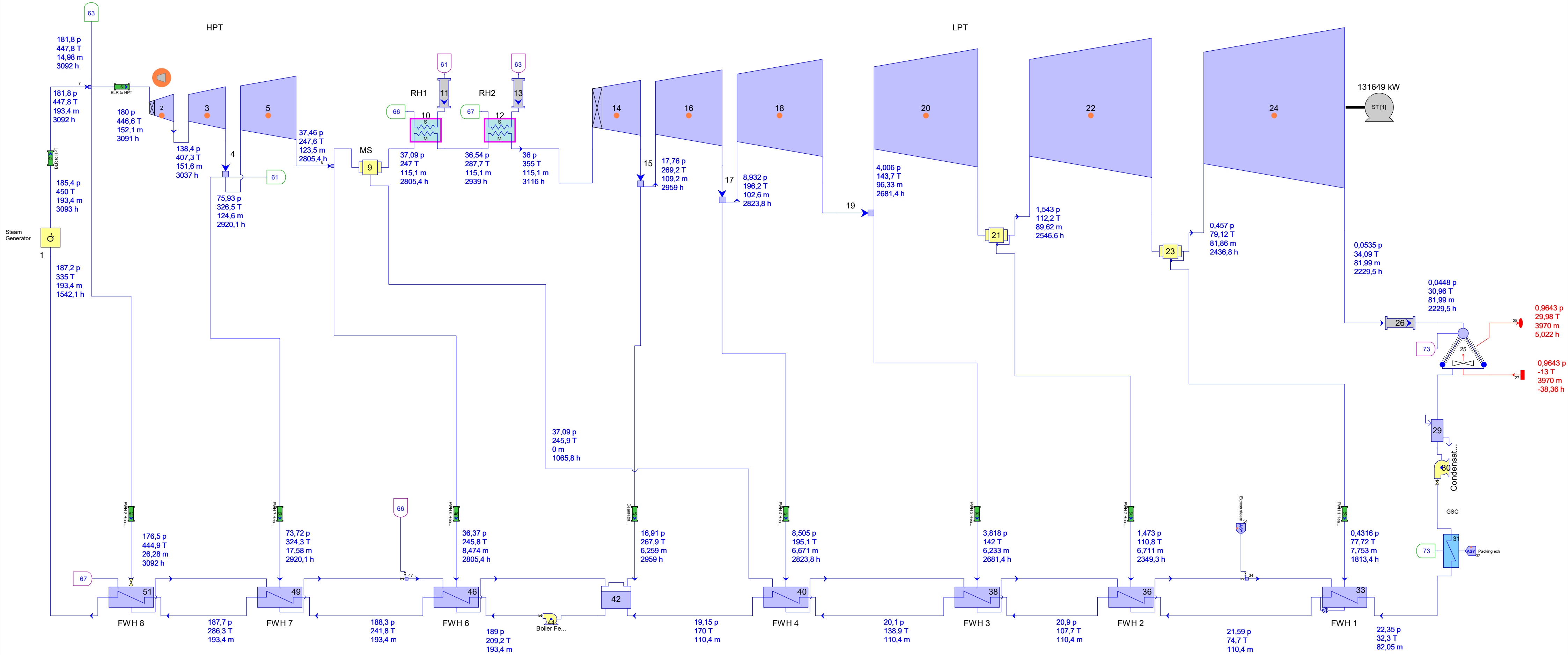
bar | C
kg/s | kJ/kg



Plant gross power	131649 kW
Plant net power	123551 kW
Gross efficiency	43,88 %
Net efficiency	41,18 %

Site: Ambient temperature	-13 C
Site: Ambient relative humidity	100 %

LFR Water-Steam cycle
Nominal Mode - -13C, 100% RH
T

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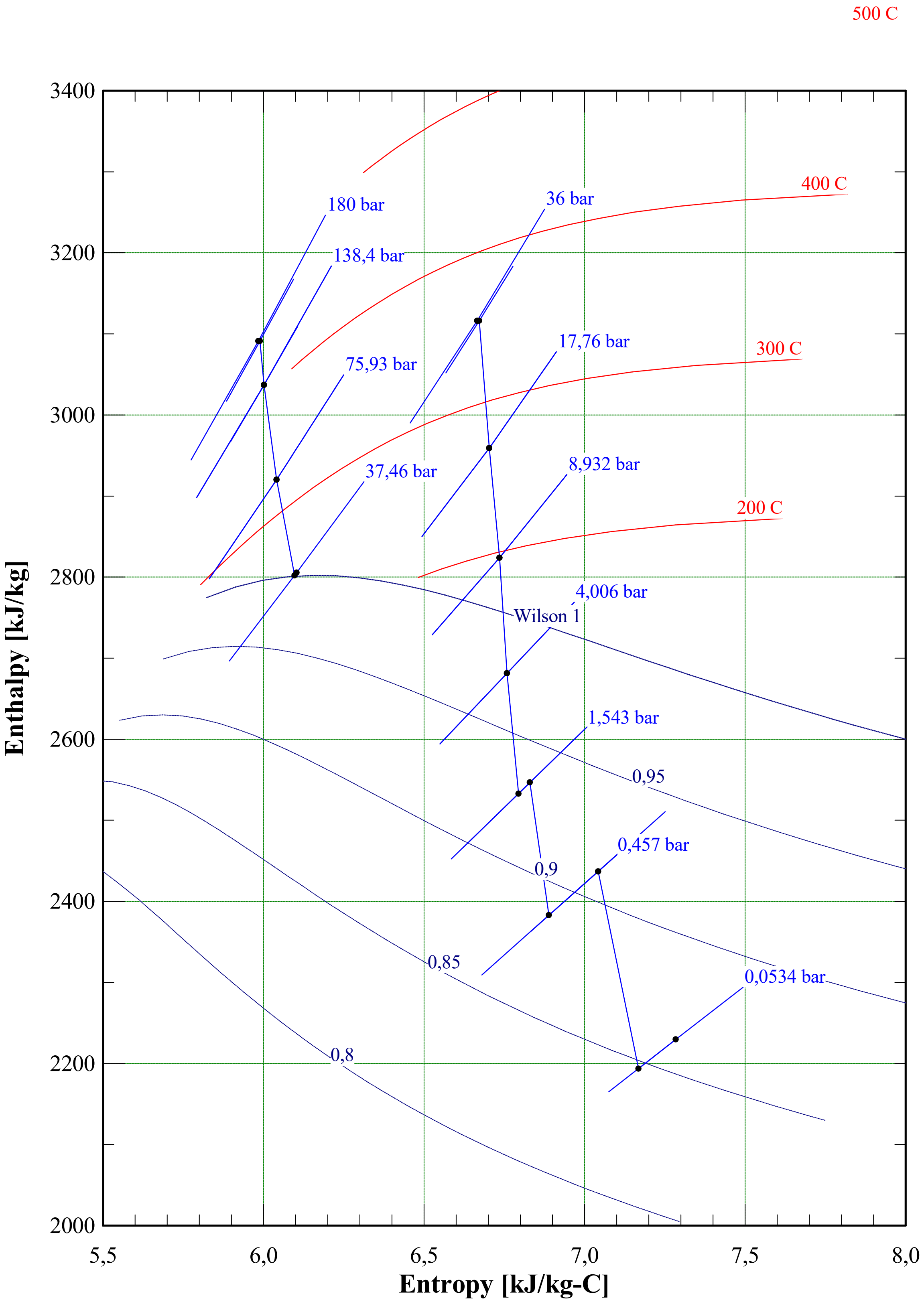
ST Mollier Chart: ST Assembly



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Appendix B Molten salts thermal storage heat and mass balances

The results of the heat and mass balances for the molten salts thermal energy storage solution design cases presented in Section 5.3 are shown in the following tables:

- Design Case T1U1: Table B- 1 – T1U1 partial loads
- Design Case T2U2: Table B- 2 – T2U2 partial loads
- Design Case T3U3: Table B- 3 – T3U3 partial loads
- Design Case T1L1: Table B- 4 – T1L1 partial loads
- Design Case T1L2: Table B- 5 – T1L2 partial loads
- Design Case T2L1: Table B- 6 – T2L1 partial loads
- Design Case T2L2: Table B- 7 – T2L2 partial loads
- Design Case T3L1: Table B- 8 – T3L1 partial loads
- Design Case T3L2: Table B- 9 – T3L2 partial loads

Table B- 1 – T1U1 partial loads

Parameter	Unit	BaseCase	Case1	Case2	Case3
Plant gross power	kW-e	149060	144002	138668	133047
Plant net power	kW-e	135966	131083	125928	120491
% of Nominal net power	%	114.4	110.2	105.9	101.3
Unloading steam mass flow	kg/s	28.7	21.9	14.8	7.5
Molten salts mass flow	kg/s	345.8	259.3	172.9	86.4
Hot salts thermal input	kW-th	347582	260686	173791	86895
Cold salts thermal output	kW-th	-289093	-215942	-143376	-71403
Unloading thermal power	kW-th	58489	44744	30415	15493
Gross efficiency	%	41.58	41.77	41.97	42.17
Net efficiency	%	37.93	38.02	38.11	38.19

Table B- 2 – T2U2 partial loads

Parameter	Unit	BaseCase	Case1	Case2	Case3
Plant gross power	kW-e	169297	159181	148521	137238
Plant net power	kW-e	153553	143827	133572	122682
% of Nominal net power	%	129.1	121.0	112.3	103.2
Unloading steam mass flow	kg/s	57.5	43.9	29.8	15.1
Molten salts mass flow	kg/s	690.4	517.8	345.2	172.6
Hot salts thermal input	kW-th	694068	520551	347034	173517
Cold salts thermal output	kW-th	-577220	-431165	-286275	-142570
Unloading thermal power	kW-th	116847	89386	60759	30947
Gross efficiency	%	40.61	40.88	41.17	41.47
Net efficiency	%	36.84	36.94	37.03	37.07

Table B- 3 – T3U3 partial loads

Parameter	Unit	BaseCase	Case1	Case2	Case3
Plant gross power	kW-e	209507	189403	168250	145742
Plant net power	kW-e	187110	167966	147757	126134
% of Nominal net power	%	157.4	141.3	124.3	106.1
Unloading steam mass flow	kg/s	114.9	87.7	59.7	30.4
Molten salts mass flow	kg/s	1368.7	1026.5	684.4	342.2
Hot salts thermal input	kW-th	1375955	1031966	687978	343989
Cold salts thermal output	kW-th	-1144074	-854572	-567395	-282594
Unloading thermal power	kW-th	231881	177394	120583	61395
Gross efficiency	%	39.39	39.67	40.00	40.33
Net efficiency	%	35.18	35.18	35.13	34.90

Table B- 4 – T1L1 partial loads

Parameter	Unit	BaseCase	Case1	Case2
Plant gross power	kW-e	91759	101637	111674
Plant net power	kW-e	80578	90317	100104
% of Nominal net power	%	67.8	76.0	84.2
Loading steam mass flow	kg/s	60.9	45.7	30.4
Molten salts mass flow	kg/s	512.1	384.1	256.0
Hot salts thermal input	kW-th	-513833	-385518	-257004
Cold salts thermal output	kW-th	429884	322413	214942
Loading thermal power	kW-th	83949	63105	42062
Gross efficiency	%	58.57	54.91	51.25
Net efficiency	%	54.84	51.14	47.39

Table B- 5 – T1L2 partial loads

Parameter	Unit	BaseCase	Case1	Case2
Plant gross power	kW-e	51864	71513	91559
Plant net power	kW-e	41489	60894	80487
% of Nominal net power	%	34.9	51.2	67.7
Loading steam mass flow	kg/s	121.8	91.3	60.9
Molten salts mass flow	kg/s	1023.5	767.6	511.7
Hot salts thermal input	kW-th	-1027154	-770541	-513846
Cold salts thermal output	kW-th	859161	644371	429580
Loading thermal power	kW-th	167993	126170	84266
Gross efficiency	%	73.29	65.89	58.61
Net efficiency	%	69.83	62.35	54.92

Table B- 6 – T2L1 partial loads

Parameter	Unit	BaseCase	Case1	Case2
Plant gross power	kW-e	85962	95833	105848
Plant net power	kW-e	73620	83332	93183
% of Nominal net power	%	61.9	70.1	78.4
Loading steam mass flow	kg/s	60.9	45.7	30.4
Molten salts mass flow	kg/s	512.1	384.1	256.0
Hot salts thermal input	kW-th	-513824	-385510	-256998
Cold salts thermal output	kW-th	429884	322413	214942
Loading thermal power	kW-th	83940	63097	42056
Gross efficiency	%	56.63	52.98	49.30
Net efficiency	%	52.52	48.81	45.08

Table B- 7 – T2L2 partial loads

Parameter	Unit	BaseCase	Case1	Case2
Plant gross power	kW-e	46551	65348	85746
Plant net power	kW-e	35046	53532	73513
% of Nominal net power	%	29.5	45.0	61.8
Loading steam mass flow	kg/s	121.8	91.3	60.9
Molten salts mass flow	kg/s	1023.5	767.6	511.7
Hot salts thermal input	kW-th	-1025897	-770525	-513836
Cold salts thermal output	kW-th	859161	644371	429580
Loading thermal power	kW-th	166736	126154	84256
Gross efficiency	%	71.10	63.83	56.67
Net efficiency	%	67.26	59.90	52.59

Table B- 8 – T3L1 partial loads

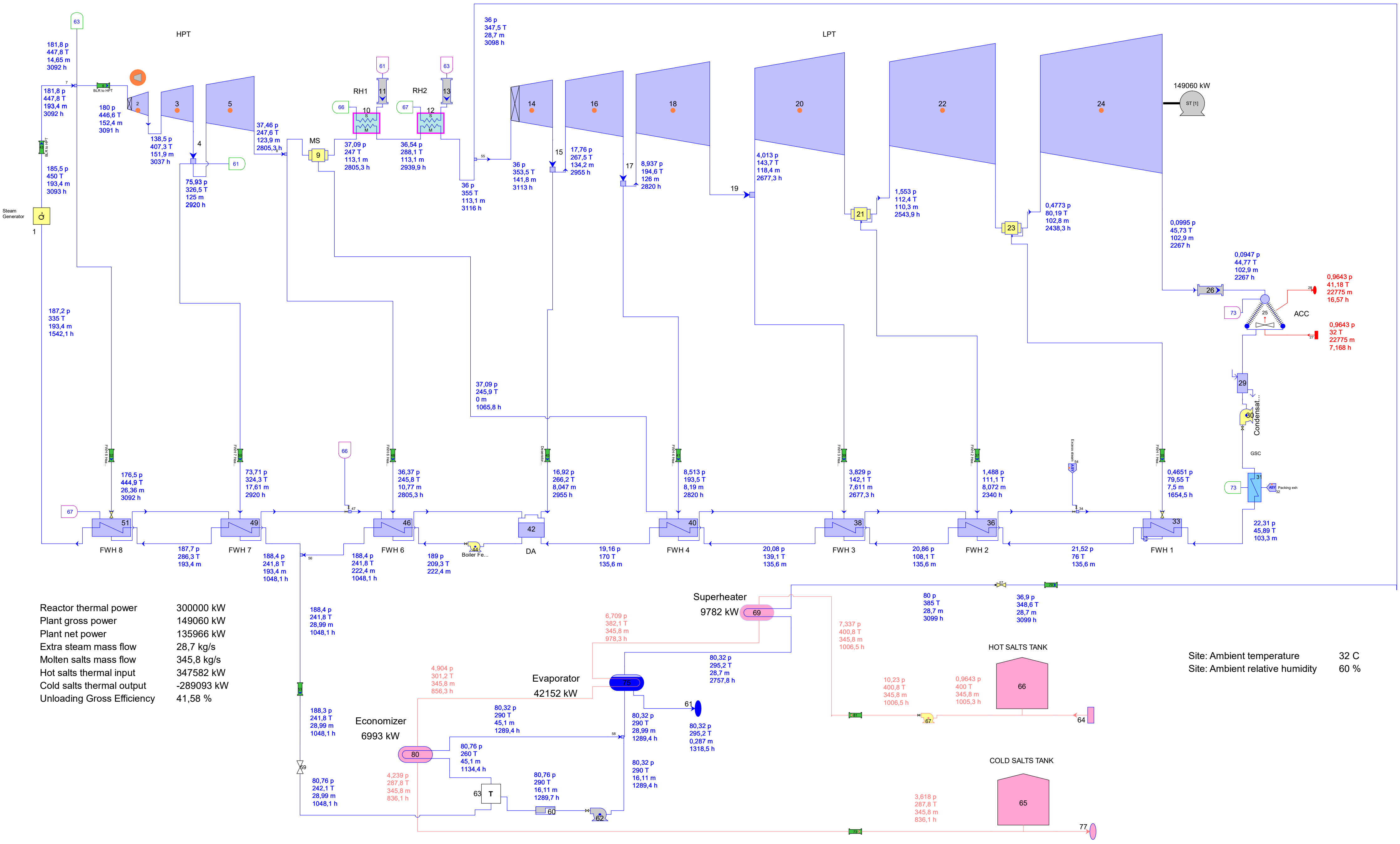
Parameter	Unit	BaseCase	Case1	Case2
Plant gross power	kW-e	82891	92702	102684
Plant net power	kW-e	68250	77886	87625
% of Nominal net power	%	57.4	65.5	73.7
Loading steam mass flow	kg/s	60.9	45.7	30.4
Molten salts mass flow	kg/s	512.1	384.1	256.0
Hot salts thermal input	kW-th	-513826	-385510	-256998
Cold salts thermal output	kW-th	429884	322413	214942
Loading thermal power	kW-th	83942	63097	42056
Gross efficiency	%	55.61	51.93	48.25
Net efficiency	%	50.73	46.99	43.23

Table B- 9 – T3L2 partial loads

Parameter	Unit	BaseCase	Case1	Case2
Plant gross power	kW-e	43871	62512	82679
Plant net power	kW-e	30138	48270	68146
% of Nominal net power	%	25.3	40.6	57.3
Loading steam mass flow	kg/s	121.8	91.3	60.9
Molten salts mass flow	kg/s	1023.5	767.6	511.7
Hot salts thermal input	kW-th	-1025880	-770525	-513840
Cold salts thermal output	kW-th	859161	644371	429580
Loading thermal power	kW-th	166719	126154	84260
Gross efficiency	%	70.20	62.89	55.65
Net efficiency	%	65.62	58.14	50.80

The heat and mass balance schematics for the Base Cases presented above are shown in the following pages.

bar	C
kg/s	kJ/kg



Reactor thermal power	300000 kW
Plant gross power	149060 kW
Plant net power	135966 kW
Extra steam mass flow	28,7 kg/s
Molten salts mass flow	345,8 kg/s
Hot salts thermal input	347582 kW
Cold salts thermal output	-289093 kW
Unloading Gross Efficiency	41,58 %

Site: Ambient temperature	32 C
Site: Ambient relative humidity	60 %

Molten salts thermal storage
Unloading Mode
T1U1-BaseCase

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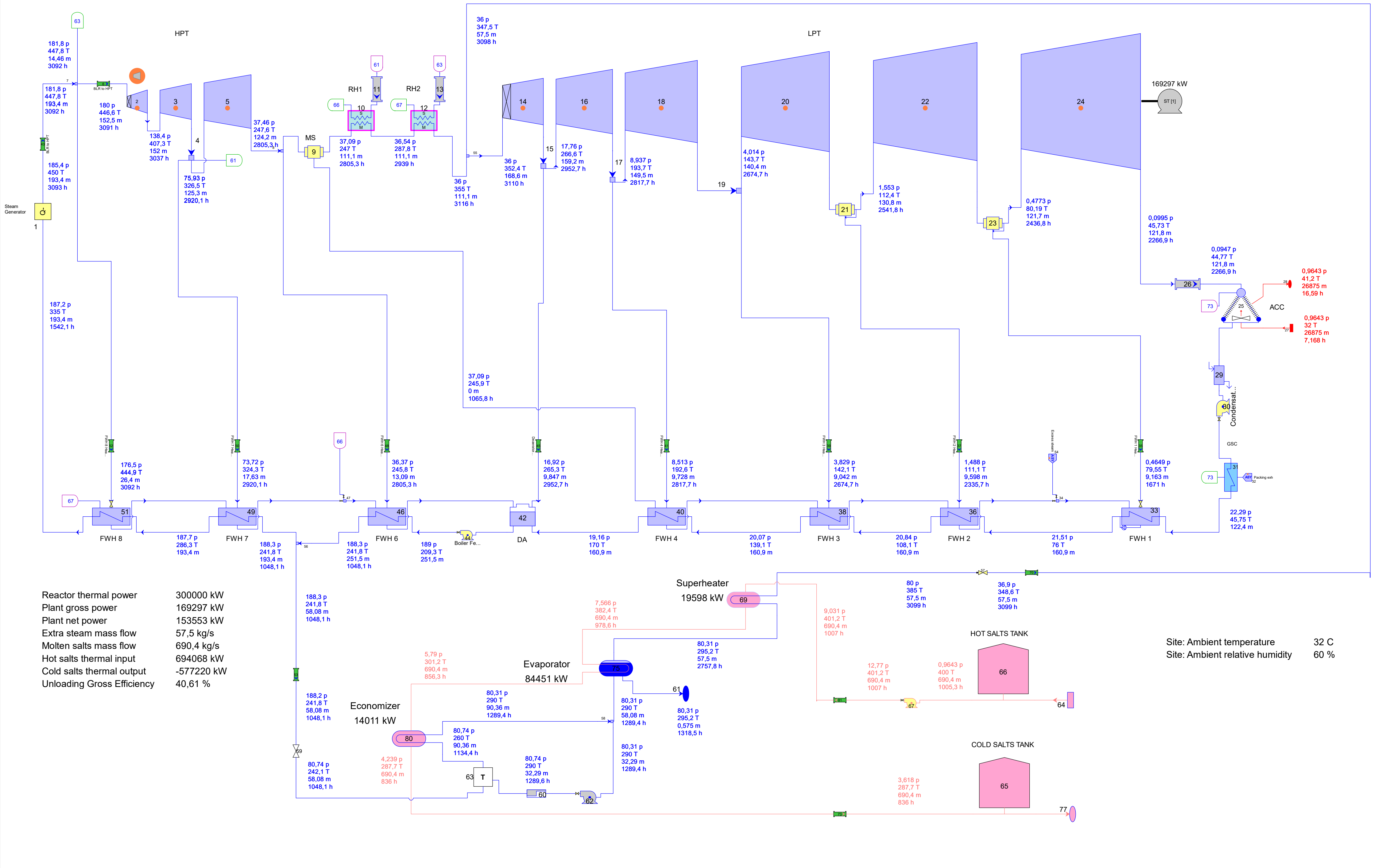
bar | C
kg/s | kJ/kg



Reactor thermal power	300000 kW
Plant gross power	169297 kW
Plant net power	153553 kW
Extra steam mass flow	57,5 kg/s
Molten salts mass flow	690,4 kg/s
Hot salts thermal input	694068 kW
Cold salts thermal output	-577220 kW
Unloading Gross Efficiency	40,61 %

Site: Ambient temperature	32 C
Site: Ambient relative humidity	60 %

Molten salts thermal storage
Unloading Mode
T2U2-BaseCase

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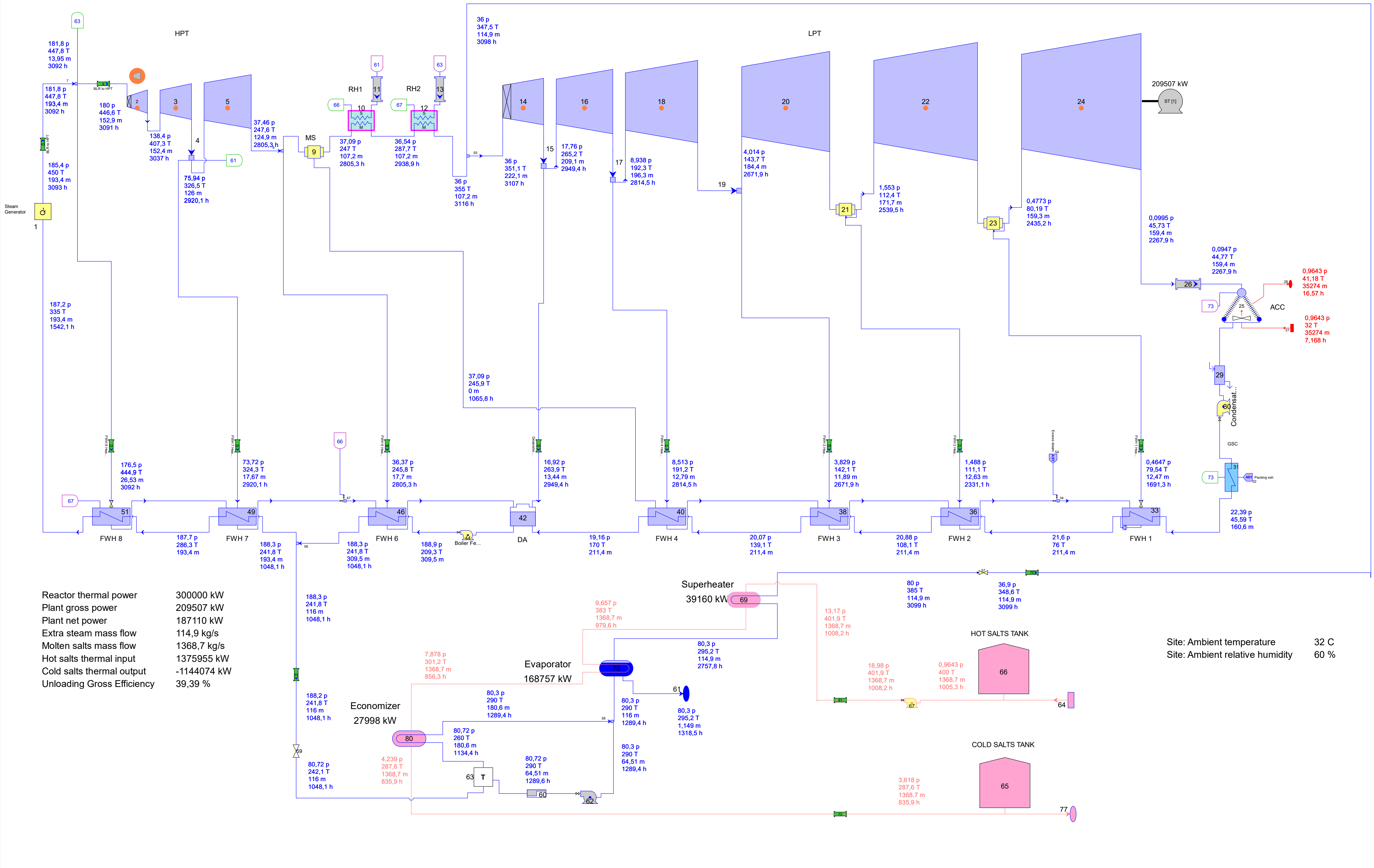
bar | C
kg/s | kJ/kg



Reactor thermal power	300000 kW
Plant gross power	209507 kW
Plant net power	187110 kW
Extra steam mass flow	114,9 kg/s
Molten salts mass flow	1368,7 kg/s
Hot salts thermal input	1375955 kW
Cold salts thermal output	-1144074 kW
Unloading Gross Efficiency	39,39 %

Site: Ambient temperature	32 C
Site: Ambient relative humidity	60 %

Molten salts thermal storage
Unloading Mode
T3U3-BaseCase

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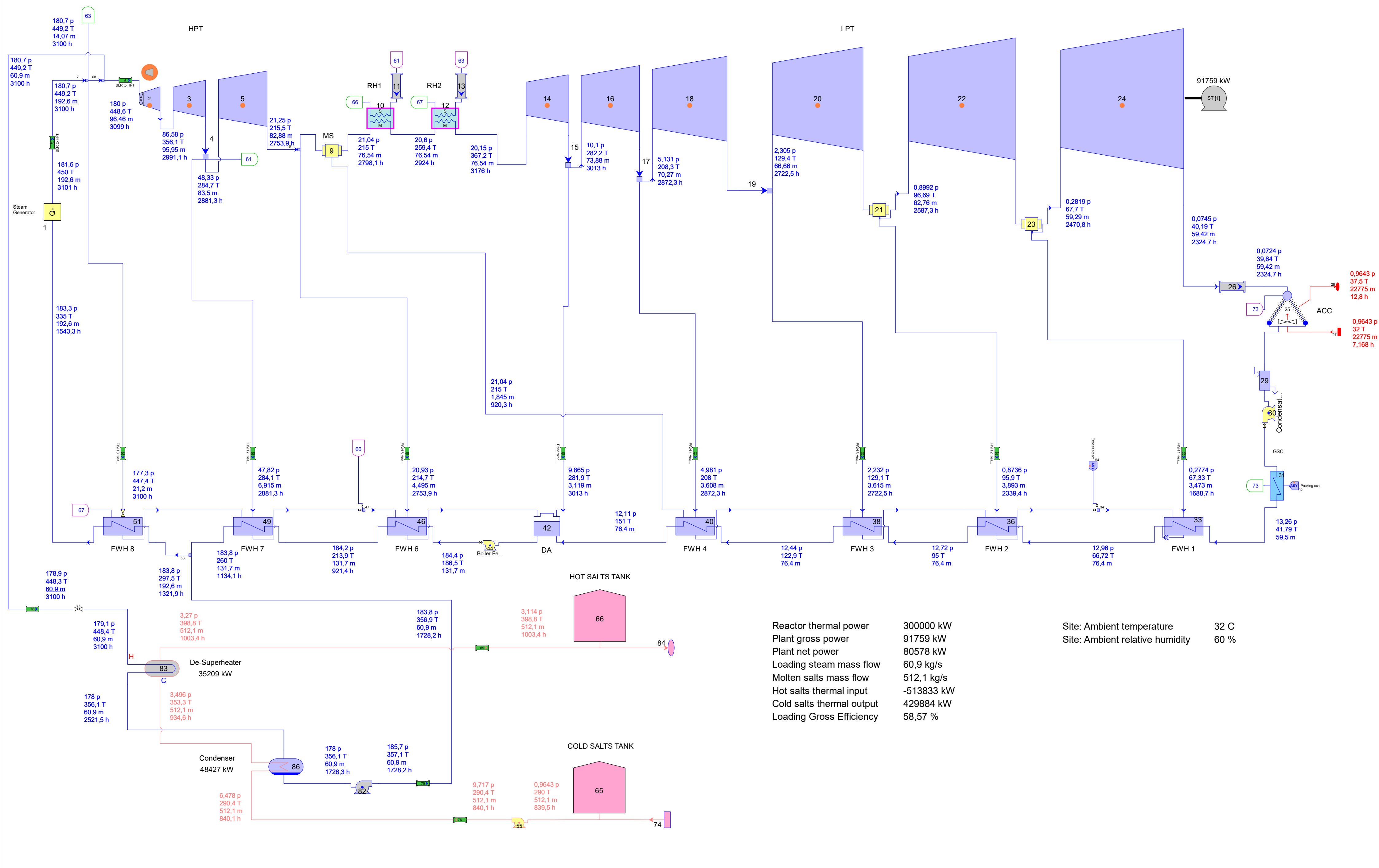
bar | C
kg/s | kJ/kg



Reactor thermal power	300000 kW
Plant gross power	91759 kW
Plant net power	80578 kW
Loading steam mass flow	60,9 kg/s
Molten salts mass flow	512,1 kg/s
Hot salts thermal input	-513833 kW
Cold salts thermal output	429884 kW
Loading Gross Efficiency	58,57 %

Site: Ambient temperature	32 C
Site: Ambient relative humidity	60 %

Molten salts thermal storage
Loading Mode
T1L1-BaseCase

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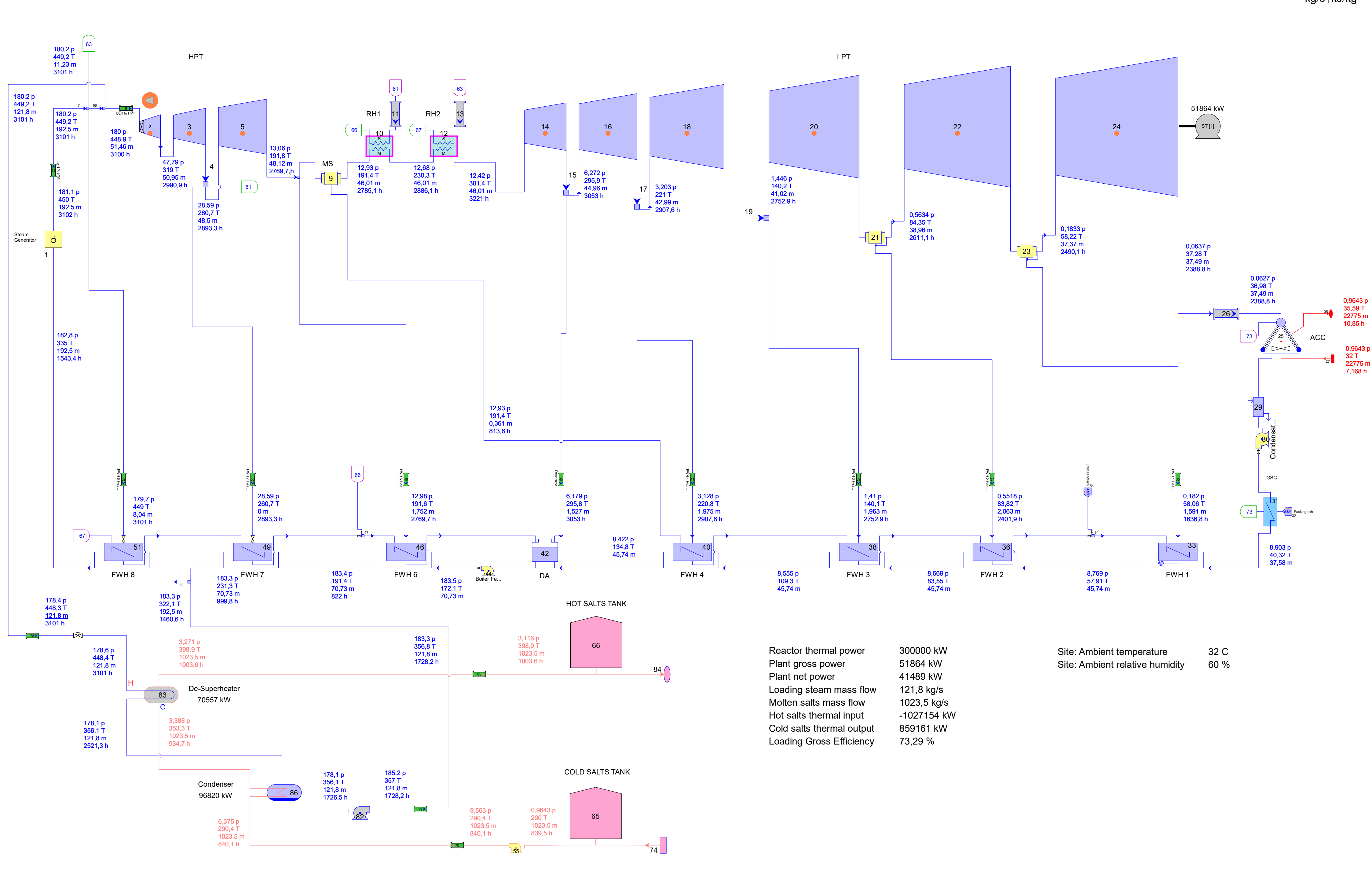
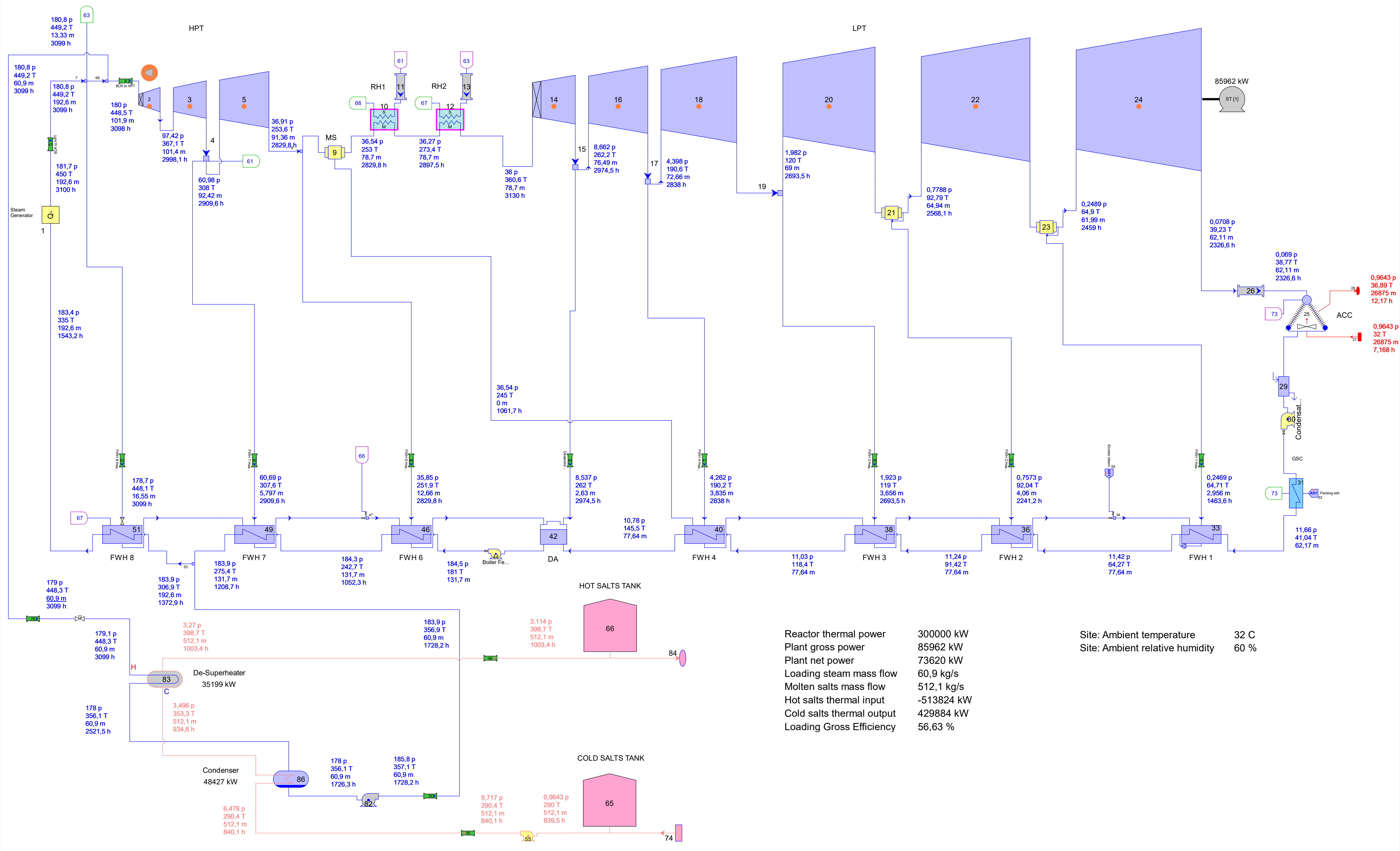


Molten salts thermal storage
Loading Mode
T1L2-BaseCase

EMPRESARIOS AGRUPADOS

bar | C
kg/s | kJ/kg



Reactor thermal power	300000 kW
Plant gross power	85962 kW
Plant net power	73620 kW
Loading steam mass flow	60,9 kg/s
Molten salts mass flow	512,1 kg/s
Hot salts thermal input	-513824 kW
Cold salts thermal output	429884 kW
Loading Gross Efficiency	56,63 %

Site: Ambient temperature	32 C
Site: Ambient relative humidity	60 %

Molten salts thermal storage
Loading Mode
T2L1-BaseCase

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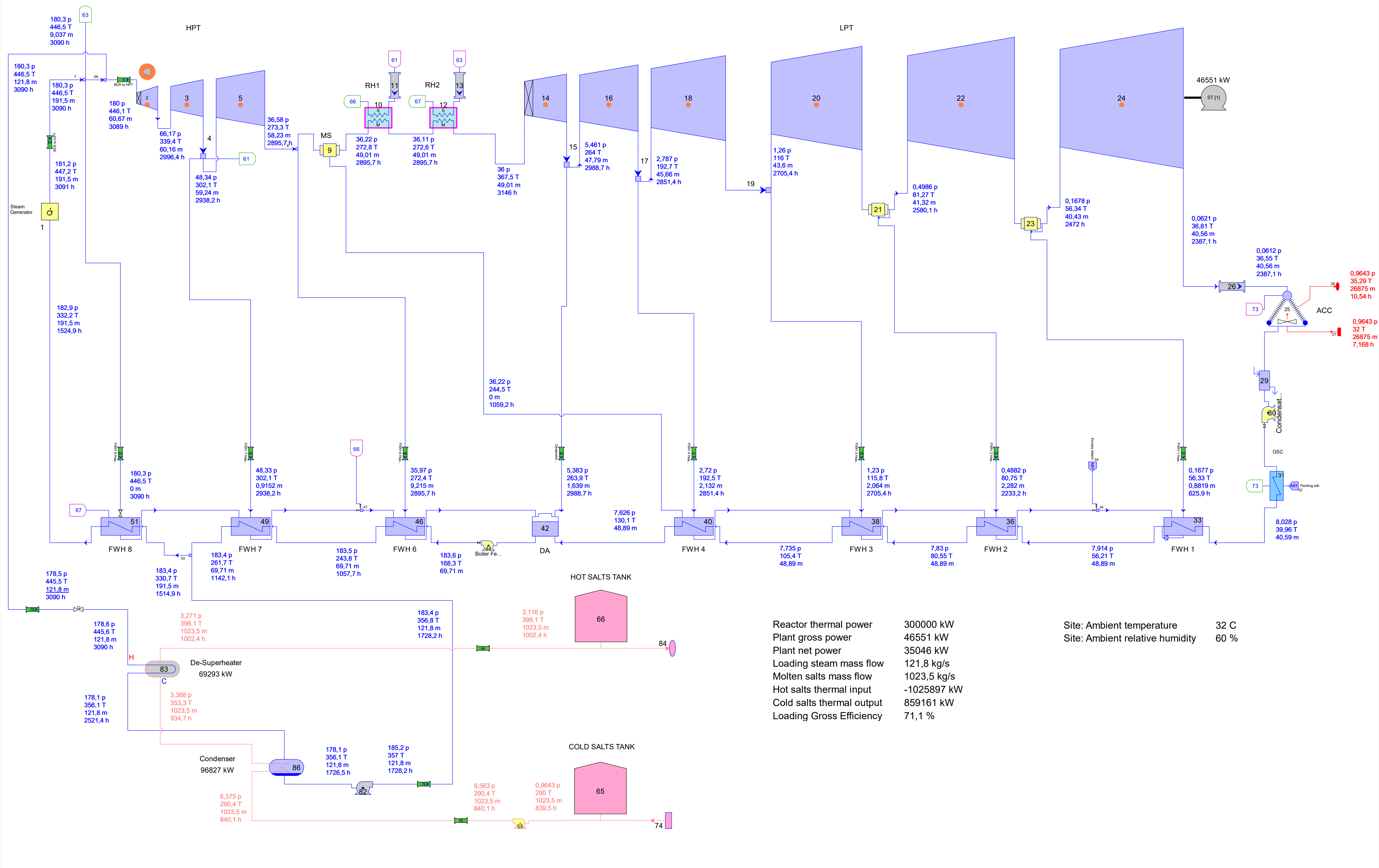
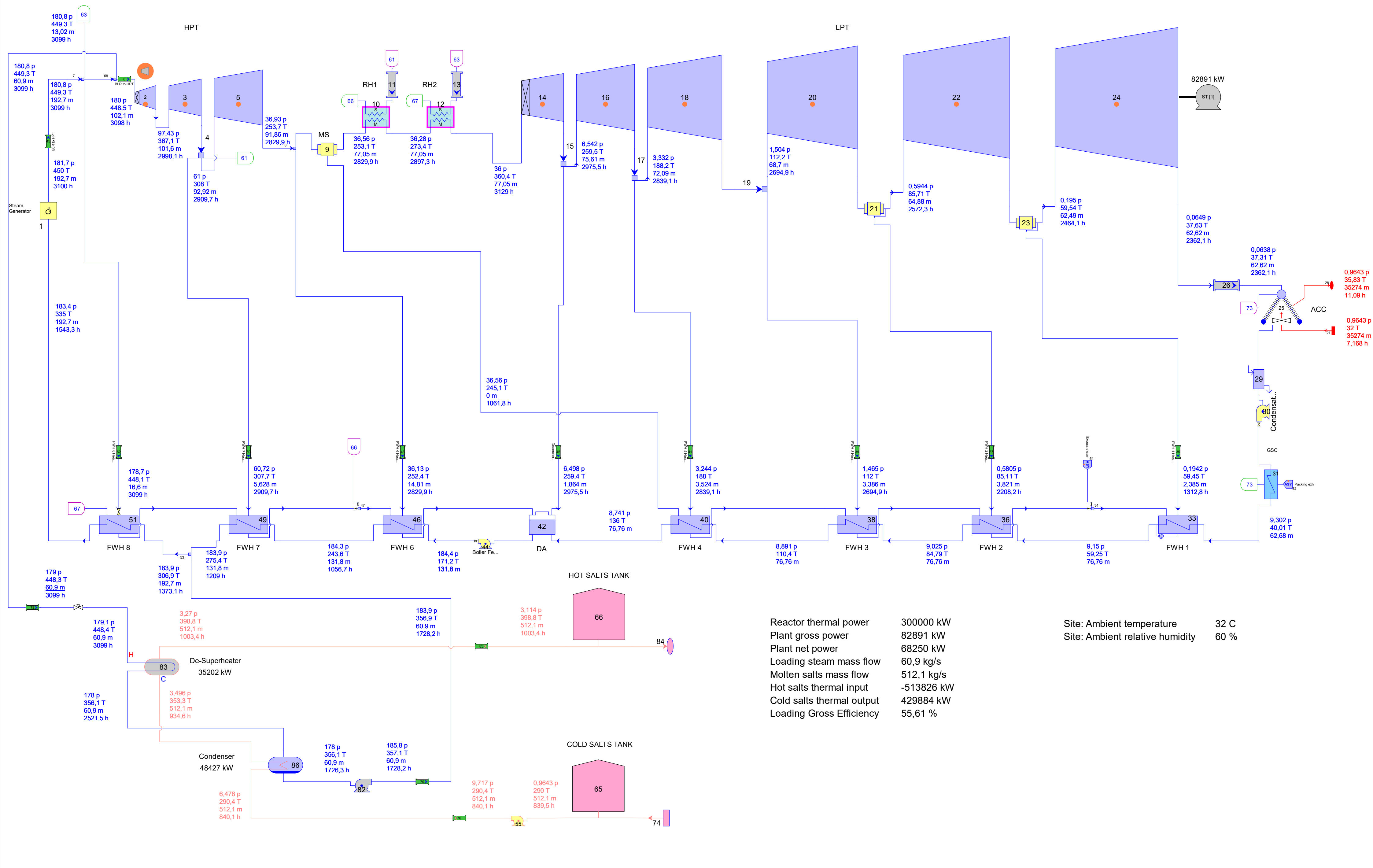
bar | C
kg/s | kJ/kg



Molten salts thermal storage
Loading Mode
T2L2-BaseCase

EMPRESARIOS AGRUPADOS

bar | C
kg/s | kJ/kg



Reactor thermal power	300000 kW
Plant gross power	82891 kW
Plant net power	68250 kW
Loading steam mass flow	60,9 kg/s
Molten salts mass flow	512,1 kg/s
Hot salts thermal input	-513826 kW
Cold salts thermal output	429884 kW
Loading Gross Efficiency	55,61 %

Site: Ambient temperature	32 C
Site: Ambient relative humidity	60 %

Molten salts thermal storage
Loading Mode
T3L1-BaseCase

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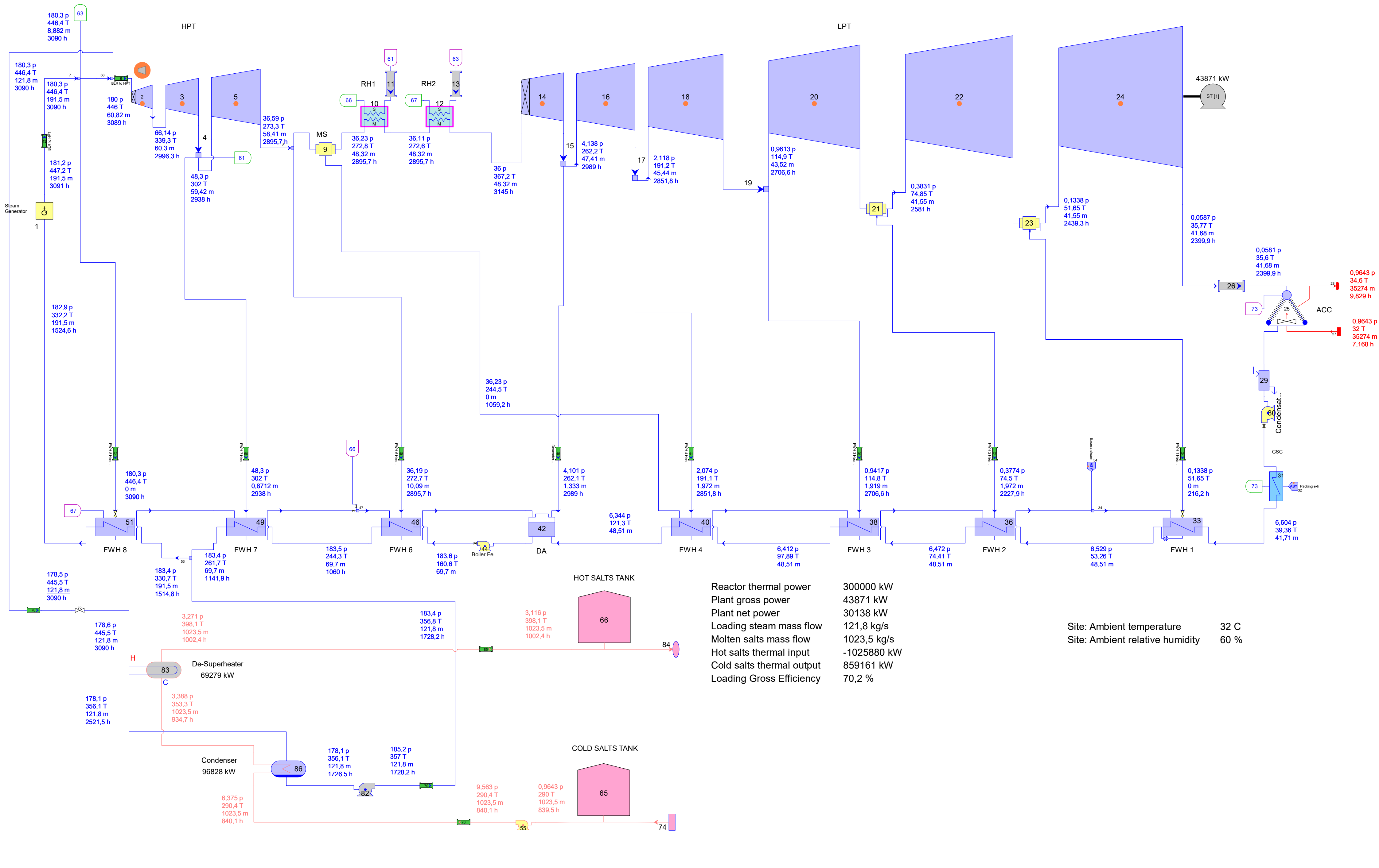
bar | C
kg/s | kJ/kg



Reactor thermal power	300000 kW
Plant gross power	43871 kW
Plant net power	30138 kW
Loading steam mass flow	121,8 kg/s
Molten salts mass flow	1023,5 kg/s
Hot salts thermal input	-1025880 kW
Cold salts thermal output	859161 kW
Loading Gross Efficiency	70,2 %

Molten salts thermal storage
Loading Mode
T3L2-BaseCase

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Appendix C Molten salts thermal storage sizing parameters

The sizing specifications for the main equipment of the Water-steam cycle Systems, Unloading System and Loading System are presented in the following Tables:

- Table C- 1 – Water-Steam Cycle (T) main equipment sizing
- Table C- 2 – Unloading System (U) main equipment sizing
- Table C- 3 – Loading System (L) main equipment sizing

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
Estimated Steam Turbine Data					
1. Steam Turbine Description					
Nameplate Capacity	150.2	173.9	197.5	244.4	MVA
Design Point Generator Power Factor	0.9	0.9	0.9	0.9	
Design Point Generator Efficiency	98.65	98.68	98.72	98.78	%
Nuclear Steam Turbine	HPT + LPT 3000 RPM	HPT + LPT 3000 RPM	HPT + LPT 3000 RPM	HPT + LPT 3000 RPM	
Nameplate Throttle Pressure	189	189	189	189	bar
Nameplate Throttle Temperature	446.6	446.6	446.6	446.6	C
Nameplate Throttle Massflow	152.2	152.4	152.6	153	kg/s
Exhaust End Type	Down Draft	Down Draft	Down Draft	Down Draft	
Number of LPT Exhaust Annuli	1	1	1	1	
Number of Extraction/Admission Ports	6	6	6	6	
Number of Auto-Extraction/Auto-Admission Ports	2	2	2	2	
2. Estimated Weights & Dimensions					
Steam Turbine Length	15.19	15.68	16.12	16.9	m
Steam Turbine Width	5.102	5.414	5.683	6.13	m
Steam Turbine Weight	225300	255250	284250	339450	kg
Generator Length (Including Exciter)	10.64	11.03	11.37	11.98	m
Generator Width	3.584	3.655	3.717	3.82	m
Generator Weight	190400	211200	231200	269000	kg
Overall ST and Generator Length	25.83	26.71	27.5	28.87	m
Overall ST and Generator Width	5.102	5.414	5.683	6.13	m
Overall ST and Generator Weight	415700	466450	515500	608500	kg
Foundation Length	28.73	29.62	30.42	31.82	m
Foundation Width	6.123	6.497	6.82	7.356	m
Estimated Air Cooled Condenser Data					
Air-cooled condenser w/ precooler					
Heat exchanger arrangement	A-Frame	A-Frame	A-Frame	A-Frame	
Total number of cells	25	36	36	49	
- Number of bays	5	6	6	7	

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
- Number of cells per bay	5	6	6	7	
1. Overall Dimensions					
Length	67.06	74.98	80.47	93.88	m
Width	67.06	74.98	80.47	93.88	m
Plot area	4497	5622	6475	8813	m^2
2. Cell Dimensions					
Width	13.41	12.5	13.41	13.41	m
Height	30.01	31.64	32.34	34.34	m
Fan deck height	20.01	22.33	22.33	24.49	m
Steam duct outer diameter	2.11	2.131	2.318	2.456	m
Steam duct thickness	6.815	6.88	7.484	7.929	mm
Weight	123753	106212	126981	124670	kg
3. Fan Design (per fan)					
Flow coefficient	0.16	0.16	0.16	0.16	
Static pressure rise coefficient	0.0562	0.0561	0.0563	0.0561	
Tip diameter	10.39	9576	10.4	10.22	m
Hub diameter	1.402	1.293	1.404	1.379	m
RPM	94.43	102.4	94.29	96.02	
Tip speed	51.36	51.36	51.36	51.36	m/s
Static pressure drop at design point	0.8052	0.804	0.8071	0.8044	mbar
Dynamic pressure at design point	0.367	0.367	0.367	0.367	mbar
Total fan DP at design point	1.172	1.171	1.174	1.171	mbar
Design volume flow	683.6	581	685.6	661.1	m^3/s
Electricity consumption at design point	111.4	94.56	111.9	107.6	kW
Estimated Steam-Heated Deaerator Data					
FWH 5-DA					
DA type	HH	HH	HH	HH	
Nameplate feedwater exit flow	696280	800633	905350	1114056	kg/hr
Total storage volume	94465	108623	122830	151145	l
Total storage capacity	7	7	7	7	Min
Number of units	1	1	1	1	
Overall height	6.744	6.952	7.142	7.479	m
Overall length	11.36	11.9	12.39	13.28	m
Storage tank					
-Thickness	27.42	28.72	29.92	32.07	mm
-Outside diameter	3.621	3.794	3.952	4.235	m
-Total length	11.36	11.9	12.39	13.28	m
Heater					
-Thickness	19.05	19.05	20.64	20.64	mm
-Outside diameter	2.513	2.548	2.58	2.634	m

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
-Total length	8.465	9.264	10.08	11.6	m
Estimated Feedwater Heater Data					
Feedwater Heater (PCE) (36)					
Feedwater Heater configuration: Includes condensing section, drain cooler					
1.Feedwater Heater Tube Description					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube layout in crossflow	Rotated Square 45	Rotated Square 45	Rotated Square 45	Rotated Square 45	
Tube material	Stainless Steel (304)	Stainless Steel (304)	Stainless Steel (304)	Stainless Steel (304)	
Total external heat transfer area	468	554	660	955	m^2
Nameplate water pressure	21.6	21.52	21.51	21.6	bar
Number of tubes per pass	410	504	598	786	
Number of passes	2	2	2	2	
Number of tubes in heater	820	1008	1196	1572	
Tube length per pass	11.45	11.02	11.07	12.18	m
Tube outer diameter	15.88	15.88	15.88	15.88	mm
Tube inner diameter	13.39	13.39	13.39	13.39	mm
Tube wall thickness	1.245	1.245	1.245	1.245	mm
Tube pitch	25.4	25.4	25.4	25.4	mm
2. Feedwater Heater Shell Description					
Nameplate steam pressure	1.481	1.481	1.481	1.481	bar
Shell material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Shell length	11.45	11.02	11.07	12.18	m
Shell inner diameter	1110	1230	1340	1530	mm
Shell wall thickness	6.35	6.35	7.938	7.938	mm
Tube sheet thickness	44.45	47.62	53.97	60.33	mm
Overall length	13	12.8	13	14.4	m
Overall outer diameter	1120.7	1241.2	1354	1550	mm
Estimated Feedwater Heater Data					
Feedwater Heater (PCE) (38)					
Feedwater Heater configuration: Includes condensing section, drain cooler					
1.Feedwater Heater Tube Description					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube layout in crossflow	Rotated Square 45	Rotated Square 45	Rotated Square 45	Rotated Square 45	
Tube material	Stainless Steel (304)	Stainless Steel (304)	Stainless Steel (304)	Stainless Steel (304)	
Total external heat transfer area	404	479	565	775	m^2
Nameplate water pressure	20.91	20.86	20.84	20.88	bar

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
Number of tubes per pass	364	447	531	697	
Number of passes	2	2	2	2	
Number of tubes in heater	728	894	1062	1394	
Tube length per pass	11.13	10.73	10.67	11.15	m
Tube outer diameter	15.88	15.88	15.88	15.88	mm
Tube inner diameter	13.39	13.39	13.39	13.39	mm
Tube wall thickness	1.245	1.245	1.245	1.245	mm
Tube pitch	26.19	26.19	26.19	26.19	mm
2. Feedwater Heater Shell Description					
Nameplate steam pressure	3.823	3.823	3.823	3.823	bar
Shell material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Shell length	11.13	10.73	10.67	11.15	m
Shell inner diameter	1080	1190	1300	1490	mm
Shell wall thickness	6.35	6.35	7.938	7.938	mm
Tube sheet thickness	38.1	44.45	47.62	53.97	mm
Overall length	12.7	12.5	12.6	13.3	m
Overall outer diameter	1089.3	1205.8	1316.2	1505.7	mm
Estimated Feedwater Heater Data					
Feedwater Heater (PCE) (40)					
Feedwater Heater configuration: Includes condensing section, drain cooler					
1.Feedwater Heater Tube Description					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube layout in crossflow	Rotated Square 45	Rotated Square 45	Rotated Square 45	Rotated Square 45	
Tube material	Stainless Steel (304)	Stainless Steel (304)	Stainless Steel (304)	Stainless Steel (304)	
Total external heat transfer area	368	437	511	680	m^2
Nameplate water pressure	20.1	20.08	20.06	20.07	bar
Number of tubes per pass	331	406	482	634	
Number of passes	2	2	2	2	
Number of tubes in heater	662	812	964	1268	
Tube length per pass	11.16	10.8	10.63	10.75	m
Tube outer diameter	15.88	15.88	15.88	15.88	mm
Tube inner diameter	13.39	13.39	13.39	13.39	mm
Tube wall thickness	1.245	1.245	1.245	1.245	mm
Tube pitch	26.19	26.19	26.19	26.19	mm
2. Feedwater Heater Shell Description					
Nameplate steam pressure	8.511	8.511	8.511	8.511	bar
Shell material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Shell length	11.16	10.8	10.63	10.75	m

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
Shell inner diameter	1030	1140	1240	1420	mm
Shell wall thickness	6.35	6.35	6.35	7.938	mm
Tube sheet thickness	31.75	34.92	38.1	41.28	mm
Overall length	12.7	12.5	12.5	12.8	m
Overall outer diameter	1039.4	1149.7	1251.6	1436.7	mm
Estimated Feedwater Heater Data					
Feedwater Heater (PCE) (46)					
Feedwater Heater configuration: Includes condensing section, drain cooler					
1.Feedwater Heater Tube Description					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube layout in crossflow	Rotated Square 45	Rotated Square 45	Rotated Square 45	Rotated Square 45	
Tube material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Total external heat transfer area	958	1140	1250	1480	m^2
Nameplate water pressure	189	189	189	189	bar
Number of tubes per pass	649	746	844	1039	
Number of passes	2	2	2	2	
Number of tubes in heater	1298	1492	1688	2078	
Tube length per pass	12.33	12.78	12.39	11.87	m
Tube outer diameter	19.05	19.05	19.05	19.05	mm
Tube inner diameter	14.22	14.22	14.22	14.22	mm
Tube wall thickness	2.413	2.413	2.413	2.413	mm
Tube pitch	27.62	27.62	27.62	27.62	mm
2. Feedwater Heater Shell Description					
Nameplate steam pressure	36.37	36.37	36.37	36.37	bar
Shell material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Shell length	12.33	12.78	12.39	11.87	m
Shell inner diameter	1520	1630	1730	1920	mm
Shell wall thickness	38.1	38.1	38.1	44.45	mm
Tube sheet thickness	171	184	194	216	mm
Overall length	14.7	15.3	15.1	14.9	m
Overall outer diameter	1592.2	1701.5	1805	2007.1	mm
Estimated Feedwater Heater Data					
Feedwater Heater (PCE) (49)					
Feedwater Heater configuration: Includes condensing section, drain cooler					
1.Feedwater Heater Tube Description					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube layout in crossflow	Rotated Square 45	Rotated Square 45	Rotated Square 45	Rotated Square 45	
Tube material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
Total external heat transfer area	1180	1180	1170	1170	m^2
Nameplate water pressure	188	188	188	188	bar
Number of tubes per pass	692	692	692	692	
Number of passes	2	2	2	2	
Number of tubes in heater	1384	1384	1384	1384	
Tube length per pass	14.21	14.2	14.18	14.16	m
Tube outer diameter	19.05	19.05	19.05	19.05	mm
Tube inner diameter	14.22	14.22	14.22	14.22	mm
Tube wall thickness	2.413	2.413	2.413	2.413	mm
Tube pitch	27.62	27.62	27.62	27.62	mm
2. Feedwater Heater Shell Description					
Nameplate steam pressure	73.72	73.72	73.72	73.72	bar
Shell material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Shell length	14.21	14.2	14.18	14.16	m
Shell inner diameter	1.57	1.57	1.57	1.57	m
Shell wall thickness	69.85	69.85	69.85	69.85	mm
Tube sheet thickness	152	152	152	152	mm
Overall length	16.7	16.7	16.7	16.6	m
Overall outer diameter	1705.1	1705.1	1705.1	1705.1	mm
Estimated Feedwater Heater Data					
Feedwater Heater (PCE) (51)					
Feedwater Heater configuration: Includes desuperheating section, condensing section, drain cooler					
1.Feedwater Heater Tube Description					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube layout in crossflow	Rotated Square 45	Rotated Square 45	Rotated Square 45	Rotated Square 45	
Tube material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Total external heat transfer area	1160	1160	1160	1160	m^2
Nameplate water pressure	188	188	188	188	bar
Number of tubes per pass	774	774	774	774	
Number of passes	2	2	2	2	
Number of tubes in heater	1548	1548	1548	1548	
Tube length per pass	12.57	12.55	12.53	12.49	m
Tube outer diameter	19.05	19.05	19.05	19.05	mm
Tube inner diameter	14.22	14.22	14.22	14.22	mm
Tube wall thickness	2.413	2.413	2.413	2.413	mm
Tube pitch	27.62	27.62	27.62	27.62	mm
2. Feedwater Heater Shell Description					
Nameplate steam pressure	137	137	137	137	bar

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
Shell material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Shell length	12.57	12.55	12.53	12.49	m
Shell inner diameter	1.66	1.66	1.66	1.66	m
Shell wall thickness	133	133	133	133	mm
Tube sheet thickness	108	108	108	108	mm
Overall length	15.3	15.2	15.2	15.2	m
Overall outer diameter	1922.3	1922.3	1922.3	1922.3	mm
Estimated Feedwater Heater Data					
Feedwater Heater w/ Pump (PCE) (33)					
Feedwater Heater configuration: Includes condensing section only					
1.Feedwater Heater Tube Description					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube layout in crossflow	Rotated Square 45	Rotated Square 45	Rotated Square 45	Rotated Square 45	
Tube material	Stainless Steel (304)	Stainless Steel (304)	Stainless Steel (304)	Stainless Steel (304)	
Total external heat transfer area	321	395	469	616	m^2
Nameplate water pressure	22.38	22.3	22.29	22.39	bar
Number of tubes per pass	295	362	429	563	
Number of passes	2	2	2	2	
Number of tubes in heater	590	724	858	1126	
Tube length per pass	10.91	10.93	10.96	10.98	m
Tube outer diameter	15.88	15.88	15.88	15.88	mm
Tube inner diameter	13.39	13.39	13.39	13.39	mm
Tube wall thickness	1.245	1.245	1.245	1.245	mm
Tube pitch	25.4	25.4	25.4	25.4	mm
2. Feedwater Heater Shell Description					
Nameplate steam pressure	0.4547	0.4547	0.4547	0.4547	bar
Shell material	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel	
Shell length	10.91	10.93	10.96	10.98	m
Shell inner diameter	940	1.04	1.13	1.3	mm
Shell wall thickness	6.349	6.35	6.35	7.938	mm
Tube sheet thickness	38.1	44.45	47.62	53.97	mm
Overall length	12.3	12.4	12.6	12.9	m
Overall outer diameter	953	1053.8	1146.1	1314.2	mm
Off-design Heat Balance Results					
General HX (10)					
Performance					
Heat transfer	15373	15226	14860	14331	kW
Heat loss	0				kW

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
Current UA	821.4	830.3	796	767	kW/C
Design point UA	813.1	819.3	785.2	757.3	kW/C
Pinch	6.075	5.739	6.031	6.043	C
Off-design Heat Balance Results					
General HX (12)					
Performance					
Heat transfer	20395	19940	19694	18998	kW
Heat loss	0				kW
Current UA	446.8	438.4	431.9	416.4	kW/C
Design point UA	446.7	439	431.3	416	kW/C
Pinch	29.95	29.83	29.91	29.93	C
Estimated Pump Data					
Pump (PCE) (30)					
Pump type	Multistage centrifugal	Multistage centrifugal	Multistage centrifugal	Multistage centrifugal	
Drive type	Fixed RPM	Fixed RPM	Fixed RPM	Fixed RPM	
Number per ST	3 - 50%	3 - 50%	3 - 50%	3 - 50%	
1. Nameplate Conditions (per existing unit)					
Nameplate (unrounded) mass flow	46.61	57.14	67.67	88.52	kg/s
Nameplate (unrounded) head	222.2	221.4	221.1	221.3	m
Nameplate volume flow	3028	3785	4164	5678	lpm
Nameplate head	228.6	228.6	228.6	228.6	m H2O
Pump shaft speed	3000	3000	3000	3000	RPM
Shaft power	200	250	275	350	hp
Pump isentropic efficiency	75	75	75	75	%
Pump mechanical efficiency	97	97	97	97	%
Estimated Pump Data					
Pump (PCE) (44)					
Pump type	Multistage centrifugal	Multistage centrifugal	Multistage centrifugal	Multistage centrifugal	
Drive type	Variable RPM	Variable RPM	Variable RPM	Variable RPM	
Number per Boiler	2 - 100%	2 - 100%	2 - 100%	2 - 100%	
1. Nameplate Conditions (per existing unit)					
Nameplate (unrounded) mass flow	214.9	247	279.1	342.6	kg/s
Nameplate (unrounded) head	2013.6	2014.2	2013.6	2013.5	m
Nameplate volume flow	15142	18927	20820	24605	lpm
Nameplate head	2011.7	2011.7	2011.7	2011.7	m H2O
Pump shaft speed	3000	3000	3000	3000	RPM
Shaft power	8000	9000	11000	13000	hp
Pump isentropic efficiency	75	75	75	75	%

Table C- 1 – Water-Steam Cycle (T) main equipment sizing

Equipment / Parameter	T	T1	T2	T3	Unit
Pump mechanical efficiency	97	97	97	97	%

Table C- 2 – Unloading System (U) main equipment sizing

Equipment / Parameter	U1	U2	U3	Unit
Estimated Shell-Tube Heat Exchanger Data				
Shell-Tube Economiser (PCE) (80)				
Number of units	1	1	1	
1. Tube Description (per unit)				
Tube type	Integral Low Fin Tube	Integral Low Fin Tube	Integral Low Fin Tube	
Tube material	Carbon steel	Carbon steel	Carbon steel	
Total external heat transfer area	464	872	1660	m^2
Nameplate tube flow pressure	80.76	80.74	80.72	bar
Fin outer diameter	15.88	15.88	15.88	mm
Tube inner diameter	9.199	9.199	9.199	mm
Wall thickness under fins	1.751	1.751	1.751	mm
Tube layout in crossflow	Rotated Square	Rotated Square	Rotated Square	
Number of tubes per pass	644	1292	2582	
Number of passes	2	2	2	
Number of tubes in heater	1288	2584	5164	
Tube length per pass	2.622	2.455	2.337	m
Tube pitch	25.4	25.4	25.4	mm
Fin height	1.588	1.588	1.588	mm
Fin thickness	0.3048	0.3048	0.3048	mm
Fin spacing (between adjacent surfaces)	1.032	1.032	1.032	mm
Number of fins per meter	748	748	748	
Heat transfer area ratio (Ao/Ai)	4.755	4.755	4.755	
2. Shell Description (per unit)				
Nameplate shell flow pressure	3.353	4.239	6.326	bar
Shell material	Carbon steel	Carbon steel	Carbon steel	
Shell length	2.622	2.455	2.337	m
Tube bundle diameter	1.04	1.47	2.08	mm
Shell inner diameter	1.06	1.49	2.09	mm
Shell wall thickness	6.35	7.938	12.7	mm
Tube sheet thickness	26.99	38.1	52.39	mm
Overall length	3.2	3.3	3.5	m
Shell type	Two pass shell	Two pass shell	Two pass shell	
Number of baffles	2	2	2	
Baffle spacing	874	818	779	mm
Baffle cut / equivalent pass diameter	33	33	33	%

Table C- 2 – Unloading System (U) main equipment sizing

Equipment / Parameter	U1	U2	U3	Unit
Equivalent pass diameter	754	1057.3	1483.5	mm
Shell outer diameter	1073.1	1504.6	2116.8	mm
Estimated Shell-Tube Heat Exchanger Data				
Shell-Tube Evaporating HX (PCE) (75)				
Number of units	1	1	1	
1. Tube Description (per unit)				
Tube type	Bare Tube	Bare Tube	Bare Tube	
Tube material	Carbon steel	Carbon steel	Carbon steel	
Total external heat transfer area	453	905	1800	m^2
Nameplate tube flow pressure	5.158	6.015	8.105	bar
Tube outer diameter	15.88	19.05	19.05	mm
Tube inner diameter	13.39	16.56	16.56	mm
Tube wall thickness	1.245	1.245	1.245	mm
Tube layout in crossflow	Rotated Square	Rotated Square	Rotated Square	
Number of tubes per pass	594	775	1536	
Number of passes	2	2	2	
Number of tubes in heater	1188	1550	3072	
Tube length per pass	7.647	9.76	9.78	m
Tube pitch	23.81	28.58	28.58	mm
Heat transfer area ratio (Ao/Ai)	1.186	1.15	1.15	
2. Shell Description (per unit)				
Nameplate shell flow pressure	80.32	80.31	80.3	bar
Shell material	Carbon steel	Carbon steel	Carbon steel	
Shell length	9.94	12.69	12.71	m
Tube bundle diameter	942	1.29	1.81	mm
Shell inner diameter	1.7	2.32	3.25	mm
Shell wall thickness	57.15	76.2	102	mm
Tube sheet thickness	98.42	133	184	mm
Overall length	12.1	15.6	16.8	m
Shell outer diameter	1809.9	2471.7	3454	mm
Estimated Shell-Tube Heat Exchanger Data				
Shell-Tube Superheater (PCE) (69)				
Number of units	1	1	1	
1. Tube Description (per unit)				
Tube type	Bare Tube	Bare Tube	Bare Tube	
Tube material	Carbon steel	Carbon steel	Carbon steel	
Total external heat transfer area	346	645	1200	m^2
Nameplate tube flow pressure	80.32	80.31	80.3	bar
Tube outer diameter	15.88	15.88	15.88	mm
Tube inner diameter	11.05	11.05	11.05	mm
Tube wall thickness	2.413	2.413	2.413	mm

Table C- 2 – Unloading System (U) main equipment sizing

Equipment / Parameter	U1	U2	U3	Unit
Tube layout in crossflow	Rotated Square	Rotated Square	Rotated Square	
Number of tubes per pass	1033	2070	4138	
Number of passes	2	2	2	
Number of tubes in heater	2066	4140	8276	
Tube length per pass	3.357	3.123	2.904	m
Tube pitch	25.4	25.4	25.4	mm
Heat transfer area ratio (Ao/Ai)	1.437	1.437	1.437	
2. Shell Description (per unit)				
Nameplate shell flow pressure	5.786	7.48	11.62	bar
Shell material	Carbon steel	Carbon steel	Carbon steel	
Shell length	3.357	3.123	2.904	m
Tube bundle diameter	1.32	1.86	2.62	mm
Shell inner diameter	1.33	1.88	2.64	mm
Shell wall thickness	7.938	9.525	15.88	mm
Tube sheet thickness	33.34	46.83	63.5	mm
Overall length	4.1	4.1	4.3	m
Shell type	Two pass shell	Two pass shell	Two pass shell	
Number of baffles	2	2	2	
Baffle spacing	1119	1041	968	mm
Baffle cut / equivalent pass diameter	30	30	30	%
Equivalent pass diameter	948	1331.1	1870.8	mm
Shell outer diameter	1350.4	1895	2670.9	mm
Engineering Design Heat Balance Results				
General Pump (62)				
Pump type	Single stage centrifugal	Single stage centrifugal	Single stage centrifugal	
Drive type	Variable RPM	Variable RPM	Variable RPM	
Number	2 - 100%	2 - 100%	2 - 100%	
1. Nameplate Conditions (per existing unit)				
Nameplate (unrounded) mass flow	18.03	36.04	71.59	kg/s
Nameplate (unrounded) head	6.172	5.936	5.742	m
Nameplate volume flow	1514.2	3028	6624	lpm
Nameplate head	6.096	6.096	6.096	m H2O
Pump shaft speed	3000	3000	3000	RPM
Shaft power	1.643	3.154	1.300	hp
Pump isentropic efficiency	85	85	85	%
Pump mechanical efficiency	97	97	97	%
Estimated Pump Data				
Pump (PCE) (67)				
Pump type	Single stage centrifugal	Single stage centrifugal	Single stage centrifugal	
Drive type	Variable RPM	Variable RPM	Variable RPM	

Table C- 2 – Unloading System (U) main equipment sizing

Equipment / Parameter	U1	U2	U3	Unit
Number	3 - 50%	3 - 50%	3 - 50%	
1. Nameplate Conditions (per existing unit)				
Nameplate (unrounded) mass flow	192.1	383.6	760.4	kg/s
Nameplate (unrounded) head	51.52	65.64	100.1	m
Nameplate volume flow	6624	13249	26498	lpm
Nameplate head	53.34	68.58	106.7	m H2O
Pump shaft speed	1500	1500	1500	RPM
Shaft power	175	400	1300	hp
Pump isentropic efficiency	85	85	85	%
Pump mechanical efficiency	97	97	97	%

Table C- 3 – Loading System (L) main equipment sizing

Equipment / Parameter	L1	L2	Unit
Estimated Shell-Tube Heat Exchanger Data			
Shell-Tube Condensing HX (PCE) (86)			
Number of units	1	1	
1. Tube Description (per unit)			
Tube type	Bare Tube	Bare Tube	
Tube material	Carbon steel	Carbon steel	
Total external heat transfer area	1190	2480	m^2
Nameplate tube flow pressure	5.379	5.276	bar
Tube outer diameter	15.88	19.05	mm
Tube inner diameter	11.66	14.22	mm
Tube wall thickness	2.108	2.413	mm
Tube layout in crossflow	Rotated Square	Rotated Square	
Number of tubes per pass	1113	1495	
Number of passes	2	2	
Number of tubes in heater	2226	2990	
Tube length per pass	10.76	13.85	m
Tube pitch	23.81	28.58	mm
Heat transfer area ratio (Ao/Ai)	1.362	1.339	
2. Shell Description (per unit)			
Nameplate shell flow pressure	178	178	bar
Shell material	Carbon steel	Carbon steel	
Shell length	10.76	13.85	m
Tube bundle diameter	1.28	1.78	mm
Shell inner diameter	1.73	2.41	mm
Shell wall thickness	121	165	mm
Tube sheet thickness	68.26	95.25	mm
Overall length	11.8	15.4	m
Shell outer diameter	1974.2	2736.1	mm

Table C- 3 – Loading System (L) main equipment sizing

Equipment / Parameter	L1	L2	Unit
Estimated Shell-Tube Heat Exchanger Data			
Shell-Tube General HX (PCE) (83)			
Number of units	1	1	
1. Tube Description (per unit)			
Tube type	Integral Low Fin Tube	Bare Tube	
Tube material	Carbon steel	Carbon steel	
Total external heat transfer area	5810	8750	m^2
Nameplate tube flow pressure	179	179	bar
Fin outer diameter	19.05	19.05	mm
Tube inner diameter	11.05	12.95	mm
Wall thickness under fins	2.413	3.048	mm
Tube layout in crossflow	Rotated Square	Rotated Square	
Number of tubes per pass	1093	2734	
Number of passes	2	2	
Number of tubes in heater	2186	5468	
Tube length per pass	15.76	26.74	m
Tube pitch	30.48	30.48	mm
Fin height	1.588	N/A	mm
Fin thickness	0.3048	N/A	mm
Fin spacing (between adjacent surfaces)	1.032	N/A	mm
Number of fins per meter	748	N/A	
Heat transfer area ratio (Ao/Ai)	4.863	1.471	
2. Shell Description (per unit)			
Nameplate shell flow pressure	2.396	2.288	bar
Shell material	Carbon steel	Carbon steel	
Shell length	15.76	26.74	m
Tube bundle diameter	1.63	2.56	mm
Shell inner diameter	1.64	2.58	mm
Shell wall thickness	9.525	15.88	mm
Tube sheet thickness	63.5	99.22	mm
Overall length	16.7	28.2	m
Shell type	Two pass shell	Two pass shell	
Number of baffles	6	4	
Baffle spacing	2251.1	5348	mm
Baffle cut / equivalent pass diameter	40	40	%
Equivalent pass diameter	1166.4	1827.7	mm
Shell outer diameter	1662	2609.9	mm
Engineering Design Heat Balance Results			
General Pump (82)			
Pump type	Multistage centrifugal	Multistage centrifugal	
Drive type	Variable RPM	Variable RPM	

Table C- 3 – Loading System (L) main equipment sizing

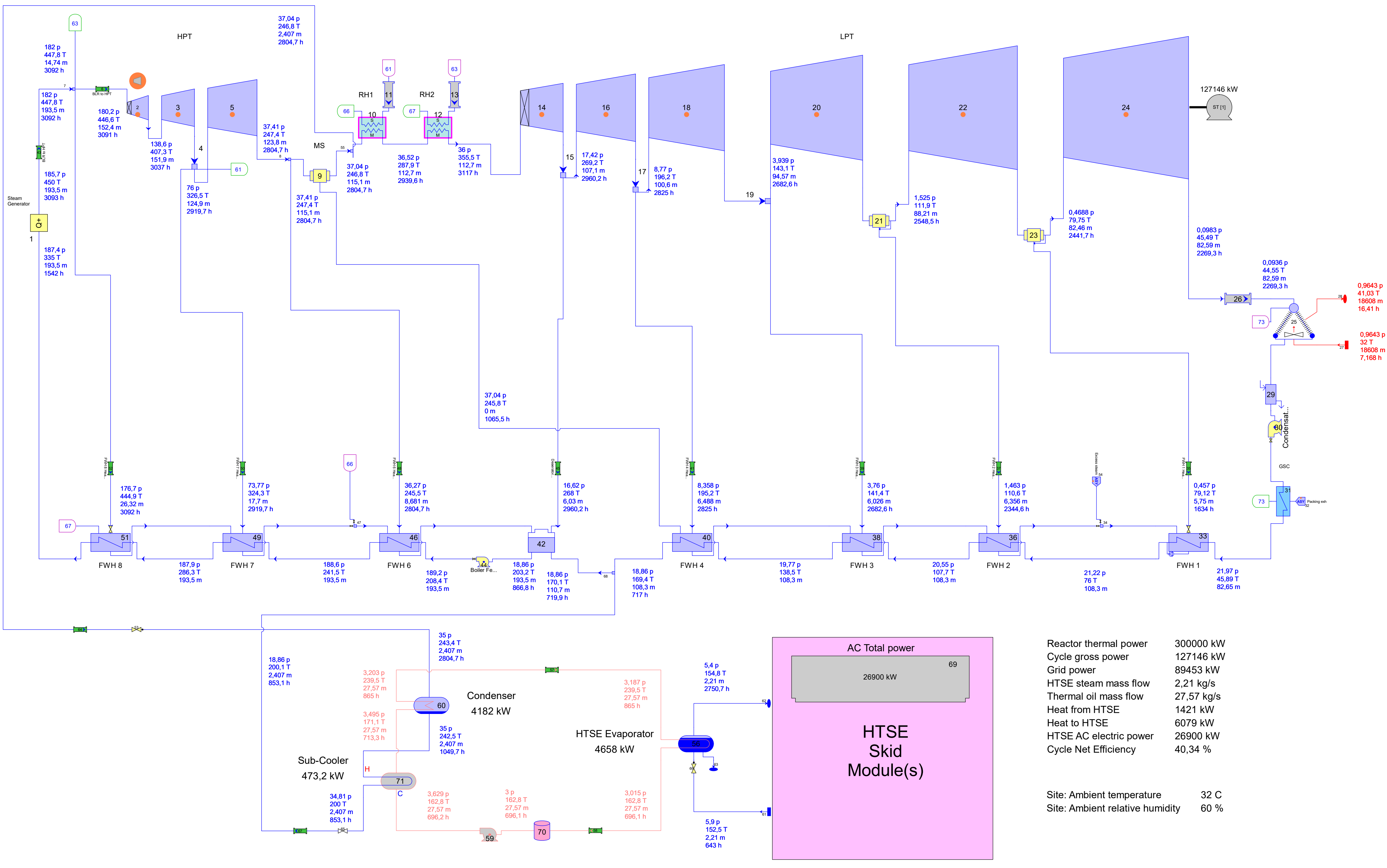
Equipment / Parameter	L1	L2	Unit
Number	2 - 100%	2 - 100%	
1. Nameplate Conditions (per existing unit)			
Nameplate (unrounded) mass flow	67.67	135.3	kg/s
Nameplate (unrounded) head	144.4	133.9	m
Nameplate volume flow	7571	15142	lpm
Nameplate head	152.4	137.2	m H2O
Pump shaft speed	3000	3000	RPM
Shaft power	163.7	303.5	hp
Pump isentropic efficiency	74	74	%
Pump mechanical efficiency	97	97	%
Estimated Pump Data			
Pump (PCE) (55)			
Pump type	Single stage centrifugal	Single stage centrifugal	
Drive type	Variable RPM	Variable RPM	
Number	3 - 50%	3 - 50%	
1. Nameplate Conditions (per existing unit)			
Nameplate (unrounded) mass flow	284.5	568.6	kg/s
Nameplate (unrounded) head	46.87	46.04	m
Nameplate volume flow	9464	18927	lpm
Nameplate head	53.34	45.72	m H2O
Pump shaft speed	3000	1500	RPM
Shaft power	225	450	hp
Pump isentropic efficiency	85	85	%
Pump mechanical efficiency	97	97	%

Appendix D Hydrogen production heat and mass balances

The heat and mass balance schematics for the hydrogen production solution design cases presented in Section 6.3 are shown in the following pages:

- Design Case TH1
- Design Case TH2
- Design Case TH3
- Design Case TH4

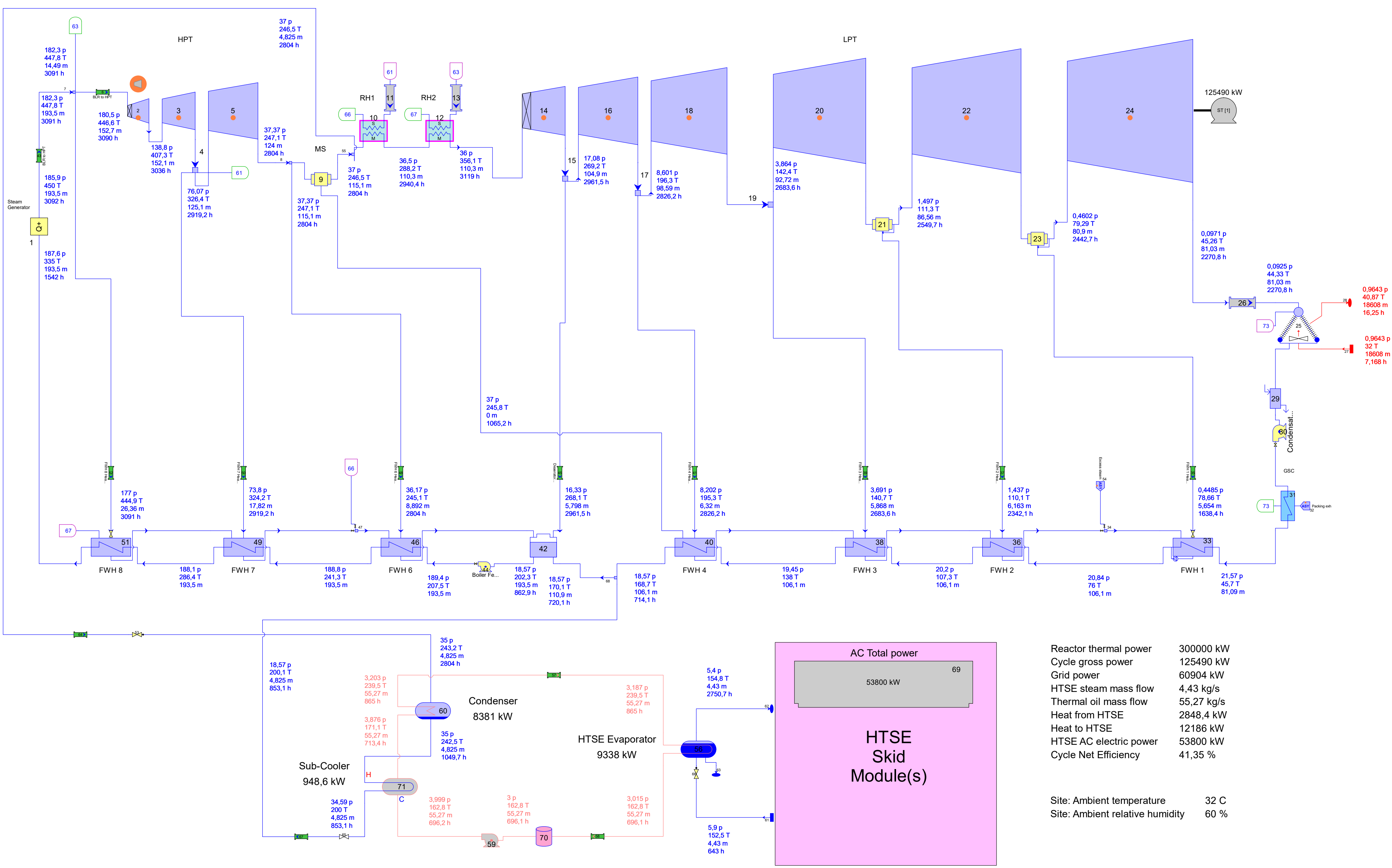
bar | C
kg/s | kJ/kg



Hydrogen Production
TH1-BaseCase

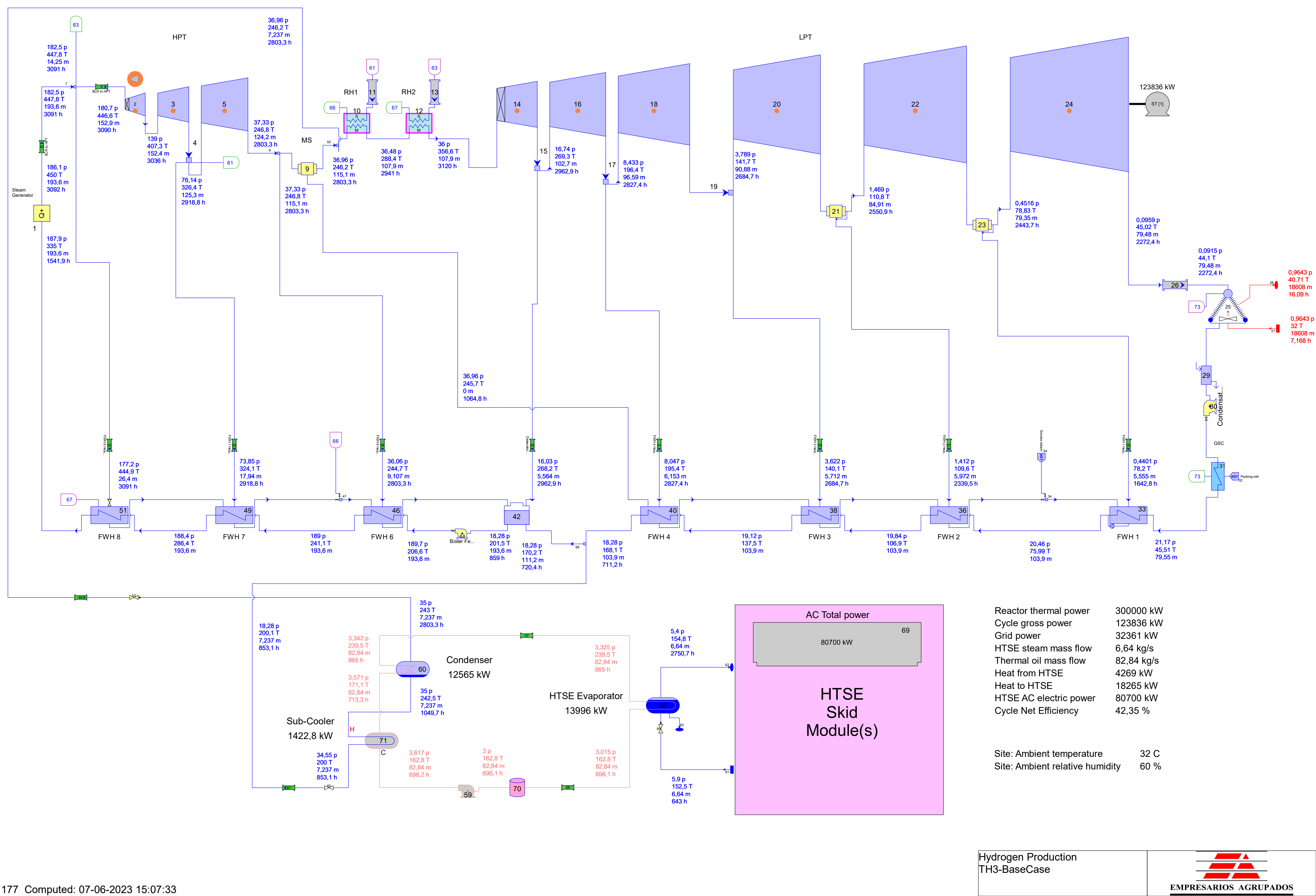
EMPRESARIOS AGRUPADOS

bar | C
kg/s | kJ/kg

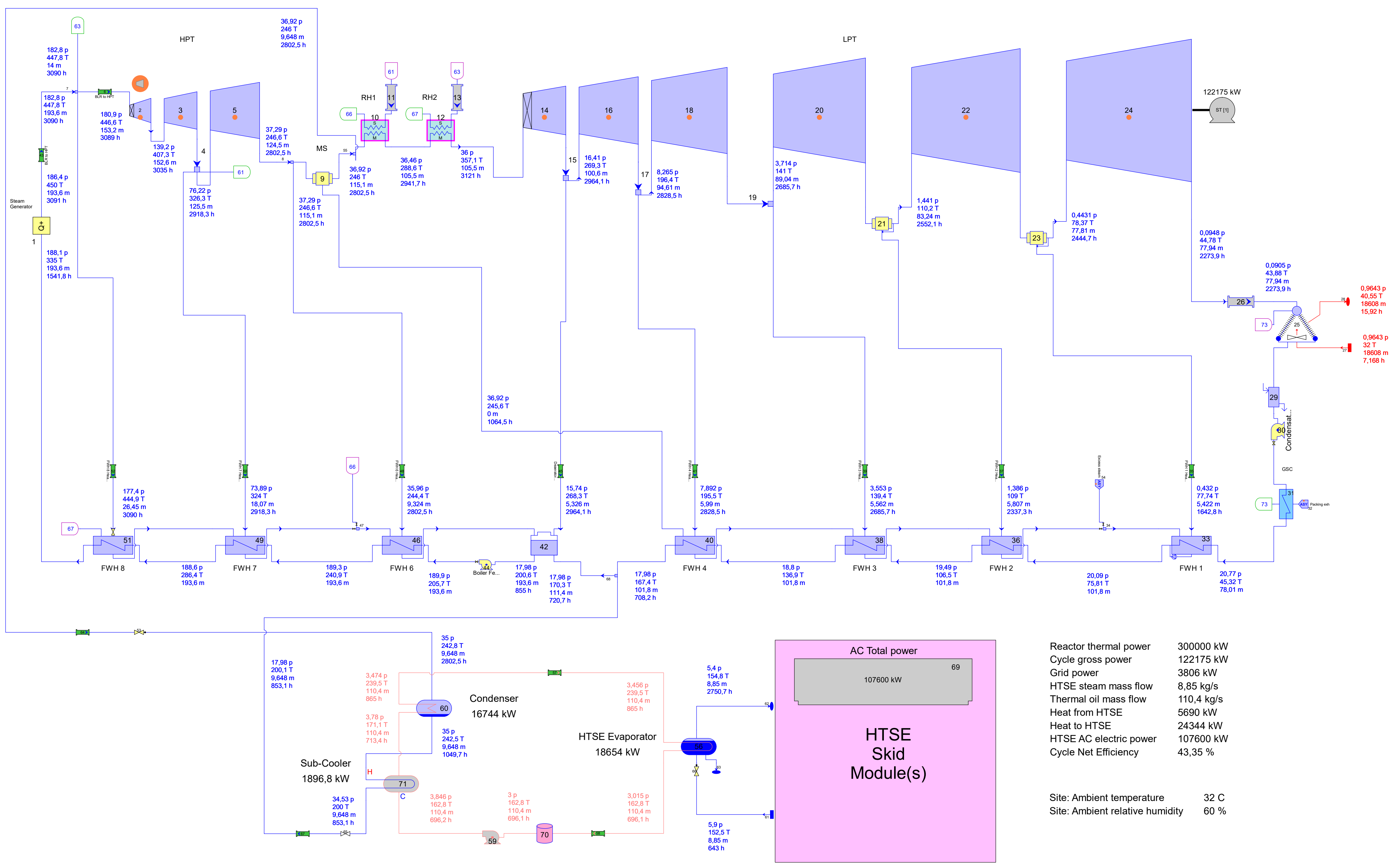


Hydrogen Production
TH2-BaseCase

EMPRESARIOS AGRUPADOS


bar | C
kg/s | kJ/kg
HPT
LPT
MS
RH1
RH2
123836 kW
Steam Generator
FWH 8
FWH 7
FWH 6
FWH 4
FWH 3
FWH 2
FWH 1
GSC
Boiler Fe...
Condenser
12565 kW
Sub-Cooler
1422,8 kW
HTSE Evaporator
13996 kW
AC Total power
80700 kW
HTSE
Skid
Module(s)
Reactor thermal power 300000 kW
Cycle gross power 123836 kW
Grid power 32361 kW
HTSE steam mass flow 6,64 kg/s
Thermal oil mass flow 82,84 kg/s
Heat from HTSE 4269 kW
Heat to HTSE 18265 kW
HTSE AC electric power 80700 kW
Cycle Net Efficiency 42,35 %
Site: Ambient temperature 32 C
Site: Ambient relative humidity 60 %
Hydrogen Production
TH3-BaseCase
EMPRESARIOS AGRUPADOS

bar | C
kg/s | kJ/kg



Reactor thermal power	300000 kW
Cycle gross power	122175 kW
Grid power	3806 kW
HTSE steam mass flow	8,85 kg/s
Thermal oil mass flow	110,4 kg/s
Heat from HTSE	5690 kW
Heat to HTSE	24344 kW
HTSE AC electric power	107600 kW
Cycle Net Efficiency	43,35 %

Site: Ambient temperature	32 C
Site: Ambient relative humidity	60 %

Hydrogen Production
TH4-BaseCase

EMPRESARIOS AGRUPADOS

Appendix E Hydrogen production sizing parameters

The sizing specifications for the main equipment of the Hydrogen production systems are shown in Table E- 1 – Hydrogen Systems (H) main equipment sizing.

Table E- 1 – Hydrogen Systems (H) main equipment sizing

Equipment / Parameter	H1	H2	H3	H4	Unit
Estimated Shell-Tube Heat Exchanger Data					
Shell-Tube Condensing HX (PCE) [60]					
Number of units	1	1	1	1	
1. Tube Description (per unit)					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube material	Carbon steel	Carbon steel	Carbon steel	Carbon steel	
Total external heat transfer area	210	321	664	802	m^2
Nameplate tube flow pressure	3.495	3.876	3.571	3.78	bar
Tube outer diameter	15.88	15.88	15.88	15.88	mm
Tube inner diameter	13.39	13.39	13.39	13.39	mm
Tube wall thickness	1.245	1.245	1.245	1.245	mm
Tube layout in crossflow	Rotated Square	Rotated Square	Rotated Square	Rotated Square	
Number of tubes per pass	208	278	673	778	
Number of passes	3	3	2	2	
Number of tubes in heater	624	834	1346	1556	
Tube length per pass	6.746	7.725	9.887	10.34	m
Tube pitch	23.81	23.81	23.81	23.81	mm
Heat transfer area ratio (Ao/Ai)	1.186	1.186	1.186	1.186	
2. Shell Description (per unit)					
Nameplate shell flow pressure	35	35	35	35	bar
Shell material	Carbon steel	Carbon steel	Carbon steel	Carbon steel	
Shell length	6.746	7.725	9.887	10.34	m
Tube bundle diameter	687	792	1000	1080	mm
Shell inner diameter	928	1070	1350	1450	mm
Shell wall thickness	12.7	15.88	19.05	22.22	mm
Tube sheet thickness	15.88	18.26	23.02	24.61	mm
Overall length	7.7	8.8	10.6	11.1	m

Table E- 1 – Hydrogen Systems (H) main equipment sizing

Equipment / Parameter	H1	H2	H3	H4	Unit
Shell outer diameter	953	1100.8	1390.4	1496.8	mm
Estimated Shell-Tube Heat Exchanger Data					
Shell-Tube General HX (PCE) [71]					
Number of units	1	1	1	1	
1. Tube Description (per unit)					
Tube type	Integral Low Fin Tube	Integral Low Fin Tube	Integral Low Fin Tube	Integral Low Fin Tube	
Tube material	Carbon steel	Carbon steel	Carbon steel	Carbon steel	
Total external heat transfer area	20.81	42.63	77.06	93.79	m^2
Nameplate tube flow pressure	35	35	35	35	bar
Fin outer diameter	15.88	15.88	15.88	15.88	mm
Tube inner diameter	10.21	10.21	10.21	10.21	mm
Wall thickness under fins	1.245	1.245	1.245	1.245	mm
Tube layout in crossflow	Rotated Square	Rotated Square	Rotated Square	Rotated Square	
Number of tubes per pass	24	35	53	68	
Number of passes	2	2	2	2	
Number of tubes in heater	48	70	106	136	
Tube length per pass	3.155	4.432	5.291	5.019	m
Tube pitch	25.4	25.4	25.4	25.4	mm
Fin height	1.588	1.588	1.588	1.588	mm
Fin thickness	0.3048	0.3048	0.3048	0.3048	mm
Fin spacing (between adjacent surfaces)	1.032	1.032	1.032	1.032	mm
Number of fins per meter	748	748	748	748	
Heat transfer area ratio (Ao/Ai)	4.283	4.283	4.283	4.283	
2. Shell Description (per unit)					
Nameplate shell flow pressure	3.629	3.999	3.617	3.846	bar
Shell material	Carbon steel	Carbon steel	Carbon steel	Carbon steel	
Shell length	3.155	4.432	5.291	5.019	m
Tube bundle diameter	214	256	311	350	mm
Shell inner diameter	224	265	321	360	mm
Shell wall thickness	6.349	6.349	6.349	6.349	mm
Tube sheet thickness	6.35	6.35	6.35	6.35	mm
Overall length	3.3	4.6	5.5	5.2	m
Shell type	One pass shell	One pass shell	One pass shell	One pass shell	
Number of baffles	6	4	2	2	
Baffle spacing	451	886	1763.6	1673	mm
Baffle cut	89.6	106	128	144	mm
Shell outer diameter	237	278	333	373	mm
Estimated Shell-Tube Heat Exchanger Data					
Shell-Tube Evaporating HX (PCE) [56]					

Table E- 1 – Hydrogen Systems (H) main equipment sizing

Equipment / Parameter	H1	H2	H3	H4	Unit
Number of units	1	1	1	1	
1. Tube Description (per unit)					
Tube type	Bare Tube	Bare Tube	Bare Tube	Bare Tube	
Tube material	Carbon steel	Carbon steel	Carbon steel	Carbon steel	
Total external heat transfer area	198	396	486	577	m^2
Nameplate tube flow pressure	3.187	3.187	3.325	3.456	bar
Tube outer diameter	15.88	15.88	15.88	15.88	mm
Tube inner diameter	13.39	13.39	13.39	13.39	mm
Tube wall thickness	1.245	1.245	1.245	1.245	mm
Tube layout in crossflow	Rotated Square	Rotated Square	Rotated Square	Rotated Square	
Number of tubes per pass	242	485	545	612	
Number of passes	2	2	2	2	
Number of tubes in heater	484	970	1090	1224	
Tube length per pass	8.189	8.19	8.948	9.456	m
Tube pitch	23.81	23.81	23.81	23.81	mm
Heat transfer area ratio (Ao/Ai)	1.186	1.186	1.186	1.186	
2. Shell Description (per unit)					
Nameplate shell flow pressure	5.4	5.4	5.4	5.4	bar
Shell material	Carbon steel	Carbon steel	Carbon steel	Carbon steel	
Shell length	10.65	10.65	11.63	12.29	m
Tube bundle diameter	607	853	903	956	mm
Shell inner diameter	1.090	1.530	1.630	1.720	mm
Shell wall thickness	6.35	7.938	9.525	9.525	mm
Tube sheet thickness	25.4	25.4	25.4	25.4	mm
Overall length	11.8	12.2	13.3	14.1	m
Shell outer diameter	1105.3	1550.8	1644.4	1739.7	mm
Engineering Design Heat Balance Results					
General Pump [59]					
Type	Variable RPM	Variable RPM	Variable RPM	Variable RPM	
Number	1 - 100%	1 - 100%	1 - 100%	1 - 100%	
Number operating	1	1	1	1	
Heat transfer fluid	THERMIN OL 66	THERMIN OL 66	THERMIN OL 66	THERMIN OL 66	
1. Nameplate Conditions (per existing unit)					
Nameplate (unrounded) mass flow	30.64	61.41	92.05	122.7	kg/s
Nameplate (unrounded) head	7.042	11.18	6.9	9.468	m
Nameplate volume flow	2082	4164	6624	8517	lpm
Nameplate head	7.62	12.19	7.62	10.67	m H2O
Pump shaft speed	1464.6	1464.6	1464.6	1464.6	RPM
Shaft power	3.182	3.182	3.182	3.182	hp

Table E- 1 – Hydrogen Systems (H) main equipment sizing

Equipment / Parameter	H1	H2	H3	H4	Unit
Pump isentropic efficiency	84.7	84.7	84.7	84.7	%
Pump mechanical efficiency	96.7	96.7	96.7	96.7	%