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Start-up and Shut-down times of power CCUS facilities

Summary of Study report

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Prepared by	Checked by	Verified by	Approved by
Klim MacKenzie			
Jamie Calvert Graduate Engineer Klim MacKenzie Senior Process Engineer	Graeme Cook Fuel Transition Consultant	Andy Cross Project Manager	David Hope Technical Director, Power & Energy

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Prepared for:

Department for Business, Energy & Industrial Strategy

Prepared by:

Jamie Calvert
Graduate Engineer

Klim Mackenzie
Senior Process Engineer

AECOM Limited
3rd Floor, Portwall Place
Portwall Lane
Bristol BS1 6NA
United Kingdom

T: +44 117 901 7000
aecom.com

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1. Executive Summary

The Department for Business, Energy and Industrial Strategy (BEIS) has commissioned AECOM to investigate potential improvements to the start-up and shut-down times of gas-fired power Carbon Capture, Utilisation and Storage (power CCUS) facilities. This report summarises the outputs of the study, including process modelling to demonstrate the performance of a range of configuration variants and inputs to the BEIS Dynamic Dispatch Model. A reference or 'standard' configuration case was identified to achieve 95% capture of normal carbon dioxide emissions from a modern H-Class Combined Cycle Gas Turbine power plant. The standard configuration was developed from open literature, project history and AECOM experience of carbon capture processes and is recorded in the Basis of Design, which is appended to this report. Results of the literature review are also provided in an appendix to this report.

A concept design was developed for the power CCUS facility, using Thermoflow 29 for the power cycle and ProMax 5.0 for the carbon capture process. Results of the simulation work are presented in the report, including concept material balances and estimated electrical and heat consumption of a 95% post-combustion capture plant. 35% MEA (no other solvent) was the solvent chosen for this study as an open-art, technology-neutral solvent.

The performance of the standard configuration plant at start-up and shut-down was evaluated, considering issues such as:

- Full system start-up and shut-down times
- Minimum up time and minimum down time between runs
- Ramp rates
- CO_2 capture rates and residual emissions during start-up and shut-down
- Minimum environmentally-compliant stable generation
- Fuel burn during start-up and shut-down
- Gross and net thermal efficiencies and penalty for operating 95% capture plant compared to unabated

Further, three separate configurations plus one additional noteworthy option have been investigated for their potential to improve the full system performance based on the above metrics. Particular attention was paid to:

- Improvements to the start time, which will inform the likely merit order positioning for power CCUS plant competing against other fossil fuel facilities in a market with significant quantities of renewable generation.
- Residual emissions during transient events, which govern an increasing share of plant operating life at lower capacity factors.

The un-optimised scenario (referred to as 'standard configuration') was modelled as a benchmark plant configured only for baseload operation i.e. with no measures taken to maintain high capture rates through plant starts or stops. The standard configuration was found to produce incremental emissions during start-up and shut-down and would not be expected to meet a 95% capture target in operation during start-up and shut-down. Four configuration options considered for their potential to improve the flexible performance of the standard configuration plant were:

1. Segregating solvent inventory during start-up between separate absorber and regenerator loops (without adding any extra solvent storage);
2. Added solvent storage and solvent buffer volume to maintain capture rate until regenerated lean amine is available;
3. Dedicated storage of heat for pre-heating the regenerator;
4. Fast-starting steam cycle technologies such as Benson boiler and/or HP bypass extraction to reduce the delay before steam extraction to the PCC plant.

Segregated inventory alone was found to give overall start-up capture rate of approximately 87% and therefore would not provide 95% capture throughout start-ups. However, segregated solvent inventory was found to readily combine with the three other options, reducing the impact of deploying any of the storage options to deliver an effective design.

2. Nomenclature

The following nomenclature have been used within this document.

Abbreviation	Description
BAT	Best Available Techniques
BEIS	Department for Business, Energy and Industrial Strategy
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine (Gas Turbine + Steam Turbine)
CCS	Carbon Capture and Storage
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CWS	Cooling Water Supply
CWR	Cooling Water Return
DCC	Direct Contact Condenser
FEED	Front End Engineering Design
GJ	Giga Joules
GT	Gas Turbine
GW	Giga Watts
HHV	Higher Heating Value
HMB	Heat and Material Balance
HRSG	Heat Recovery Steam Generator
ISO	International Standards Organisation
ITT	Invitation to Tender
LHV	Lower Heating Value
mbar	Millibar
MEA	Monoethanolamine
MW	Megawatt
MW.e	Megawatt electricity (distinguish from thermal)
MWh	Megawatt hours
MW.th	Megawatt thermal (distinguish from electrical)
NOx	Nitrogen Oxides

Abbreviation	Description
NTS	Notice to Synchronise
OPEX	Operating Expenditure
PCC	Post-combustion Carbon Capture
PFD	Process Flow Diagram
ppmv	Parts per million by volume
RH	Relative Humidity
SCR	Selective Catalytic Reduction
ST	Steam Turbine
TTES	Tank Thermal Energy Store
WN	Wobbe Number

3. Introduction

3.1 Project Overview

The Department for Business, Energy and Industrial Strategy (BEIS) is currently exploring the role that gas-fired power with Carbon Capture, Utilisation and Storage (power CCUS) can play in the UK electricity system. This was a commitment in the Government's 2018 'UK CCUS Deployment Pathway: An Action Plan'. Development of UK-based CCUS technology has been recognised by the Climate Change Committee as a key component of the most cost-effective pathway to meeting the UK's climate change emissions reduction targets[1].

Power CCUS can provide an important part of the electricity grid decarbonisation process, giving firm dispatchable low carbon generation. However, power CCUS may need to operate at lower load factors, such as mid-merit, as greater amounts of intermittent renewable energy systems are added to the electricity system between now and 2050[2].

Previous work on power CCUS can be broadly categorised as either:

- Various engineering studies from Concept through to Front End Engineering Design (FEED)-level definition based on defining a process for base-load generation. Limited detail of start-up behaviour, as the process design basis for these studies was to capture from a plant operating at baseload (and therefore typically no more than 20 starts per year total), with start/stop effects taken as negligible.
- Various academic studies considering optimisations including non-linear programming techniques to maximise revenue in a particular operating scenario or investigate the dynamic performance of a particular configuration in a specific scenario, rather than collecting plant characteristics at start-up and shut-down.

Relatively few papers have considered start-up, shut-down and ramping performance in detail[3] and fewer still for modern H-Class CCGT plants with fast starting performance. BEIS has therefore commissioned AECOM to carry out a study to determine the performance of power CCUS plant during transient events, given future abated plant may run in a mid-merit role to support renewables, rather than supply baseload power.

This study has also been based on a 95% capture rate of carbon dioxide emissions, as opposed to most of the other literature which was in the 80%-90% range, to reflect the anticipated future requirements for power CCUS plant that will contribute to a net zero energy system. 95% capture was chosen for this study following guidance from BEIS to provide an early indication whether higher capture rates than 80-90% would be achievable, or whether fundamental equilibrium issues would be encountered at 95%.

3.2 Purpose

This report presents a concise summary of the study work to date, incorporating work done in the Basis of Design and literature review. The purpose of this report is to present the modelling assumptions, modelling results and provide a summary of overall study findings.

3.3 Study Objectives

The first objective of this study was to determine a technology-neutral PCC process to deliver 95% that could be considered a 'standard' PCC configuration for further investigation. Areas of study included:

- Determine an appropriate technology-neutral process (solvent choice, concentration and circulation rate)
- Dynamic response within the amine absorber from transient effects on CO_2 rate
- Dynamic response on the amine regeneration process (and reclaiming process if continuously operating) from available steam extraction rate and quality

An investigation of the potential options to improve the standard configuration power CCUS plant was then carried out, with three top configurations identified for further investigation according to a high-level checklist:

- Is the potential option compliant with current Best Available Techniques (BAT) for Large Combustion Plant?

[1] CCC welcomes Government's commitment to Carbon Capture and Storage technology; CCC; 2018; https://www.theccc.org.uk/2018/11/28/ccc-welcomes-governments-recommitment-to-carbon-capture-and-storage-technology/
[2] Net Zero: The UK's contribution to stopping global warming; CCC; 2019; https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/
[3] Flexibility of low-CO2 gas power plants: integration of the CO2 capture unit with CCGT operation; Ceccarelli, N. et al.; 2014; Energy Procedia; pp. 1703-1726

- What is the reduction in carbon capture plant response time due to dynamic changes in the power plant?
- Does the reduction in carbon capture response time eliminate the time spent generating unabated while starting the PCC plant?
- Can the plant running at part-load qualify for the higher emissions limits currently available below a certain MW generation threshold?
- What residual emissions are expected, if any?
- What are the associated engineering, commercial and technology risks for new-build plants?
- What are the associated challenges for retrofit of standard configuration CCGT+PCC plants with the selected options?

The three options with the top checklist scores were investigated further.

Finally, the study objectives included providing the results of the option investigation and data for flexible power CCUS plant to update the assumptions of the BEIS Dynamic Dispatch Model.

4. Reference Documents

Reference	Document Title
1	Literature Review
2	Basis of Design

5. Methodology

An initial literature review was carried out to gather evidence of power with Carbon Capture, Utilisation and Storage (power CCUS) processes and determine a typical or 'standard' configuration for investigation. The literature review aimed to answer questions posed by the Department for Business, Energy and Industrial Strategy (BEIS) in the Invitation to Tender (ITT):

1. How do unabated Combined Cycle Gas Turbine (CCGT) and standard configuration post-combustion Carbon Capture Utilisation and Storage (CCUS) power plants perform?
2. What is the best available evidence on the start-up and shut-down times associated with alternative configurations and/or operating strategies for CCUS power plants?
3. Based on a qualitative assessment, what three alternative configurations are best suited for further analysis, based on:
    a. Their ability to improve the start-up times of 'standard configuration' power CCUS facilities without significantly impacting the power generation and CO_2 capture rate
    b. The engineering and cost challenges associated involved in either newly building such facilities or retro-fitting 'standard configuration' power + CCUS stations to incorporate the alternative configurations and operating strategies
4. Based on metrics such as time, CO2 vented, total cost etc., how would the selected alternative configurations perform in relation to the parameters identified in the first question?

The full literature review is provided in Ref. 1. Following the Literature Review, the next stage of the study was to set the design basis for the simulation work based on a wide variety of background information including gathered data from the literature review and AECOM's own project experience and judgement.

A representative conservative model of the power plant was then developed in Thermoflow, with outputs to a ProMax flowsheet containing the Post-Combustion Capture (PCC) model. The Thermoflow model was used to gather performance data on the reference power plant performance and inputs such as fuel gas composition, ambient conditions and site cooling strategy.

In order to simulate how the plant performs during the transient periods of start-up and shut-down, a number of key snapshots were identified during both transients of the power plant's operation. These snapshots represent the key characteristic points in the start-up and shut-down process. For example, defining the time at which steam extraction is available to start heating the reboiler, followed by the time at which the reboiler has received enough heat to begin regenerating amine in the stripper.

Based on the findings of the literature review, the chosen configuration options selected to improve flexibility were modelled using ProMax in addition to the base configuration PCC flowsheet. This software is a more developed resource for modelling carbon capture compared to Thermoflow, having rigorous reaction kinetic models to predict real column behaviour with no reliance upon simplified approaches to equilibrium. For each of the configuration options, as well as the standard PCC power plant, a summarised heat and material balance (HMB) sheet with the corresponding process flow diagram (PFD) was completed to record all the key data of the overall process. By comparing each of the HMB sheets and using them in further calculations, the different configurations were compared based on areas identified in the evaluation checklist discussed earlier in the Study Objectives.

6. Literature Review

The content within the Literature Review (Ref. 1) has been structured based on the key questions posed in the ITT. This document is provided in Appendix A of this report for reference and is summarised in the following paragraphs.

The first section related to the performance of unabated CCGT plants and assessed CCGT plants with PCC to characterise a hypothetical 'standard' configuration. The different performance indicators considered within the review include: the time and associated costs with start-up and shut-down, minimum up-time and down-time between operating cycles, ramping rates and minimum turndown of current CCGT plant, CO_2 capture rates and residual emissions, and thermal efficiency of the whole plant. By analysing each of these indicators for the unabated CCGT plant based on existing technical research and data from current plants in operation, an in-depth understanding of the plant's operation has been determined and used as the base of the further study.

Since the process of PCC for both coal and gas-fired power plants are comparable, with the use of PCC more established with coal-fired power plants, knowledge and performance characteristics from these plants can be applied to this study with minor adjustments.

The second section of the review focussed on the flexible operation of amine-based PCC and the different methods studied within academic papers. A large portion of the research within the area of power plant flexibility relates to the economic factors associated with the operation, as opposed to start-up and shut-down times. This means that only a limited number of sources were found that specifically investigate flexibility in terms of operating timings. From these select papers, several different strategies were investigated and compared with the main findings of each of the papers summarised in the Literature Review. This supported the final choice of the three configuration options to be further analysed in this study and gave an approximate idea of the likely impact each would have on the plant's operation.

7. Plant Configuration

7.1 Basis of Design for standard configuration

Having outlined each of the design conditions for the plant, the configuration of the standard CCGT plant for the study was defined. The selection of the equipment and layout of the plant was based on the current BAT for a large combustion plant, as requested in the ITT.

The chosen configuration of the standard unabated CCGT plant has the following characteristics:

- Gas inlet to the two Combined Cycle Gas Turbine (CCGT) trains of Siemens SGT5-9000HL for an unabated export capacity of approximately 1,740MW at International Standards Organisation (ISO) conditions (15°C, 60% relative humidity and sea level). Siemens SGT5-9000HL units have been used for the prime mover calculations carried out in this study as a typical example of modern H-Class CCGT. The power island was simulated in Thermoflow 29, using 2019 performance data. However, suitable design margins were added in the concept design work for the carbon capture plant to ensure a technology-neutral basis for the prime mover;
- Two (1 x 1) CCGT H-Class trains – Estimated capacity of approximately 1,740 MW (at the generator terminals) at site conditions (9°C, 80% relative humidity and 1013mbara per Ref. 2), each consisting of:
  - 1 Gas Turbines (GT) - Nominal capacity approximately 588 MW at ISO conditions;
  - 1 Heat Recovery Steam Generators (HSRG), configured as 3-pressure cycle with reheat and flue gas ducting connection to enable Post-Combustion Capture (PCC), horizontal layout to enable ducting connection;
  - 1 Steam Turbine (ST) - Nominal capacity approximately 277 MW at ISO conditions, condensing;
- Flue gas pre-treatment with Selective Catalytic Reduction (SCR), for NO_x removal.

Figure 1. Typical impression of two 1x1 H-Class CCGTs with post-combustion carbon capture

Addition of 95% PCC to each train of CCGT plant reduces the export capacity to approximately 1.47GW total. Additional equipment comprises:

- Axial fan blowers to overcome pressure losses through the gas treatment path (approximately 90mbar);
- Direct Contact Cooler (DCC) circulating water for capturing residual contaminants (mainly NO_x and residual SO_2) and cooling the flue gas for absorption;
- 35wt% MEA-based CO_2 capture system to reduce plant total CO_2 emissions during steady-state operation by 95%, comprising:
  - Absorber with water wash section for entrained amine removal;
  - Regenerator operating at approximately 2.2bara and 125°C to regenerate amine from 0.45mol/mol loading to 0.25mol/mol as a semi-optimised loading profile for energy efficiency;
  - Amine rich/lean cross-exchanger of plate-and-frame type;
  - Circulating amine and water pumps;
  - Heat exchangers for heat rejection to site cooling water circuit;
  - Site cooling water circuit along with heat rejection method (mechanical draft cooling towers, shared with the power plant);
  - Lean amine storage tank for draining during shut-down;
  - CO_2 compression and dehydration train for export at 150bara;

1 x 1 configuration was selected for the CCGT over 2 x 1 mainly due to alignment with the European market and previous work in the Energy Technologies Institute (ETI) Generic Business Case study[4]. Reference information was more readily available in the Literature Review to compare performance for 1 x 1 over 2 x 1, particularly with open-art MEA-based PCC. In addition, some small benefits have been noted for:

- Improved efficiency of 0.05-0.1% for 1x1;
- Higher overall output capacity by approximately 0.08% at base load;
- Lower auxiliary power consumption

Another reason for preferring a 1x1 arrangement for combining with PCC is fewer bespoke modifications to the steam cycle over 2x1. A 1x1 arrangement need only consider modifications to allow steam extraction in direct proportion to the overall plant load, whereas a 2x1 arrangement should also consider times with only one GT on demand. The 2x1 arrangement will likely have to support steam extraction at much lower relative HRSG turndown than 1x1 given that 100% loading of a single GT gives only 50% loading of the HRSG and ST.

SCR was included in all designs to reduce NO_x by 90% as this technology is now common on modern H-Class CCGT to meet emissions performance guarantees in normal operation.

The basis of other configuration selections is outlined in the Basis of Design report (Ref. 2).

[4] Thermal Power with CCS; ETI; 2017; https://www.eti.co.uk/programmes/carbon-capture-storage/thermal-power-with-ccs

8. Process Modelling Scenarios

8.1 Design Conditions

In order to model the plant power, input conditions for the simulation models in both Thermoflow and ProMax were detailed in full. These have been described in depth within the Basis of Design (Ref. 2) with the following design conditions defined:

- Plant characteristics – Location, site, operation and CO_2 capture rate
- Feedstock and utility specification – Natural gas, plant make-up water, waste water treatment and chemicals supply specifications
- Environmental emissions basis – NO_x and CO production
- CCS plant design – Flue gas and blower, solvent, absorber, stripper, heat exchangers, pumps, compressor and reclaimer

8.2 Start-up / Operating Scenarios

In assessing the start-up process, the timings of the various key stages through the start-up procedure depend on the type of start, based on temperature of the plant, i.e. hot, warm or cold starts. The temperature of the plant is dependent on how long the plant has been offline before receiving notice to start back up. For a hot start, the defined shut-down period of the power plant is less than 8 hours, whereas for a cold start, the shut-down period is greater than 64 hours (see detailed definition of start type in Table 1). An operational start between these two periods is considered a warm start. Hot and cold starts are clearly defined. However, the exact threshold between the longer end of a warm start and the shorter end of a cold start varies. The downtime following a weekend shut-down approaches the threshold to be considered a cold start. Therefore, for annual emissions calculations, this study has conservatively categorised all starts as either hot or cold.

Table 1. Definition of plant start in power plant, for reference

Shut-down duration	Type of start	Typical scenario
<8 hours	Hot	Weekday starts
8 – 64 hours	Warm	Restart after weekend shut-down
>64 hours	Cold	Start from ambient after overhaul

During the operation of a power plant, the number of starts will depend on the loading scenario employed by the operator. Three different load scenarios are presented in Table 2 with an estimated number of starts and operating hours calculated based on the reliability and availability of typical single shaft CCGT plants.

Table 2. Estimated number of starts and operating hours for different load scenarios, for reference

Load scenario	Overall number of starts (hot + cold)	Number of operating hours
Baseload	30 (24 + 6)	8094
Two-shift	276 (221 + 55)	3854
Mid-merit	395 (355 + 40)	1802

8.3 Modelling Methodology

The modelling approach used to assess the start-up process in this study was to consider forward-looking steady-state snapshots, as a conservative approach, and apply the maximum GT flue gas emissions (and therefore capture demand on the PCC plant) at the end of each snapshot period across the whole time period between snapshots. No credit was taken for the lower emissions during ramping from the previous snapshot. Therefore, the estimates of emissions both from the HRSG and the residual emissions into the stack are conservative throughout. The start-up sequence described in Section 8.4.1 allows snapshots to be selected at appropriate times to characterise the flue gas behaviour at start-up. This approach was reversed for modelling of the shut-down process.

The start-up sequence described also takes no credit for steam extraction until the IP/LP cross-over pressure is expected to have stabilised to allow extraction, and therefore no credit is taken for intermediate extraction flows. The availability of some steam is worth noting qualitatively from the perspective that real plant performance would be somewhat better than the scenarios considered in this study. However, the exact timings and ramp rates would be project-specific rather than generally applicable. Thus, availability of partial steam extraction was ignored in this study to draw generic conclusions that would be applicable across modern plant.

8.4 CCS Plant Snapshots

The processes of both start-up and shut-down of the CCS plant have been broken down into the key events with the timings and flowrate data defined. This helps to separate the overall transient profile into smaller periods to focus on during further analysis. A full description of each process can be found in the Basis of Design (Ref. 2) which describes the overall start-up process of the power plant and the CCS plant.

The following subsections present a summary of the snapshots identified for both the start-up and shut-down process used throughout the modelling of the CCS plant. These snapshots were chosen as they capture the distinct key events during the transient period and would be clearly defined when modelled.

8.4.1 CCS Plant Start-up Snapshots

The general start-up process for the 'standard' CCGT configuration with post-combustion CCS has been separated into five key stages with the below activities:

Snapshot 0: Receiving notice to synchronise (NTS) from the grid to start generation

Snapshot 1: Ignition within the GT occurs after the rotational speed setpoint is reached and the GT then accelerates to 3000rpm and picks up approximately 15% load (plus design margin). The PCC plant simulation ignores the changes in CO2 emissions during the period from ignition to 15% and takes emissions during the entirety of the time from ignition to Snapshot 1 as those at 15% GT load (plus design margin).

Snapshot 2: GT is ramped up to 50% load. CCS plant simulation takes taking emissions during the ramping from 15% to 50% as the 50% level (plus design margin) for the entire Snapshot duration.

Snapshot 3: GT is ramped to 75% for a hot start (emissions taken as 75% load immediately) or held at 50% for a cold start (emissions stay at 50% load). Snapshot 3 is the first point where credit for steam extraction is taken and the simulation takes steam into the PCC plant for the heating of the stripper column.

Snapshot 4: Plant operating at full capacity and CCGT start-up process is complete, GT is ramped to 100% load for a hot start or held at 50% for a cold start. PCC plant start-up continues until the regenerator start-up is complete.

A summary of the start-up process is presented in Table 3 with the relevant timings of both the hot co-start and cold start as well as the approximate flowrates of flue gas for each snapshot. This represents the performance of the power plant at its design baseload conditions with the entire start-up process taking 30 and 200 minutes for hot starts and cold starts, respectively.

Table 3. Snapshots of flue gas flowrate to CCS plant during start-up, starting at time = 0

Description	Snapshot No.	Time for hot co-start, mins	Time for cold start, mins	Flue gas flowrate, kg/s
Notice to synch, start-up sweep	0 (initial)	0	0	Nil
First firing	1	5	15	511 (Note 1)
Ramping up, 50% full load	2	20	25	681 (Note 1)
Steam export	3	25	60	823 (Note 1)
Full load	4	30	200	1,021 (Note 1)

Note 1 – start-up flue gas flows given are those direct from the Thermoflow material balance with no design margin, rather than based on fractions of the design flow for the PCC plant itself (1,100kg/s). The concept design of the CCS plant was carried out at the design flow of the PCC plant and then performance estimated off-design at the Table 3 part-load values.

8.4.2 CCS Plant Shut-down Snapshots

The final snapshot for start-up when the plant is operating at full capacity can be used as the initial snapshot of the shut-down process with the continuation of the numbering system. As with the start-up process, the shut-down sequence can be separated into five key stages with steady-state snapshots identified as follows:

Snapshot 4: Order from control centre to initiate shut-down process when operating at full capacity

Snapshot 5: Load of both GT and ST held briefly having ramped down to 30% of the GT's full load

Snapshot 6: ST completes its shut-down sequence while the GT load is held. Available steam for extraction assumed to be negligible. Regenerator stripping from Snapshot 6 is on residual heat in PCC plant only.

Snapshot 7: GT load reduced to 5% and held to allow the power generator to split from the system

Snapshot 8: Final load from the plant is removed and GT shaft is decoupled

As with the start-up process, a summary of the process, with the timings of each snapshot and the approximate flue gas flowrate, can be presented as shown in Table 4.

Table 4. Snapshots of flue gas flowrate to CCS plant during shut-down, starting at time = 0

Description	Snapshot No.	Time for shut-down, mins	Fuel Gas Flowrate, kg/s
Initiate unit shut-down at full load	4 (initial)	0	1020
Ramping down, 30% full load	5	5	547
ST complete shut-down	6	15	547
GT load hold, 5% full load	7	30	499
No plant load	8	45	Nil

9. Modelling Results

9.1 Introduction

Thermoflow material balance data was input to the ProMax flowsheet and a 35wt% MEA-based process was developed to achieve 95% capture from the flue gas of the Siemens 9000HL 1x1 CCGT. Margins were applied on the flue gas flow rates, rounding up to 1,100kg/s flue gas as outlined in the Basis of Design Section 5.6. This represents the un-improved base case or 'standard' configuration examined in this study to determine the limitations of the standard configuration.

9.2 Standard Configuration

The key process variables for the standard configuration are shown in Table 5 below. Note that the generating penalties from reboiler steam consumption and Post-Combustion Capture (PCC) plant electrical consumption are somewhat counteracted by reduced condenser duty in the power plant. Steam condensate from the amine reboiler can be returned directly to the Heat Recovery Steam Generator (HRSG) rather than passing through the condenser.

Table 5. Steady-state amine process outputs, single train basis

Parameter	Value	Units
Lean amine solution circulation rate	1500	kg/s
Amine rich loading	0.45	mol/mol
Amine lean loading	0.25	mol/mol

Parameter	Value	Units
Reboiler temperature	125	°C
Stripper condenser temperature	50	°C
Reboiler heat consumption	336	MW.th
PCC auxiliary electrical consumption	44.9	MW.e (~25.1MW.e to compressor)
PCC plant heat rejection duty	537	MW.th (See Section 9.2.1)
CO_2 design rate into PCC plant	85	kg/s
CO_2 capture rate	95	%
CO_2 residual emissions	4.1	kg/s

9.2.1 Standard configuration – heat rejection

The design basis for the PCC plant heat rejection is to share cooling duty with the power plant via mechanical draft cooling towers. Handling the extra 537MW.th heat rejection for the PCC plant in the CCGT cooling towers would be expected to increase net auxiliary electrical consumption for the site cooling by up to 3MW.e to account for the extra load on:

- Cooling water pumps (approximately 2MW.e net) and;
- Tower fan load to cool water returned from the PCC plant (approximately 1MW.e net).

Approximately 50% of the CCGT steam condenser duty would not be required during PCC operation, replaced instead by an increase in cooling water flow and increased cooling tower fan duty. The 3MW.e electrical consumption for PCC plant cooling represents approximately 0.3 absolute percentage points of generating efficiency. The application of different approaches for PCC plant heat rejection would explain much of the range of efficiency penalties calculated by other authors in open literature.

- Power plant cooling duty alone: approximately 414MW.th
- PCC plant cooling duty alone: approximately 537MW.th

PCC power plant combined cooling demand: approximately 673MW.th (HRSG condenser in combined plant has reduced load by 278MW.th)

For this process, the combined auxiliary electrical load attributed to the PCC process is approximately 44.9MW.e or 5.0 absolute percentage points at 100% load. In addition, 336MW.th of heat would be consumed, equivalent to approximately 74MW.e generation loss from the steam turbine.

9.2.2 Standard configuration overall generating efficiency

Net efficiency values for the 95% capture process are given in Table 6 below. PCC efficiency penalty is estimated at approximately 8.5 absolute percentage points. This value is broadly consistent with other works based on MEA investigated in the literature review (≈10%) which are normally based on 80%-90% CO_2 capture rate rather than 95% as used in this study. This disparity is likely due to other authors not normally taking credit for sharing the power plant cooling solution and reduced steam condenser load, as well as normally considering 30wt% MEA, whereas this study has considered 35wt% MEA and allows for lower regeneration energy consumption per tonne of CO_2 captured. Note that efficiency penalties are expected be lower if a proprietary or different solvent is used instead of a system based on MEA.

Table 6. Power plant performance with 95% PCC by 35wt% MEA, single train basis

Parameter	Value	Units
Normal generating capacity (before PCC) at site conditions	847	MW.e (870 MW.e at the generator terminals)
Site fuel consumption	1389	MW.th (LHV)
Normal net generating efficiency (before PCC)	60.9	% (LHV. 62.6% less Cooling towers, auxiliaries)
Site generating capacity with 95% PCC	722.7	MW.e
Site net generating efficiency with 95% PCC	51.9	% (LHV)

Source: Thermoflow material balance simulations

9.2.3 Amine inventory calculation for standard un-improved configuration

The standard configuration has been specified with approximately 30 minutes of process inventory at full circulation rate, as set in the Basis of Design (Ref. 2). 30 minutes of inventory is equivalent to:

$$1500\frac{kg}{s} \times 30\,\mathrm{min} \times 35\mathrm{wt\%} \times \frac{1\mathrm{kmol}}{61kg} = 15{,}492\ kmol\ MEA$$

At the initial acid loading of 0.25 mol/mol for the lean amine supplied from the storage tank ('fresh lean amine'), the quantity of CO_2 dissolved in the lean amine is given by:

$$0.25\frac{mol\ CO_2}{mol\ MEA} \times 15{,}492\ kmol\ MEA = 3873\ kmol\ CO_2$$

During the first 30 minutes of operation, fresh lean amine is passed through the absorber from the lean amine storage tank, as shown in Figure 2 below. Rich amine is then returned to the tank and the conservative assumption has been made that the tank is always well-mixed, therefore the loading is recalculated at each Snapshot based on the total quantity of CO_2 absorbed.

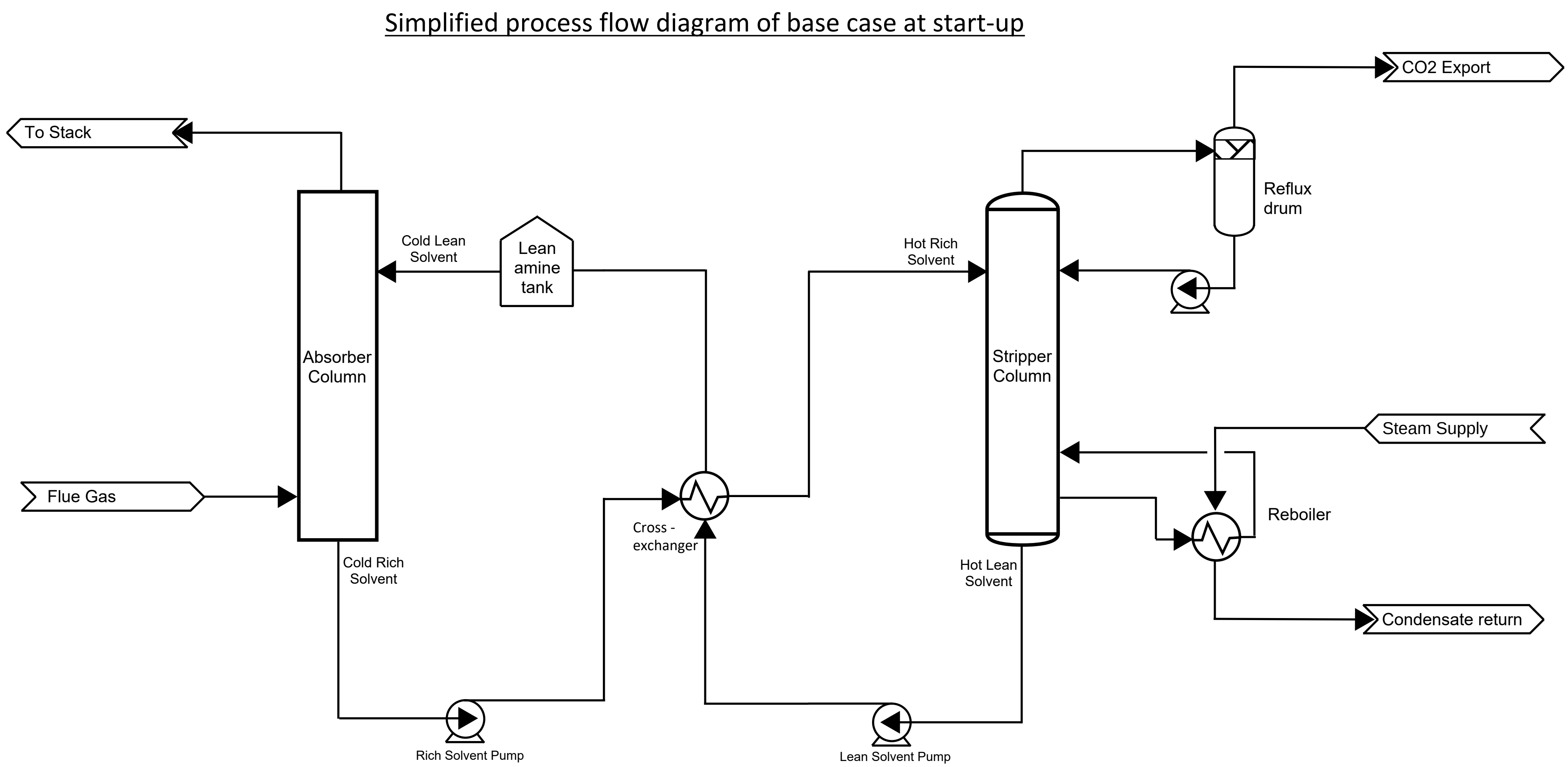

Figure 2. Post-combustion capture process considered for 'standard configuration'

9.2.3.1 Calculating amine loading rise through start-up

The loading in the amine tank throughout the initial period during the 30-minute rich amine collection period was calculated as a function of:

- Quantity of CO_2 already stored in the lean amine (3,873 kmol), plus;
- Quantity of CO_2 absorbed from the flue gas as the gas turbine is ramped from minimum load to load at 30 minutes.

Using the basis of 15,492 kmol total MEA inventory, the overall amine loading throughout the start-up snapshots is calculated as:

$$Loading\ at\ end\ of\ Snapshot = Loading\ at\ start\ of\ Snapshot + \frac{kmols\ CO_2\ absorbed\ during\ Snapshot}{15{,}492\ kmol\ MEA}, where:$$

$$Loading\ at\ start\ of\ Snapshot = 0.25\frac{mol}{mol} for\ Snapshot\ 1\ and\ rises\ thereafter,$$

$$mols\ CO_2\ absorbed\ during\ Snapshot\ = \frac{mass\ CO_2\ absorbed\ during\ Snapshot}{44\frac{kg\ CO_2}{kmol\ CO_2}},$$

$$\begin{aligned} &mass\ CO_2\ absorbed\ during\ Snapshot\ 1 \\ &\qquad = (mass\ flow\ of\ CO_2\ from\ HRSG\ at\ GT\ loading \\ &\qquad - mass\ flow\ of\ CO_2\ in\ treated\ gas\ to\ stack) \times duration\ of\ Snapshot \end{aligned}$$

$$\begin{aligned} mass\ CO_2\ absorbed\ during\ Snapshot\ 1 &= GT\ taken\ as\ 25\%, so\ \left(31.6\frac{kg}{s}\ CO_2 - 0.192\frac{kg}{s}CO_2\right) \times 15\ mins \\ &= 31.4\frac{kg}{s} \times 15\ mins = 28{,}267 kg\ or\ 28.27t\,, \end{aligned}$$

$$Loading\ at\ end\ of\ Snapshot\ 1 = 0.25\frac{mol}{mol} + \frac{28{,}267\ kg}{15{,}492\ kmol\ MEA \times 44\frac{kg}{mol}} = 0.29\frac{kmol}{kmol}$$

Loading for the rest of the snapshots is given according to Table 6 below. The amine inventory is seen to saturate with CO_2 by the end of Snapshot 6 (0.45 mol/mol), indicating that the standard configuration is no longer able to capture CO_2 and continuing emissions from the GT are effectively unabated in CO_2.

Table 7. Calculating amine loading at the end of each Snapshot

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	Snap 6	Snap 7
Time after start, mins	15	22	25	30	37	48	82
Duration, mins	15	7	3	5	7	11	34
Regenerator status	No steam	Pre-heat	Pre-heat	Pre-heat	Pre-heat	Pre-heat	Pre-heat
GT load	25%	50%	75%	100%	100%	100%	100%
CO_2 rate from GT, kg/s	31.6	50	80	85	85	85	85
CO_2 rate after PCC, kg/s	0.192	0.42	0.93	3.93	35	44.5	85
CO_2 absorbed over Snapshot, t	28.27	20.82	14.23	24.32	21.00	26.73	0.00
Amine loading in tank at end of Snapshot, mol/mol	0.29	0.32	0.34	0.38	0.41	0.45	0.45

9.2.4 Stripper pre-heat energy requirement

The stripper heating time at start-up was calculated from the sum of sensible heat input required:

- To heat the amine inventory from ambient (9°C) to the stripper normal operating temperature (125°C)
- To heat the metal mass of the stripper, fittings, reboiler and interconnecting piping from ambient to the stripper normal operating temperature

For the standard (un-optimised) configuration, there will be 30 minutes of amine inventory circulation to be heated within the stripper column (2,700,000kg inventory at 1,500kg/s). Given a heat capacity of approximately

3.34kJ/kg.K from the material balance (Appendix E Stream 18) for lean amine at start-up (0.25mol/mol), the heat requirement, Q, was calculated as:

$$Q = 2{,}700{,}000\,kg \times 3.34\frac{kJ}{kg.K} \times (125℃ - 9℃) = \ 1{,}046{,}088{,}000\ kJ, or\ 1047\ GJ$$

The metal mass calculation comprised:

- Stripper column wall thickness calculation as outlined in the Basis of Design Section 5.8.2
- Stripper column mass of steel calculation given the wall thickness
- 30% design margin to allow for column dished ends, mass transfer packing, piping and associated mechanical equipment

Stripper wall thickness, t, was calculated as a low-pressure column where vacuum normally dictates the design metal thickness:

$$P_c = 2.2E_Y\left(\frac{t}{D_0}\right)^3, where^5:$$

$$P_c = 0.101325\ MPa\ for\ vacuum - rated\ column$$

$$E_y = 193\ GPa\ for\ 316L^6$$

$$D_0 = 10m\ internal\ diameter + 2t$$

$$\frac{t}{10m + 2t} = \sqrt[3]{\left(\frac{0.101325}{193000 \times 2.2}\right)} = 0.0062m, rearranging\ gives:$$

$$t = \frac{0.062m}{1 - 0.0124} = 0.063m, or\ 63mm$$

Given a minimum wall thickness of 63mm and an overall column height of approximately 40m to accommodate the fittings and sump in addition to the packing. The volume for a thin-walled cylinder is given by the annular area multiplied by the column height:

$$Area = \pi \times (R^2 - r^2) = \pi \times 5.063^2\ m^2 - 5^2 m^2 = 1.99m^2$$

$$Volume = height \times Area = 40m \times 1.99m^2 = 83m^3$$

At a density of 7,990kg/m³, the mass of stainless steel used for the cylindrical section of the column is[7]:

$$83m^3 \times 7990\frac{kg}{m^3} = 663t, +30\%\ margin = 862t$$

The thermal mass and start-up heat requirement for the metal is calculated from a heat capacity of approximately 0.5kJ/kg.K[8]:

$$Q = 862{,}000kg \times 0.5\frac{kJ}{kg.K} \times 116K = 49{,}996{,}000\ kJ, or\ 50GJ$$

The sum of the energy inputs for the standard configuration is therefore:

$$50GJ + 1047GJ \approx 1100GJ$$

9.2.4.1 Uncertainties

The pre-heat time of the stripper column was derived from the sum of energy required to heat the amine inventory and that required to heat the metal. Less than 5% of the total energy (1,100GJ) is required by the metal itself (50GJ). Therefore, even an error of 50% in the metal mass would give approximately 2% difference in heat requirement for the standard inventory.

[5] Sinnot & Towler; Chemical Engineering Design; 5th Edition; Equation 13.52
[6] AISI 316L datasheet, typical; AK Steel; https://www.aksteel.com/sites/default/files/2018-01/316316L201706_2.pdf; accessed Mar 2020
[7] AISI 316L datasheet, typical; AK Steel; https://www.aksteel.com/sites/default/files/2018-01/316316L201706_2.pdf; accessed Mar 2020
[8] AISI 316L datasheet, typical; AK Steel; https://www.aksteel.com/sites/default/files/2018-01/316316L201706_2.pdf; accessed Mar 2020

The method for calculating column metal mass is directly proportional to the column diameter. This method has been benchmarked against the stripper shipping mass given for the Kårstø FEED study report[9] (6.67m diameter, 42m length for the cylindrical section and 271t, page 7-3) and found:

$$\textit{Kårstø report mass} = 271t,$$

$$\textit{column method for Kårstø column} = \ 447t, or\ 65\%\ overestimate$$

The 65% overestimate in column mass is likely due to the wall thickness calculation being overly conservative as no credit has been taken for structural design features such as stiffening rings which offer some protection. The metal mass calculation is therefore most likely to be overly conservative and some reduction in column heat requirement would be required. However, in order to allow a margin for the mass of the piping, packing, fittings and mechanical equipment, the expected overestimate has been kept in this study.

The second part of the pre-heat time calculation for the stripper column depends on the liquid hold-up volume in the stripper and is a design choice depending on circulation rate, as well as the total solvent storage volume design basis for the plant. Both parameters are process design choices independent of the start-up procedure, not calculated variables. Therefore, no new errors are expected to be introduced, rather, any differences for different plant design should be estimated from the heat-up calculation given in Section 9.2.4.

9.2.5 Start-up steam extraction and steam ramping

The time required for the amine stripper to reach operation at start-up in the standard configuration is determined from the heat requirement (as calculated in Section 9.2.4) and the ramping heat extraction rate given by steam availability from the normal extraction point on the steam turbine. The normal extraction point has been set for the standard configuration in this study as the cross-over between the IP turbine outlet and the LP turbine inlet (i.e. the IP/LP cross-over), refer to the Design Basis (Ref. 2). In all configurations, the steam turbine capacity has been set as that for the unabated plant, without optimisation (i.e. without reduction in size) for PCC plant steam extraction in abated operation.

For the standard scenario, no credit has been taken for any fast start steam cycle equipment, as such technology has not been universally adopted for all OEM equipment. Manufacturers would only propose optional fast-starting steam cycle equipment where they see an advantage to do so and therefore fast-start capability for steam extraction has not been considered part of the standard H-Class configuration. Fast start of the steam cycle has been considered as a separate improvement option in Section 9.3.5 to directly compare the use of fast starting equipment.

Based on the snapshot outlines given in Table 3, the time at which first steam extraction is available has been conservatively assumed to be 25 minutes and 60 minutes for hot and cold starts, respectively. Note that certain plant configurations would be expected to have steam availability sooner as a result of fast start capability as an explicit capability (particularly during hot starts). However, while fast-start plants will have some steam available for extraction prior to the times adopted in this study, the exact interaction between the HRSG/ST stabilisation and extracting the quantities of steam necessary for PCC is not known at time of writing. The plant considered for the standard configuration in this study has therefore been based on a power plant with no measures taken to optimise fast-starting the steam cycle. The standard configuration PCC plant would wait to extract steam until available from the IP/LP interface, notwithstanding any improvement options which are considered explicitly later.

Predicting the start time for extraction will be an exercise in inferring power plant performance data from e.g. dump steam rate and pressure into the condenser by the ST bypass. Until some PCC plants are built at a scale appropriate to this study and data is available around the guarantees vendors are willing to offer, inferring performance introduces some inherent risks:

- Delaying credit for steam extraction being available would underestimate the performance of flexible PCC on power plant, missing out on modern developments in CCGT, and setting an overly pessimistic performance expectation for flexible operation of CCGT with PCC.
- Conversely, overestimating the performance of the plant by setting an extraction point too early would mean real plants may fail to meet the benchmarks set in this study as they seek to meet other competing performance guarantees or lead to infeasible design requirements. This risk is considered greater than underestimating plant performance.

[9] CO2 Capture Facility at Kårstø, Norway; Bechtel; FEED Study Report; https://ukccsrc.ac.uk/sites/default/files/documents/news/Karsto-FEED-Study-Report-Redacted-Updated-comp.pdf; accessed Mar 2020

Therefore, the benchmarks used in this study have been taken to give reasonable estimates for steam extraction achievable by all modern plant (be it new-build or modernised retrofits), independent of particular technology choices or market drivers.

25 minutes after the NTS, credit has been taken for some steam being available. For a hot start, the quantity of steam available during the start-up snapshots has been taken to follow the GT load percentage. For example, 75% of full-load steam requirement has been considered available for extraction once the GT reaches 75% load; with 100% of steam available at 100% GT load. Table 8 and Table 9 show the CCGT steam extraction for hot and cold starts respectively, based on a normal heat extraction of 336MW.th for the base-line CCUS process, as discussed in Section 9.2.

Table 8. CCGT steam extraction rates following hot starts, based on 336MW.th normal steam duty in the reboiler

Time post-NTS, mins	GT load, %	GT load taken as, %	CCS heat extraction, %	MW.th to reboiler
0 to 15	Start and ramping to 25%	25%	0	None
15 to **22**	Ramping to 50%	50%	0	None
22 to **26**	Ramping to 75%	75%	Start and ramping	Assume none
26 to 30	Ramping to 100%	100%	75	252
30	100%	100%	100	336

Table 9. CCGT steam extraction rates following cold starts, based on 336MW.th normal steam duty in the reboiler

Time (post-NTS), mins	GT load, %	Heat to CCS, %	MW.th to reboiler
0	Start and ramping	0	None
60	50	Start and ramping	Assume none
61	50	50	168
180	100	100	336

For a cold start, Table 8 shows an extended period of running the GT at 50% until 180 minutes. This 50% load is a typical characteristic of power island operation for cold starts, with the GT held at part-load to warm the steam system at a controlled rate. The heat soak has been estimated as approximately 1400GJ to heat the steam cycle from ambient in a cold start. In comparison, as noted in Section 9.2.4, hot starts require minimal heat soak as the equipment is already warm. The extended part-load hold is not carried out in a hot start, as the steam system is already warm. Start-up calculations for the cold start have been performed assuming the maximum rate of heat extraction available in a cold start is 50% of the extraction that would take place with the plant at steady state with 100% GT load. 50% extraction of heat (168MW.th) continues until the GT ramps to 100% at approximately 180 mins.

9.2.6 Steam reboiler start-up time calculation

Given the reboiler start-up energy requirements for the standard case (1,100GJ, Section 9.2.4) and heat supply rate from the steam cycle (described in Table 8), the start-up time was calculated to achieve normal operation in the reboiler according to:

$$\begin{aligned}&Startup\ energy\ consumed\\ &\qquad = (time\ at\ partial\ extraction \times partial\ extraction\ rate)\\ &\qquad + (time\ at\ full\ extraction \times full\ extraction\ rate)\end{aligned}$$

For 1,100GJ (1,100,000MJ) at hot start, the formula becomes:

$$1{,}100{,}000MJ = (5\ mins \times 252MW.th) + (x\ mins \times 336MW.th),$$

$$x = \frac{1{,}100{,}000MJ - 75{,}600MJ}{336MW.th} = 3048s = 51mins$$

$$Total\ start\ time = 25mins\ lag\ prior\ to\ extraction + \ 5mins\ at\ 75\% + 51mins\ at\ 100\% = \ 81mins$$

Therefore, the hot start-up time (including the 25-minute initial delay) after Notice to Synchronise (NTS) for the standard configuration was calculated as 81 mins.

For cold start, the GT will be held at part-load for an extended time as part of the ST start-up heat-soak procedure and therefore heat is soaked into the HRSG at a lower rate than during a hot start (where the steam turbine is already hot). During the cold start, only 168MW.th of heat extraction (equivalent to PCC plant heat demand at 50% plant load) is taken to be available for the PCC plant as described in Table 9. The start-up time for the power + PCC plant from a cold power plant is calculated as:

$$1{,}100{,}000MJ = (x\ mins \times 168MW.th),$$

$$x = \frac{1{,}100{,}000MJ}{168MW.th} = 6547s = 109mins$$

$$Total\ start\ time = 60mins\ lag\ prior\ to\ extraction + 109mins\ at\ 50\% = \ 169mins$$

The results of the start-up time calculation for both starts are presented in Table 10 below.

Table 10. Stripper start-up time calculation for standard configuration

Start type	Lag time post-NTS, mins	Part-load extraction duration, mins	Part-load rate, MW.th	Full-load extraction duration, mins	Full load extraction rate, MW.th	Total start-up time post-NTS, mins
Hot start	25	5	252	51	336	81
Cold start	60	109	168	N/A – start-up completed at part-load	N/A – start-up complete at part-load	169

9.2.6.1.1 Uncertainty

The stripper start-up time calculations given in Table 10 are calculated assuming instantaneous increments in steam rate, with fixed rate during each interval. It is noted that some steam extraction in the real plant would be available at some point before the 25 minute mark for hot starts and increase to the design extraction rate. The exact ramp rate and extraction start time are unknown and depend on equipment selection, instrumentation, piping and process dynamics. However, 25 minutes represent a reasonable conservative estimate by which point modern plant will be expected to support at least a part-load extraction (from the IP/LP cross-over) for hot starts. For cold starts, the corresponding figure would be approximately 60 minutes. Individual real plant would be expected to improve somewhat on the generic extraction benchmark steam extraction times used in this study.

A high-level sensitivity analysis was carried out to test the start-up time for a hot start based on:

- 0 to 25 mins: lag, any steam availability ignored including the ramping up of extraction
- 25 mins onwards: full steam extraction of 336MW.th (no discounting of extraction due to part-load GT i.e. without 5 mins at 252MW.th extraction per Table 8)

The calculated start time during a hot start was 80 mins (saving 1 minute of total pre-heating time) and represents a reduction of up to 2% on the overall plant start time.

During a cold start, the GT loading is held static at 50% until approximately 180 minutes. However, the stripper start-up time calculation shows only 136 minutes required as a maximum for starting the stripper and regenerating amine, significantly before the GT is ramped to 100%. Therefore, no significant reductions in start-up time would be expected during a cold start from considering a smaller time increment.

Note that real plant will have other options such as drawing from the HP bypass which would likely be available sooner than the IP/LP interface used in the process that is considered the standard configuration in this study. The standard configuration effectively requires much of the ST start-up and ramp to generation to be complete before extraction. HP bypass is considered as part of the improvement options in Section 9.3.5.

9.2.7 Standard configuration start-up emissions

Hot start performance for the standard configuration PCC power plant (un-improved process) is shown in Table 11 and Figure 4 below. Cold start performance and emissions are shown in Table 12 and Figure 5, respectively.

Note the decline in capture rate through both hot and cold starts as the solvent inventory is saturated, indicating that the standard configuration has a total CO_2 buffering capacity of approximately 140t CO_2. Once this quantity has been absorbed (approximately Snapshot 7 and 6 for hot and cold starts respectively), the solvent loading approaches 0.46mol/mol and further flue gas is effectively unabated until the stripper pre-heat is complete.

Once the stripper pre-heat is complete, the standard configuration has assumed that a bypass of the amine tank is used to send regenerated lean amine directly into the absorber feed line, rather than waiting for mixing the solvent into the tank. Figure 3 shows an indicative flow diagram showing the function of this bypass, which is only used as part of the PCC start-up sequence. Without this bypass, the recovery of the capture rate to 95% shown in the results would be significantly slower. The use of plant bypasses for optimising start-up is considered in detail in Section 9.3.2.

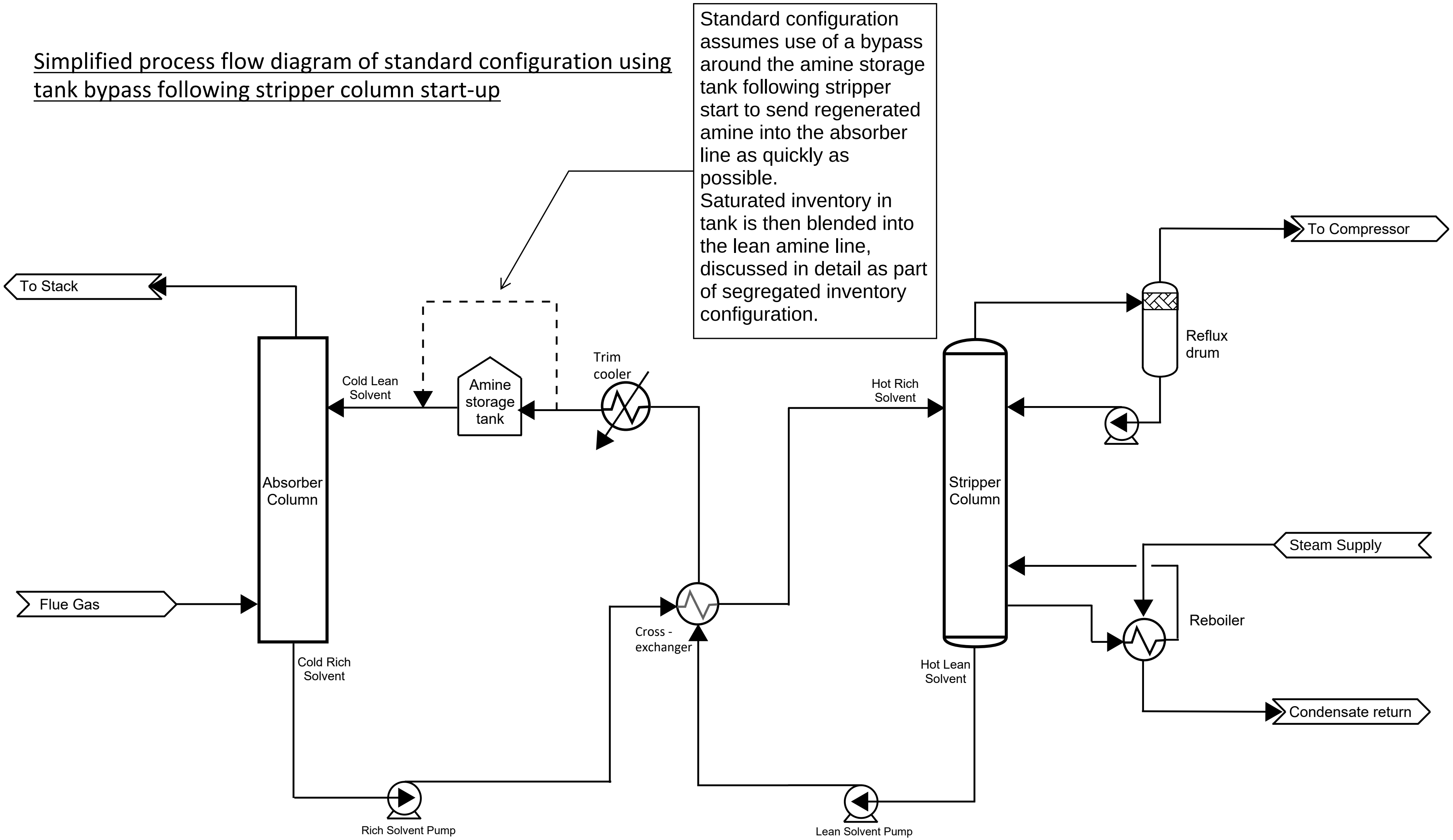

Figure 3. Standard configuration followed by tank bypass when stripper column start-up is complete

Table 11. Hot start performance for standard CCGT + 95% PCC (un-improved process)

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	Snap 6	Snap 7	End	Totals
Time after start, mins	15	22	25	30	37	48	81	82	
Duration, mins	15	7	3	5	7	11	33	1	
Regenerator status	No steam	No steam	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Complete	
GT load	25%	50%	75%	100%	100%	100%	100%	100%	
CO_2 rate from GT (inc. PCC design margin), kg/s	31.6	50	80	85	85	85	85	85	
CO_2 quantity from GT during interval, t	28.4	21.0	14.4	25.5	35.7	56.1	173.4	5.1	
CO_2 emissions rate after PCC, kg/s	0.192	0.42	0.93	3.93	35	44.5	85	4.1	
Residual CO_2 emitted after PCC, t	0.17	0.18	0.17	1.18	14.7	29.37	173.4	0.25	**219**
CO2 absorbed, t	28.27	20.82	14.23	24.32	21.00	26.73	0.00	4.85	**140**
Amine loading in amine feed to absorber	0.25	0.25	0.25	0.25	0.38	0.41	0.45	0.25	
Fuel burned, t	10.0	7.1	4.0	8.3	11.7	18.4	56.7	1.7	**118**
Fuel burned, GJ	501	355	198	417	584	918	2838	83	**5894**
Net generation rate, MW.e	217	387	549	723	723	723	723	723	
Electricity exported, MWh	54.3	45.2	27.5	60.2	84.3	132.5	409.6	12.0	**826**
Capture fraction	99%	99%	99%	95%	59%	48%	0%	95%	**39%**

The key characteristics of Table 11 are presented in Figure 4, showing the capture fraction, fuel burn and residual CO_2 emissions during the start-up scenario.

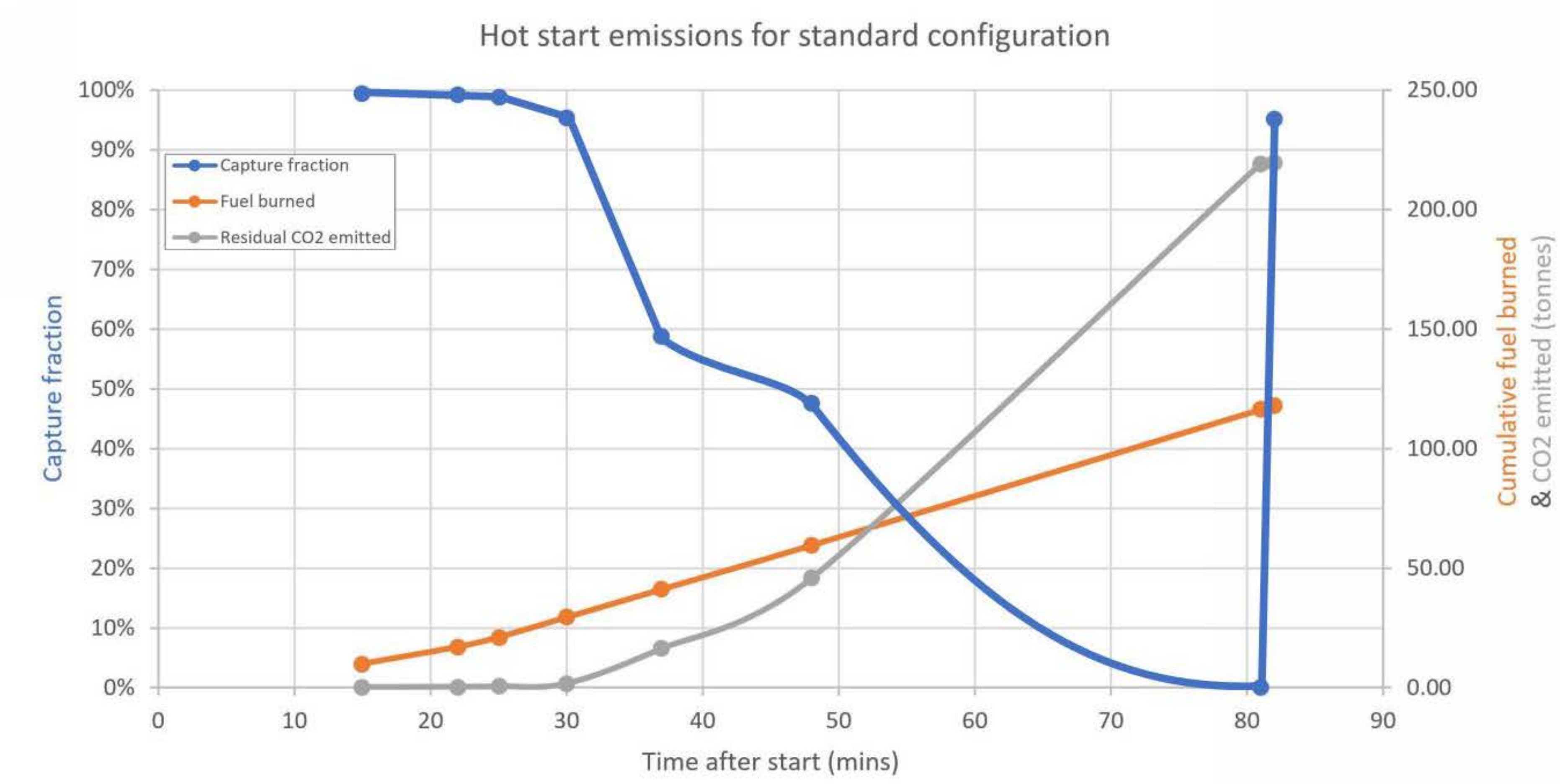

Figure 4. Hot start performance for standard CCGT + 95% PCC (un-improved process)

Table 12. Cold start emissions performance for standard CCGT + 95% PCC (un-improved process)

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	Snap 6	Snap 7	End	Totals
Time after start, mins	15	22	25	30	55	60	169	170	
Duration, mins	15	7	3	5	25	5	109	1	
Regenerator status	No steam	No steam	No steam	No steam	No steam	Pre-heating	Pre-heating	Complete	
GT load	25%	50%	50%	50%	50%	50%	50%	50%	
CO_2 rate from GT (inc. PCC design margin), kg/s	31.6	50	50	50	50	50	50	50	
CO_2 quantity from GT during interval, t	28	21	9	15	75	15	327	3	
CO_2 emissions rate after PCC, kg/s	0.192	0.42	0.42	0.42	6.31	39.44	49.5	0.42	
Residual CO_2 emitted after PCC, t	0.17	0.18	0.08	0.13	9.5	11.8	323.7	0.0	346
CO2 absorbed, t	28.3	20.8	8.9	14.9	65.5	3.2	3.3	3.0	148
Amine loading in amine feed to absorber	0.25	0.25	0.25	0.25	0.36	0.45	0.46	0.25	
Fuel burned, t	10.0	7.1	3.0	5.1	25.4	5.1	110.7	1.0	167
Fuel burned, GJ	501	355	152	254	1270	254	5536	51	8373
Net generation rate, MW.e	217	387	387	387	387	387	387	387	
Electricity exported, MWh	54.3	45.2	19.4	32.3	161.4	32.3	703.9	6.5	1055
Capture fraction	99%	99%	99%	99%	87%	21%	1%	99%	30%

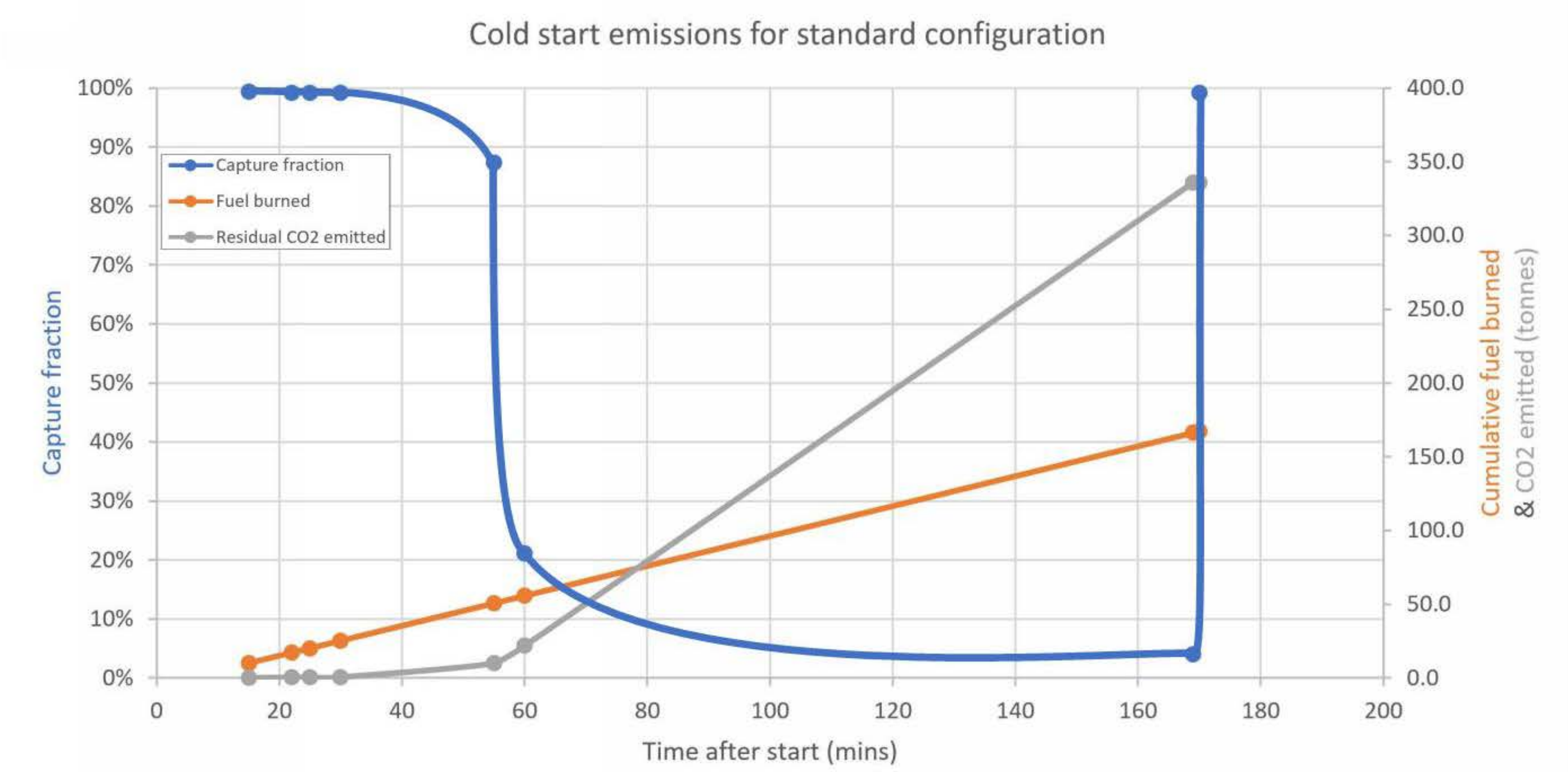

Figure 5. Cold start performance for standard CCGT + 95% PCC (un-improved process)

For both hot and cold starts, note that the initial snapshot periods with the gas turbine operating at part load (25% to 50% or 75%) show over-capture of CO_2 from the flue gas approaching 99%. Over-capture is seen at part-load due to lower gas flow than the column design basis, leading to absorption up to the equilibrium concentration of flue gas exiting the top of the packed bed and the lean amine entering the packed bed. The key results of the hot and cold start for the standard PCC plant are summarised in Table 13 below.

Table 13. Summarised outputs of the hot and cold starts for the standard configuration, for single train.

Parameter	Hot start	Cold start
Net fuel burned, t	118	167
Net fuel burned, GJ	5894	8373
Net electricity export, MWh	826	1055
CO_2 emissions to atmosphere, t	219	336
Overall capture rate, %	39	32
Specific CO_2 emissions, $kgCO_2e/MWh$	265	318

For two trains of abated CCGT, Table 13 has been recalculated with results shown in Table 14 below.

Table 14. Summarised outputs of the hot and cold starts for the standard configuration, recalculated for two trains of abated CCGT in standard configuration

Parameter	Hot start	Cold start
Net fuel burned, t	236	334
Net fuel burned, GJ	11,788	16,746
Net electricity export, MWh	1,652	2,110
CO_2 emissions to atmosphere, t	438	522
Overall capture rate, %	39	32
Specific CO_2 emissions, $kgCO_2e/MWh$	265	318

9.2.8 Standard configuration shut-down emissions

The standard configuration CCGT with PCC would be expected to shut down within 45 minutes as described in Table 4. Emissions expected during the shut-down process are shown in Table 15 below. Note that although 47.4t total carbon dioxide is captured during the shut-down period in total, Snapshots 1 and 2 happen while some steam is likely to still be available for extraction. Therefore, credit has been taken during shut-down for the first 10t (sum of Snapshot 1) of captured CO_2 to not contribute to accumulation in the amine during shut-down.

Snapshot 3 is therefore the only period of expected CO_2 accumulation in the solvent inventory, a total of 27.9t which corresponds to 635kmol of CO_2 or an increment of 0.04mol/mol to loading. Preliminary analysis of the stripper performance at part-load has found that operating with an increased stripper back-pressure of approximately 3.1bar allowed for a reboiler temperature of 137°C. Operating with elevated stripper pressure prior to shutdown would allow the stripper column inventory to store some heat and continue stripping for some time once the steam extraction is shut-down. It was also found that a lean amine production at 0.20 mol/mol during the 30 minutes preceding a shut-down was able to build up sufficient over-stripped amine and by the end of the shut-down process (45 mins), the amine will have a loading of 0.25 mol/mol ready for the next start-up process. The same calculation methodology was used to derive the required loading prior to shut-down as was used to derive start-up loadings (Section 9.2.3). It is noted that operating the real plant at 137°C reboiler temperature would accelerate the degradation of the solvent and alternative means of balancing column pressure and reboiler temperature should be explored for individual projects considering shut-down optimisation to avoid excessive periods running the reboiler at elevated temperature.

Table 15. Shut-down emissions calculation

Parameter	Snap 1	Snap 2	Snap 3	End	Totals
Time after initiation, mins	5	15	30	45	
Duration, mins	5	10	15	15	
GT load	30%	30%	5%	0%	
CO2 rate from HRSG, kg/s	35	35	4.25	0	
CO2 quantity from HRSG during interval, t	11	31.5	7.65	0	**50**
CO2 rate from stack, kg/s	1.58	1.58	0.2	0	
Treated CO2 emitted during interval, t	0.47	1.42	0.36	0.00	**2**
CO2 absorbed, t	10.0	30.1	7.3	0.0	**47.4**
Amine loading in amine feed to absorber	0.20	0.24	0.25	0.25	
Fuel burned, t	3.7	11.1	3.6	5.4	**24**
Fuel burned, GJ	185	555	180	270	**1190**
Net generation rate, MW.e	252	252	25	0	
Electricity exported, MWh	21.0	63.0	12.5	0.0	**96**
Capture fraction	95%	95%	95%	N/A	**95%**

9.2.9 Standard configuration conclusions

The standard configuration provides high-level indicative performance data for an un-improved PCC power plant during start-up and shut-down. The overall start-up capture rate was calculated to be approximately 39% and 32% in hot and cold starts, respectively (219tCO_2 and 336tCO_2 per hot and cold start, respectively). The un-improved configuration, having been developed on the assumption of base-load operation, cannot maintain 95% (or 90%) capture rates throughout the start-up process for either hot or cold start. The modelling results summarised above are presented as a reference case against which to assess the effectiveness of the various configuration improvement options outlined below.

Section 9.3 outlines general design options that would allow the plant to start and stop while still meeting 95% capture throughout.

9.3 Start-up improvement options

9.3.1 Introduction

Before considering the potential configuration improvement options of the capture plant, a number of main constraints were initially identified which limit the flexibility of the CCUS plant's operation. These include:

1. Lack of heat (normally supplied as extracted steam) availability to the rich amine reboiler for a period after the combustion cycle is started
2. Once heat can be supplied to the reboiler, significant sensible heat is required to heat the metal and liquid inventory from ambient before reboiling and amine stripping can begin.
3. A limited inventory of lean amine is available to operate the absorber while the regenerator is still warming up, leading to rapid increase in amine loading and an increase in emissions to atmosphere.
4. Lack of heat availability to the reboiler to maintain capture from residual flue gas flow once the power cycle is shut down, leading to emissions as the gas path is swept for shut-down as well as incomplete amine regeneration and elevated lean loading for next start-up

Based on these identified constraints in current CCUS processes, different options for the configuration of the carbon capture plant were discussed and reviewed within the Literature Review (Ref. 1) based on existing research conducted in the area of improving amine-based CCUS start-up and shut-down performance. Each of the options discussed aim to address at least one of the main constraints to improve the plant's flexibility.

The following subsections detail the chosen three configurations for simulation modelling detailed in the Basis of Design (Ref. 2), with an additional configuration option included ahead of the original options. Hence the option numbers between the two documents do not comply and have been re-ordered according to an initial order of preference. The number of configuration options and their order within the Basis of Design has been preserved for historical reference and is in accordance with the ITT.

9.3.2 Improvement configuration 1 – segregated amine inventory

9.3.2.1 Introduction

The first configuration option segregates amine inventory between the absorber and stripper loop during start-up, without circulation between the two columns. This configuration option has been identified as a formal configuration since the original Design Basis and Literature Review works were carried out and is therefore not reflected in those reference documents. This scenario takes an initial distribution of solvent inventory identical to the un-improved process i.e.:

- Nominal hold-up in the absorber column and piping (approximately 5 mins for process safety surge time)
- Nominal hold-up in the stripper column and piping (approximately 5 mins for process safety surge time)
- Majority of inventory (30 mins) in lean amine storage tank

During the start-up process, the heating up of the stripper and use of amine in the absorber are carried out per the un-improved process, but in this case the solvent is recirculated in two shorter loops as shown in Figure 6 below. Note the use of bypasses around the cross-exchanger during the start-up, which are instead succeeded by the bypass around the storage tank once the stripper start-up is complete. This approach allows the stripper to heat up to its normal operating temperature more quickly, and hence reduce the time until regenerated amine is available to the absorber. Once amine regeneration is established, circulation is started by transitioning from segregated inventory per Figure 6 to circulating inventory as described in Figure 7.

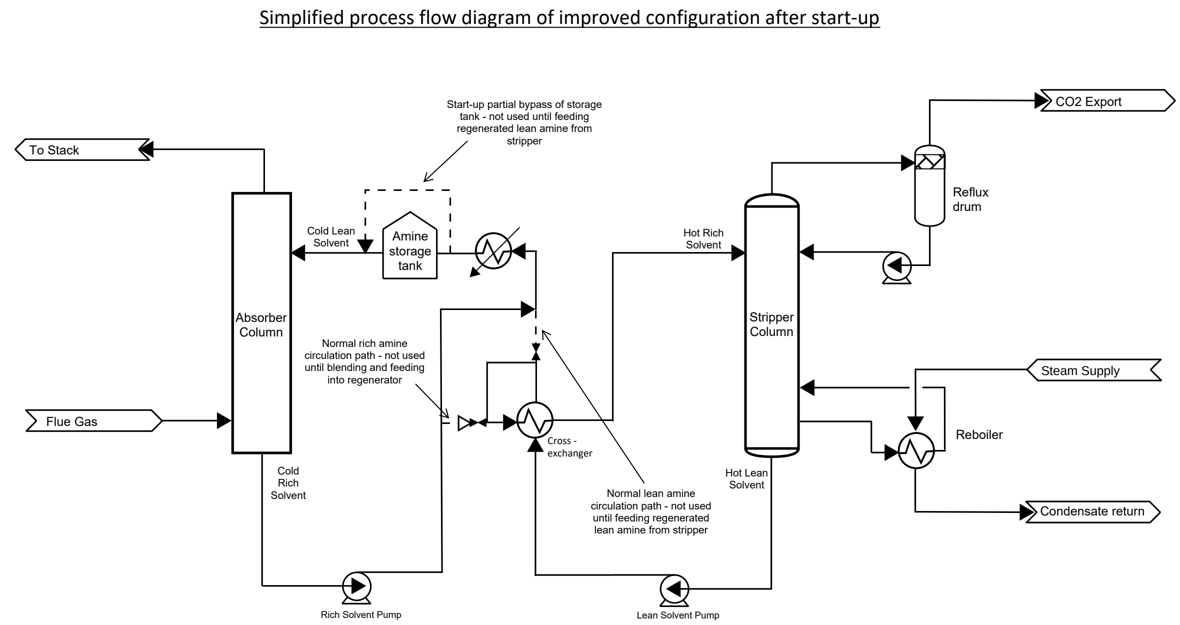

Figure 6. Flowsheet at start-up for segregated amine inventory scenario

The benefit of this option is that no new equipment is required, the improvements are instead given by modifications to the process control system and provision of start-up bypass lines (as well as associated instrumentation and controls) for use during start-up. This option can also be combined with other improvement configurations such as dedicated amine storage and combinations are discussed in each configuration option section below.

9.3.2.2 Description

This optimised configuration reduces the amount of amine inventory that must be heated at start-up. The minimum figure taken in this study is 5 minutes present in the stripper sump (450,000kg inventory) to allow surge process response time for pump safeguarding as discussed in the Basis of Design (Ref. 2) Section 5.8.1.

9.3.2.3 Start-up procedure

The initial steps (and therefore Snapshots) of the start-up procedure for Configuration 1 are similar to the un-improved process (see Section 8.4.1). During these Snapshots, the limited inventory in the absorber is used to treat the ramping flue gas. Rich amine is returned to the storage tank where it is assumed to immediately blend into the rest of the amine inventory, then the mixed stream is used to treat flue gas while the stripper inventory is heated with steam (once available). Once the stripper preheating is complete and reboiler boil-up is achieved, control valves on both the bypass streams act to gradually send amine into the normal circulation lines and bypass the storage tank. Once the stripper reboiler preheating is complete, the amine bottom product flows will be switched from the bypass to the main lines, as shown in the sequence in Figure 7 below.

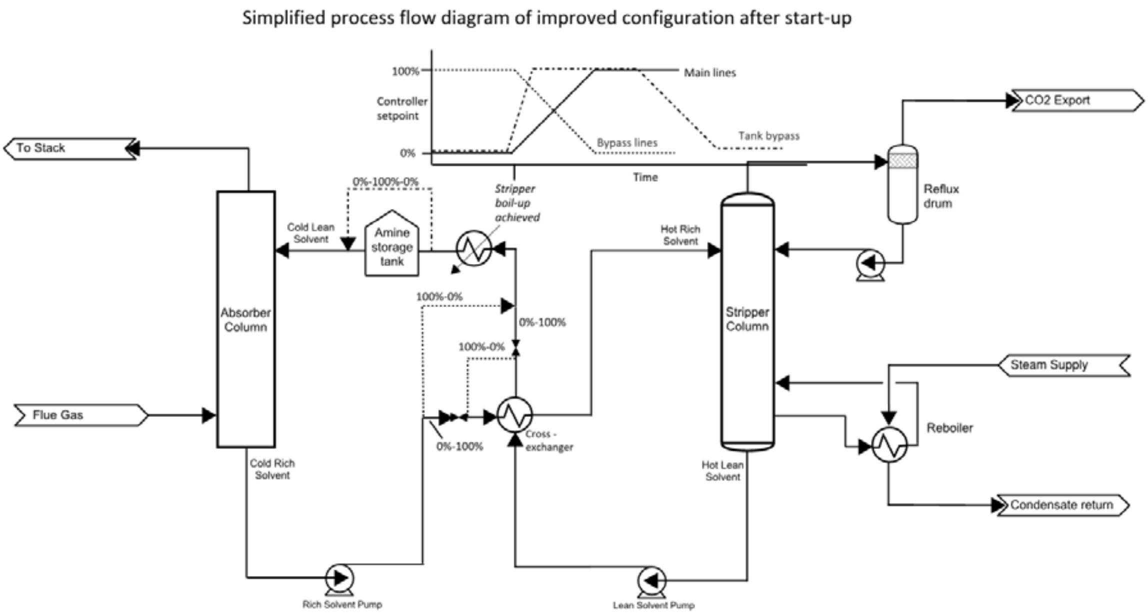

Figure 7. Segregated amine inventory configuration: transitioning from bypass flows to circulating flow once stripper boil-up is achieved

The switch-over process must balance disturbances in three main variables during the switch:

- Rich solvent temperature: introduction of colder-than-expected rich solvent to the top of the stripper caused by inadequate heat transfer into the rich amine through the cross-exchanger. This could lead to all the steam traffic in the column to condense, losing pressure in the column (activating the anti-surge controls on the compressor or potentially tripping the compressor). Solvent stripping would also be lost until vapour traffic could be re-established. Care must be taken to introduce new rich solvent to the column below the rate at which too much heat would be lost in the top stages of the column. The cross-exchanger will help to stabilise stream temperatures as flows increase.
    - An additional sub-category is introduction of richer-than-expected solvent into the top of the stripper causing an excess of vapour in the top section of the column. Noting that the increment in solvent loading is from a start-up scenario at leaner loading than the design case up to the design case, this slug of vapour would be expected to be dealt with by normal modulation of the column pressure controller and reflux controller to return condensed liquid back to the column.
- Stripper column level: loss of inventory in the stripper column caused by more flow of hot lean solvent out of the column than hot rich solvent entering the column. This could lead to loss of level in the stripper column and trip the lean solvent pump to prevent damage. Conversely, diverting more lean solvent to the main line through the cross-exchanger than the rich solvent entering the column would overfill the sump and trip the rich solvent pump to prevent damage to column internals. The rate at which solvent is diverted into the main line through the cross-exchanger must be kept controlled to maintain a relatively steady level in the stripper column
- Absorber column level: as with the stripper column, imbalances in the flows entering and leaving the absorber column can trip process pumps and must be balanced, taking advantage of the additional hold-up available in the lean amine storage tank.

For all three variables, a slow switch-over is the safest solution and can be carried out manually by an operator if carried out with appropriate time delays. However, a feed-forward controller informed with an appropriate model of the process would be able to optimise the switching procedure and directly instruct the various feedback controllers to achieve a significantly faster switch.

A feed-forward controller would still be limited by the three process variables described above (loss of boil-up, levels in absorber and stripper). However, a model of the process would allow simultaneous drawing back of the reflux flow and therefore condenser duty to compensate for the introduction of cold rich amine feed. While the stripper column is recycling with no new rich amine being added to the column (and therefore no new CO_2 to strip), the temperature of the liquid entering the top of the stripper rises and is balanced by an increase in condenser cooling duty i.e. with a fixed inventory under recirculation, the reboiler begins to evaporate more water which must be condensed rather than freeing CO_2 from the solvent, see Figure 8 below.

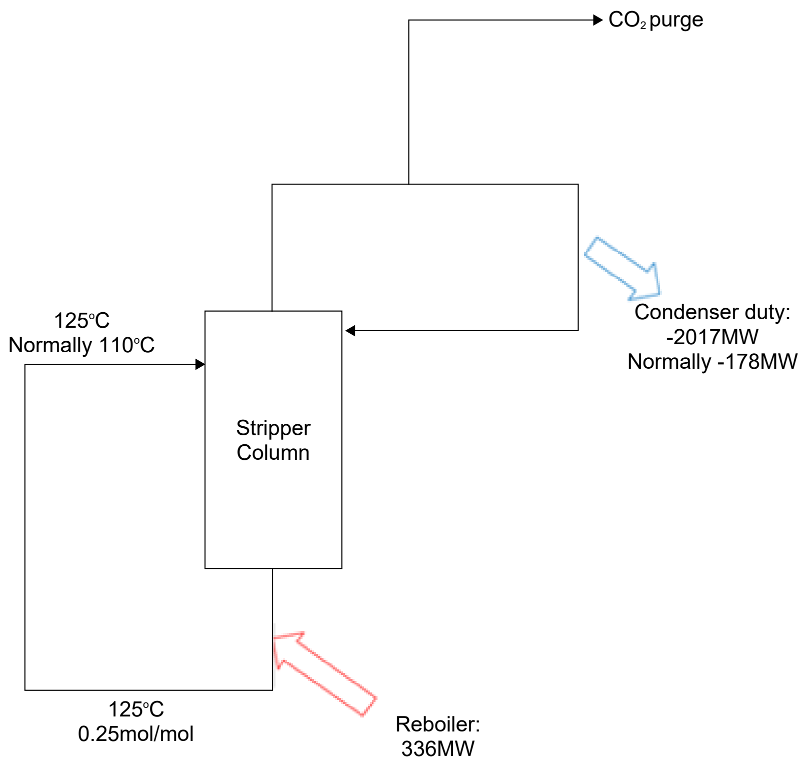

Figure 8. Recycling of stripper inventory leading to rising condenser duty

Indeed, stripping the same volume of amine continually increases the heat that must be removed by the condenser as successively less CO_2 remains in the inventory of lean amine being recycled into the rich amine feed to the column. Figure 9 describes the increase in condenser duty for a rich amine feed being recycled at the reboiler operating temperature of 125°C in orange below. Figure 9 also shows the trend in condenser duty for a rich amine feed at 110°C as during normal operation with circulation through the cross-exchanger. The condenser duty is lower by 50-80MW.th for all cases with a 110°C entry than at 125°C entry. For information, the increase in amine stream enthalpy from 110°C to 125°C is equivalent to approximately 80MW.th and explains much of the rise in overall condenser duty with excessive flashing of the amine feed entering the column, that then requires excessive cooling.

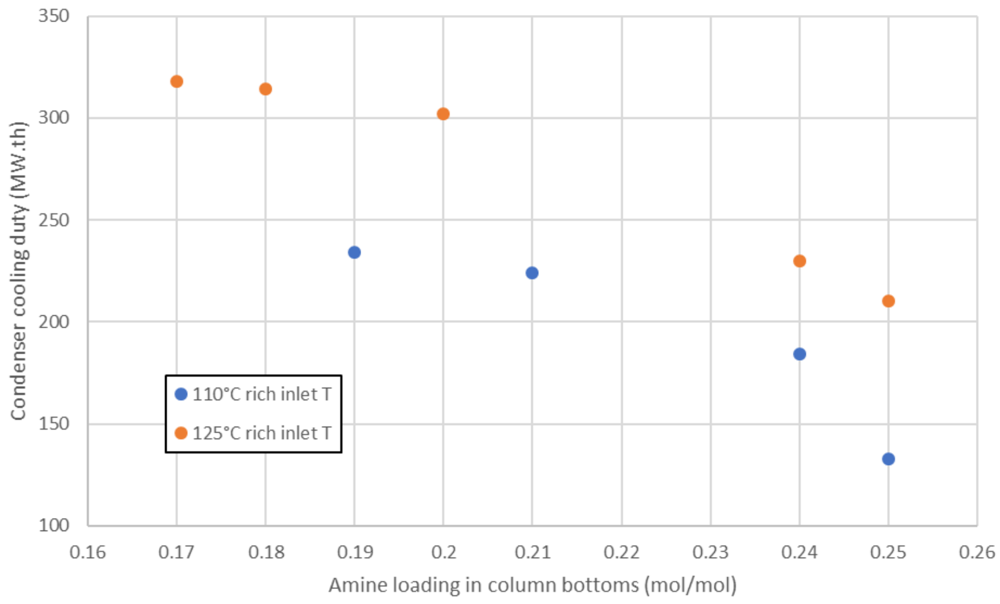

Figure 9. Increasing condenser duty as stripper amine loading drops from initial 0.25 mol/mol

As the simplified column diagram in Figure 8 shows, during the recycling period, the stripper column is not entirely in mass balance: a small flow of evaporated vapour leaves in the CO_2 purge at the top once boil-up is achieved. Introduction of new rich amine into the stripper feed at this time would help reduce condenser duty.

The issue with bringing new rich amine from the cross-exchanger into the stripper is an initial lack of pre-heating in the cross-exchanger and drop in amine feed temperature, see Figure 10 below. The rich amine from the absorber is fed at approximately 40°C but heat exchange in the cross-exchanger is initially limited as:

- The exchanger initially consumes some heat from both streams in heating the metal to operating temperature
- Initial heat transfer coefficients with low flows are potentially sub-optimal

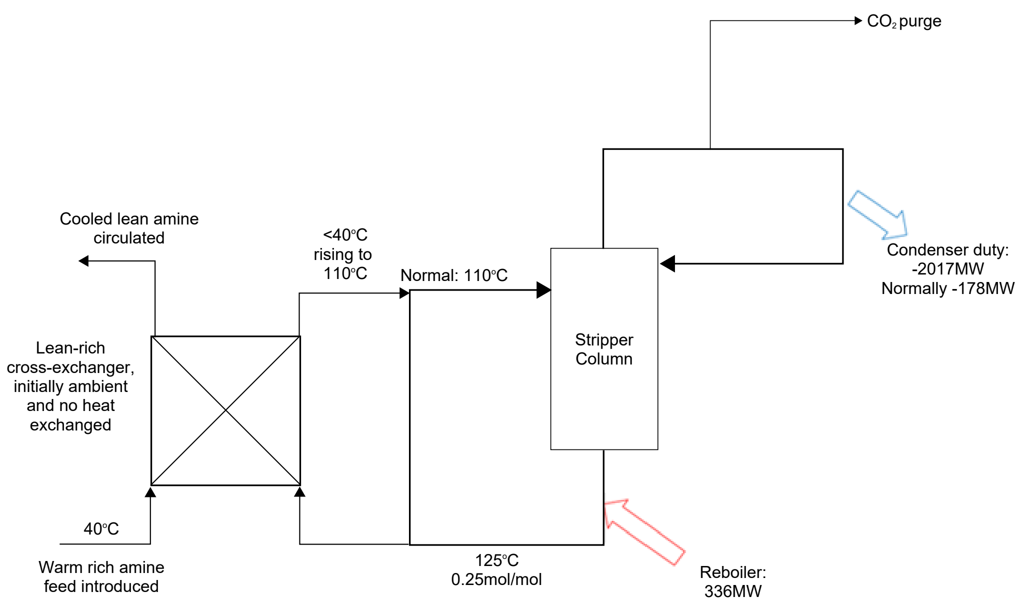

Figure 10. Introducing feed of new rich amine to cross-exchanger and extracting hot lean amine

The solution to achieve switch-over in less time would be to include the cross-exchanger within the recirculation loop by running the warming lean amine through both sides of the cross-exchanger, as shown in Figure 11.

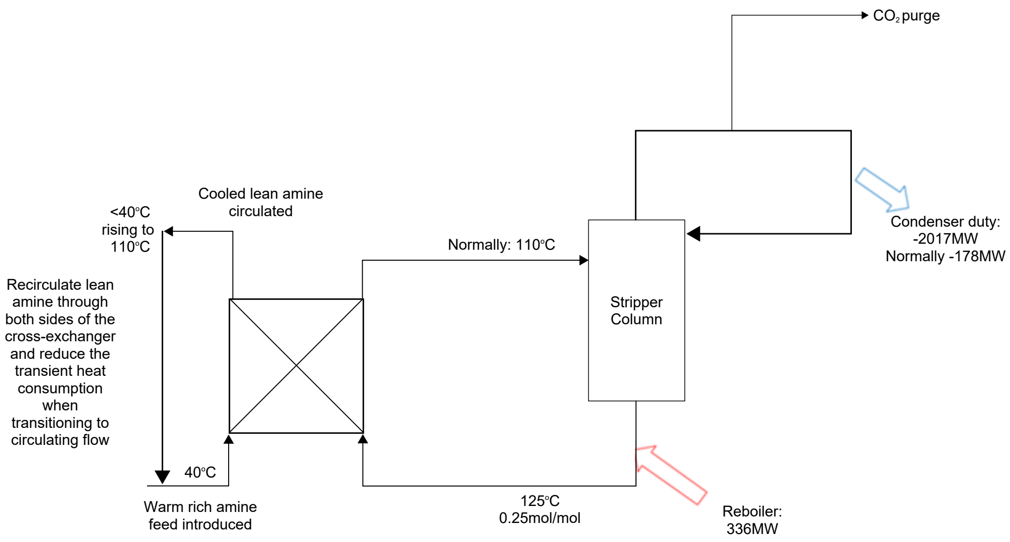

Figure 11. Introducing feed of new rich amine to cross-exchanger and extracting hot lean amine

Further investigation of the stripper column performance shows the column would accept a reduction in overall feed temperature without losing the column vapour profile down to approximately 100°C for the combined feed stream (at approximately 35% new rich amine if supplied at 40°C), see Figure 12. Below an inlet temperature of 100°C, an inflection point is seen in the condenser duty and, although the overall trend is a reduction in condenser duty other indicators of poor stripping performance are present.

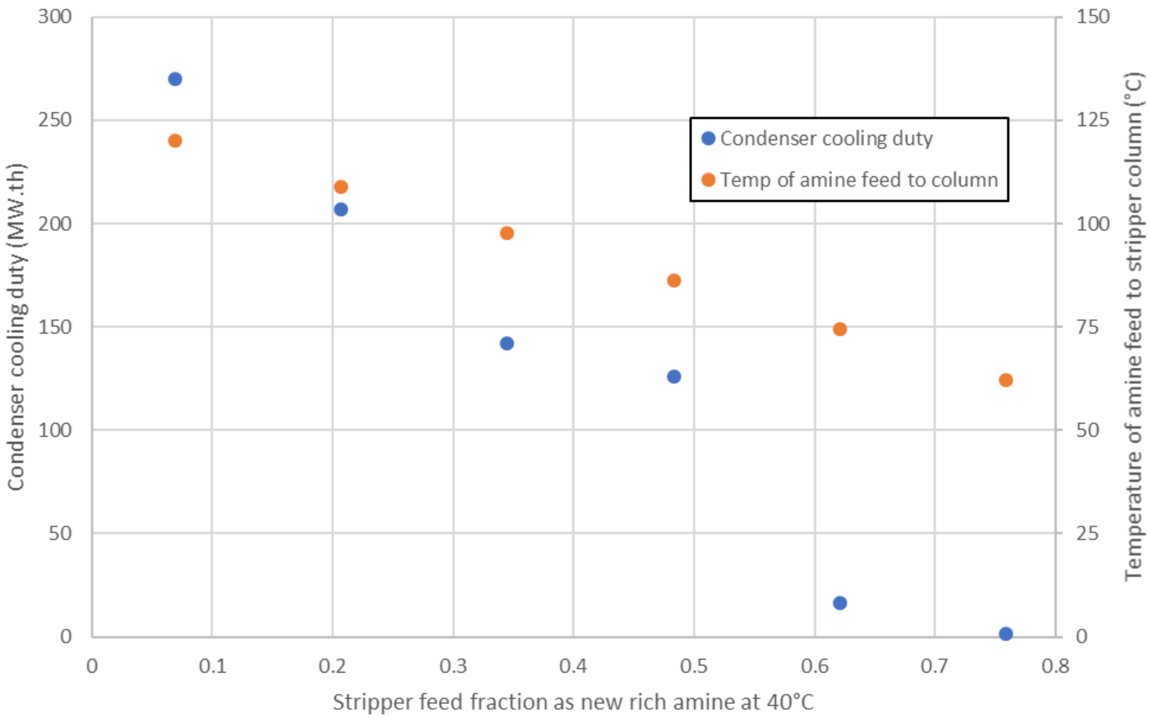

Figure 12. Effect on feed temperature and condenser duty by blending various fractions of rich amine at 40°C into stripper feed

Note that the rich amine feed temperature is itself not static at 40°C. The temperature of the rich amine leaving the cross-exchanger will rise to 110°C as more heat is exchanged with the hot lean amine. The increase in vapour generation as recirculated lean amine is gradually replaced by new rich amine, is expected to be managed by normal operation of the column reflux controls. No boundaries are expected implementing the switch from segregated recycling stripper flow to normal circulation as part of the overall column start-up procedure, pending a detailed dynamic process study on a defined configuration. This study would:

- Include selection of control valves and appropriate tuning of feedback controllers to work within the requirements of the feed-forward model
- Include estimates for dynamics such as heat consumption by warming up equipment
- Include estimates of sump and column hold-up volumes to ensure suitable suction head is available for pumps
- Identify overhead equipment and piping volumes to accurately predict and control the transient vapour flow

The findings of this dynamic study may recommend some changes to the process design (e.g. providing smaller parallel control valves for fine-tuning pump flowrates) and should be scheduled in time to feed findings back into the project development. The model could then be used to form the basis of the predictive process model informing the feed-forward start-up controller, with refinement during the testing phase targeted at equipment heat-up times and control response rates.

9.3.2.4 Stripper pre-heat energy requirement

Given a heat capacity from the material balance for lean amine at start-up, the heat requirement, Q, for this configuration was calculated using the method defined in Section 9.2.4:

$$Q = 450{,}000\,kg \times 3.34\frac{kJ}{kg.K} \times (125℃ - 9℃) = 174{,}348{,}000\,kJ, or\ 174\ GJ$$

Based on the earlier calculation of the thermal mass and start-up heat requirement for the metal stripper column of 44.4GJ in Section 9.2.4, the overall energy input for this configuration is shown below. The metal mass presents approximately 20% of the total heat requirement in this case (220GJ). Therefore, even an error of 50% in the metal mass would give approximately 10% difference in the heat requirement for this configuration.

$$44.4GJ + 174GJ \approx 220GJ$$

By comparing the stripper heat requirement of both the standard configuration against this configuration, the energy input for the optimised inventory configuration is approximately 20% of the value calculated for the un-improved configuration (1,100GJ).

9.3.2.5 Steam reboiler start-up time calculation

Using the calculation method described in Section 9.2.6, the start-up times for both hot and cold starts can be approximated using the required energy input value of 220GJ. Table 16 compares the results from the stripper start-up time calculations for the optimised inventory configuration with the standard case results for reference.

Table 16. Stripper start-up time calculation for both standard and optimised inventory configurations

Configuration	Start type	Lag time post-NTS, mins	Part-load extraction duration, mins	Part-load rate, MW.th	Full-load extraction duration, mins	Full load extraction rate, MW.th	Total start-up time post-NTS, mins
Standard	Hot start	25	5	252	51	336	81
Segregated	Hot start	25	5	252	7	336	37
Standard	Cold start	60	109	168	N/A	N/A	169
Segregated	Cold start	60	22	168	N/A	N/A	82

9.3.2.6 Start-up emissions

The performance of the configuration with segregated inventory during a hot start is captured in Table 17 and Figure 13 below.

Table 17. Hot start performance for CCGT+95% PCC with segregated amine inventory at start-up

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	End	Totals
Time after start, mins	15	22	25	30	37	38	
Duration, mins	15	7	3	5	7	1	
Regenerator status	No steam	No steam	Pre-heating	Pre-heating	Pre-heating	Complete	
GT load	25%	50%	75%	100%	100%	100%	
CO_2 rate from HRSG, kg/s	31.6	50	80	85	85	85	
CO_2 quantity from HRSG during interval, t	28.4	21.0	14.4	25.5	35.7	5.1	**130**
CO_2 rate from stack, kg/s	0.2	0.4	0.9	3.9	35.0	4.1	
Residual CO_2 emitted during snapshot, t	0.2	0.2	0.2	1.2	14.7	0.2	**17**
CO_2 absorbed from flue gas into solvent during snapshot, t	28.3	20.8	14.2	24.3	21.0	4.9	**113**
Amine loading in amine feed to absorber	0.25	0.25	0.25	0.25	0.38	0.25	
Fuel burned during snapshot, t	10.0	7.1	4.0	8.3	11.7	1.7	**43**
Fuel burned, GJ	501	355	198	417	584	83	**2140**
Net generation rate, MW.e	217	387	549	723	723	723	
Electricity exported, MWh	54.3	45.2	27.5	60.3	84.4	12.1	**284**
Capture fraction	99%	99%	99%	95%	59%	95%	**87%**

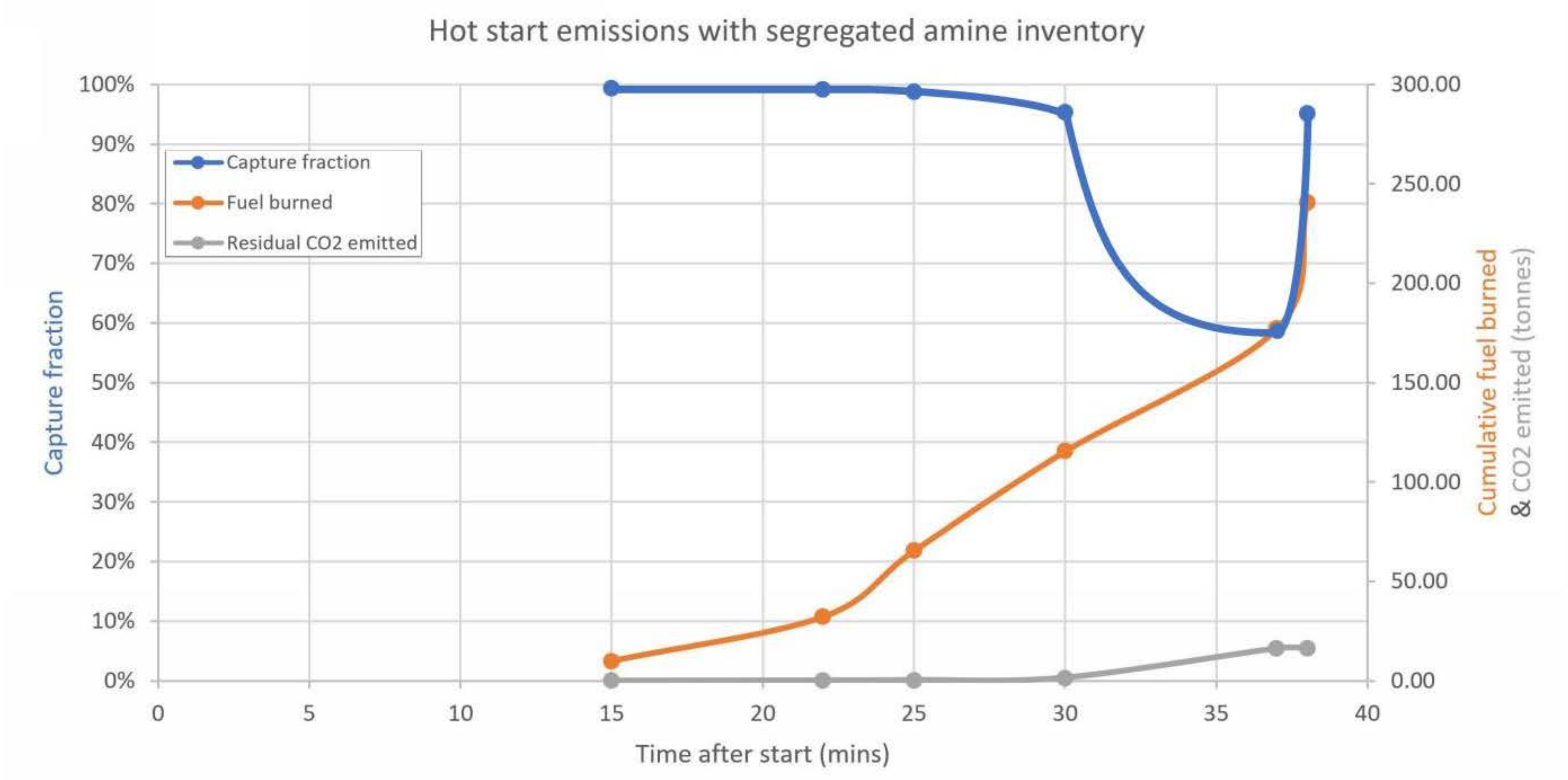

Figure 13. Hot start performance for CCGT + 95% PCC with dedicated rich amine storage and segregated amine inventory at start-up

Table 18. Cold start performance for CCGT+95% PCC with segregated amine inventory at start-up

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	Snap 6	Snap 7	End	Totals
Time after start, mins	15	22	25	30	55	60	82	83	
Duration, mins	15	7	3	5	25	5	22	1	
Regenerator status	No steam	No steam	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Complete	
GT load	25%	50%	50%	50%	50%	50%	50%	50%	
CO_2 rate from GT (inc. PCC design margin), kg/s	31.6	50	50	50	50	50	50	50	
CO_2 quantity from GT during interval, t	28	21	9	15	75	15	66	3	**232**
CO_2 emissions rate after PCC, kg/s	0.192	0.42	0.42	0.42	6.31	39.44	48	0.42	
Residual CO_2 emitted after PCC, t	0.17	0.18	0.08	0.13	9.5	11.8	63.36	0.00	**85**
CO2 absorbed, t	28.3	20.8	8.9	14.9	65.5	3.2	2.64	3.0	**147**
Amine loading in amine feed to absorber	0.25	0.25	0.25	0.25	0.36	0.45	0.46	0.25	
Fuel burned, t	10.0	7.1	3.0	5.1	25.4	5.1	22.34	1.00	**79**
Fuel burned, GJ	501	355	152	254	1270	254	1119	50	**3960**
Net generation rate, MW.e	217	387	387	387	387	387	387	387	
Electricity exported, MWh	54.3	45.2	19.4	32.3	161.4	32.3	141.9	6.5	**493**
Capture fraction	99%	99%	99%	99%	87%	21%	4%	99%	**64%**

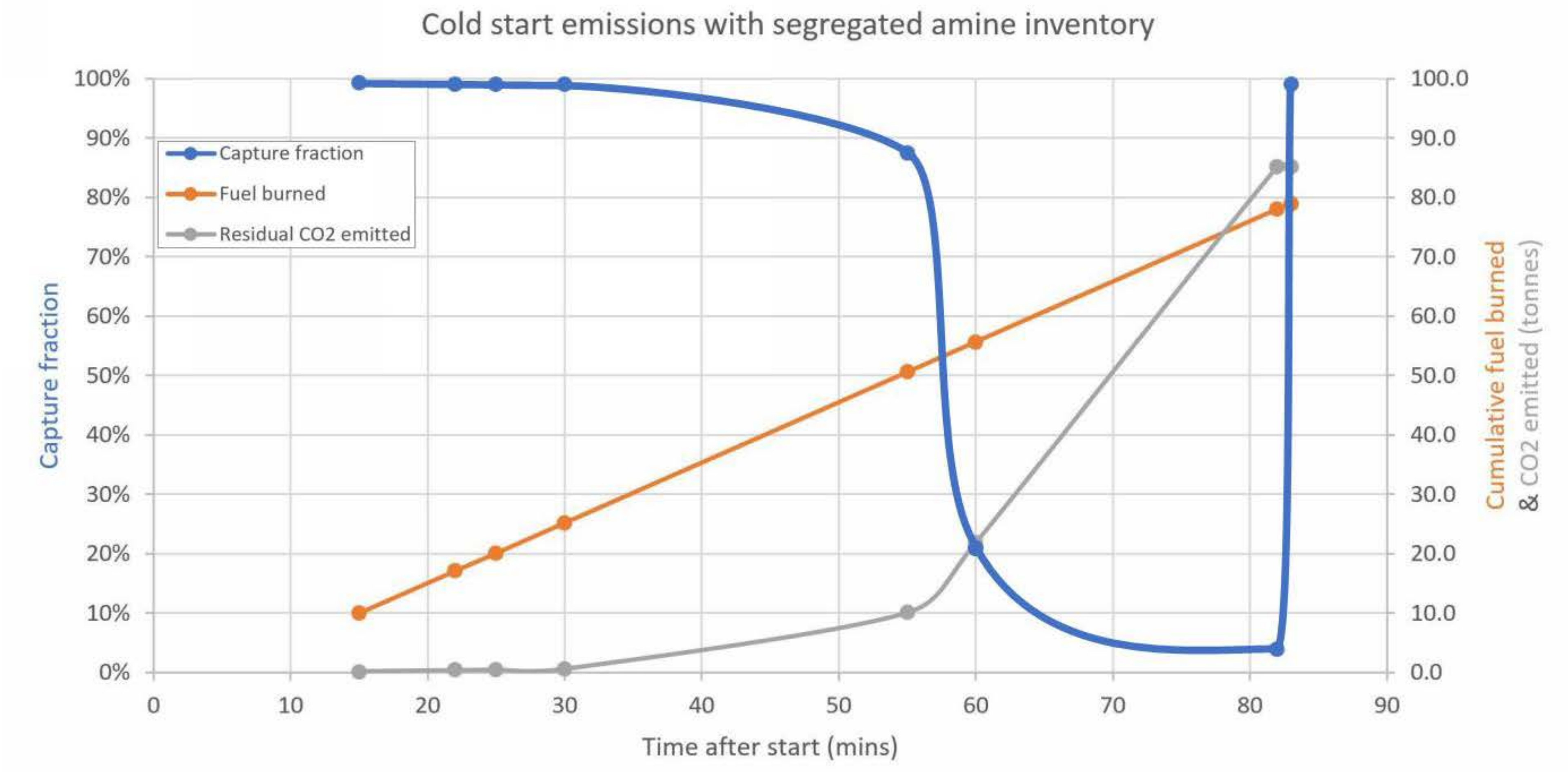

Figure 14. Hot start performance for CCGT + 95% PCC with dedicated rich amine storage and segregated amine inventory at start-up

The key results of the hot start for the PCC plant with the segregated inventory improvement option are summarised in Table 19. A total capture rate of approximately 87% was predicted for the hot start (Table 17) from the sum emissions to the PCC plant (219 t) and residual emissions (17 t). For the cold start with segregated inventory, calculated capture ratio was 64% (232t CO_2 total from the GT and 85t CO_2 residual emissions per Table 18).

Table 19. Summarised outputs of hot and cold starts with and without the segregated inventory improved configuration, for single train

Parameter	Hot start – standard	Hot start- segregated	Cold start – standard	Cold start - segregated
Time to complete PCC start, mins	81	37	170	83
Net fuel burned, t	118	43	167	79
Net fuel burned, GJ	5,894	2,140	8,373	3,960
Net electricity export, MWh	826	284A	1055	493
CO_2 emissions to atmosphere, t	219	17	336	85
Overall capture rate, %	39	87	32	64
Specific CO_2 emissions, $kgCO_2e/MWh$	265	59	318	172

For two trains of abated CCGT, the key results of the PCC power plant with the segregated inventory improvement option are summarised in Table 20.

Table 20. Summarised outputs of the hot and cold starts for the configuration with segregated inventory, recalculated for two trains

Parameter	Hot start	Cold start
Net fuel burned, t	37	83
Net fuel burned, GJ	4,280	7,920
Net electricity export, MWh	568	986
CO_2 emissions to atmosphere, t	34	170
Overall capture rate, %	87	64
Specific CO_2 emissions, $kgCO_2e/MWh$	59	172

By comparing these results to the standard PCC plant, there is a significant improvement in the start-up capture rate as well as a reduction in the specific CO_2 emissions. During hot start of the standard configuration, the PCC plant was only able to capture 40% of the emissions during start-up. Using a segregated amine inventory increases the overall capture rate to 87% during hot start, more than doubling the capture rate. As for the specific CO_2 emissions, this improvement option reduces the level of emissions over a hot start by 206kgCO$_2$e/MWh from the standard configuration (265 kgCO$_2$e/MWh down to 59 kgCO$_2$e/MWh). For cold starts, the emissions are reduced by 146 kgCO$_2$e/MWh (318 kgCO$_2$e/MWh down to 172 kgCO$_2$e/MWh).

9.3.3 Improvement configuration 2 – dedicated lean and rich amine storage

9.3.3.1 Introduction

The second configuration variant proposed incorporates an increment of storage in addition to the normal process time already provided by the standard configuration. The increment volume is calculated to provide the shortfall in lean solvent circulation time during start-up. This ensures that lean amine is readily available as soon as the amine circulation in the absorber is established to fully treat the flue gas and continue treating until the stripper pre-heat time is complete.

Once the stripper pre-heat is complete and regenerated lean amine is ready for flow back to the absorber, the storage tank is partially bypassed to supply amine direct to the absorber for flue gas treatment. Rich amine produced and stored during start-up is blended into the circulation at a controlled rate without upsetting either capture rate (if bled into the lean line) or stripper performance (if blended into the rich line).

9.3.3.2 Description

The optimum configuration for achieving robust start-up emissions performance would have a dedicated rich amine tank for storage of generated rich amine during start. The rich amine tank is presented off the main line, see Figure 15.

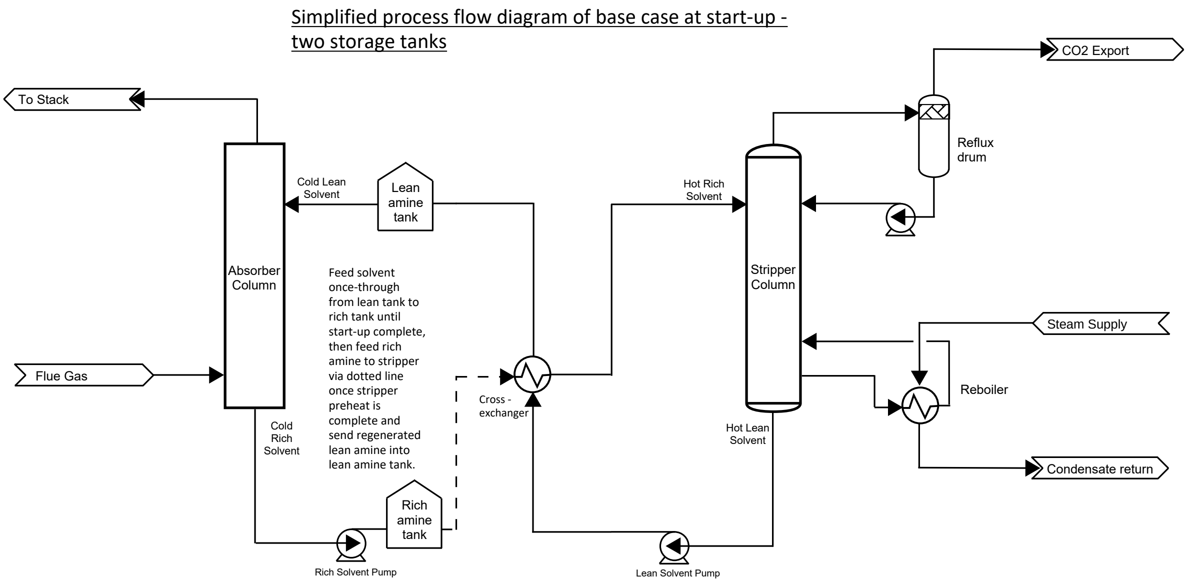

Figure 15. Rich and lean tanks for start-up buffering

The start-up storage configuration has synergies with the segregated inventory configuration and a hybrid combination of storage plus inventory segregation is shown in Figure 16.

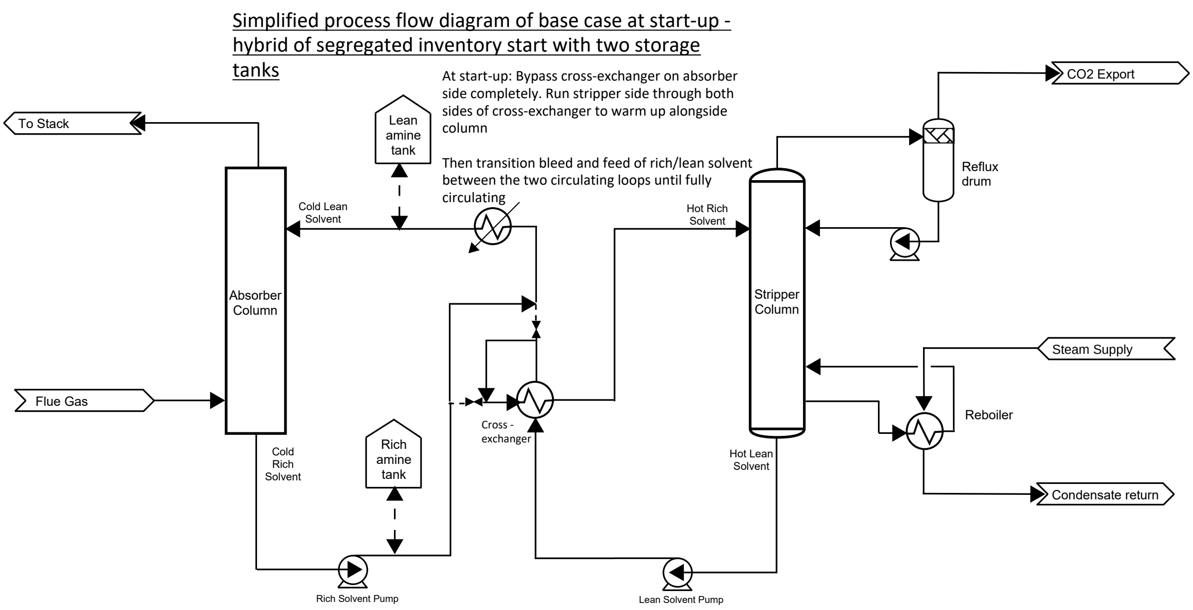

Figure 16. Combining storage with segregated solvent inventory

Alternative means for achieving start-up solvent storage include use of a single tank which can either connect into the lean line or run a dedicated blending line into the rich inventory (for use during the blending operation only). These would require more sophisticated process controls as well as start-up procedures. The selection of a rich solvent storage tank or the other configurations would be project-specific. Figure 17shows two other potential combination of solvent storage with blending using only the single amine storage tank.

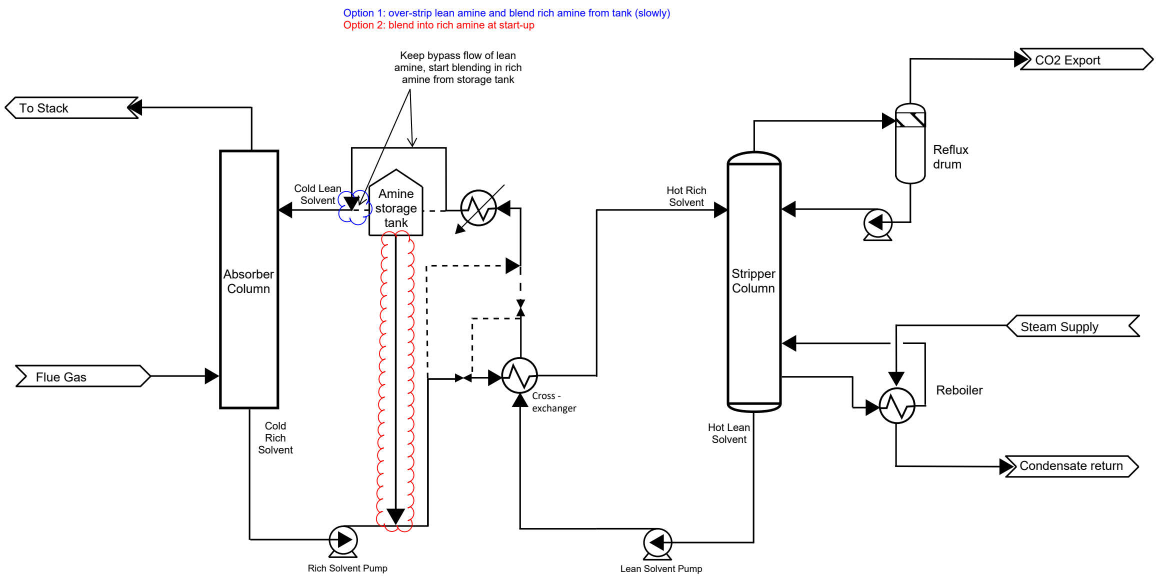

Figure 17. Using a single tank with varying bypass rates in combination with segregated solvent inventory

Prior to shut-down, the solvent inventory is then over-stripped to a lower lean amine loading than normal, to capture residual flue gas emissions during shut-down once steam is no longer available, coasting the plant to settle out with 95% capture throughout the shut-down. Shut-down would end with solvent loading of approximately 0.25mol/mol. Based on the MEA references identified in the Literature Review (Ref. 1), typical lean loading of MEA in carbon capture service is expected to range between 0.2-0.3 mol/mol. The target loading of the amine when it is being over-stripped is approximately 0.21 mol/mol and within the typical range of MEA lean loadings examined in literature.

The various configurations would all be designed to achieve the objective of maintaining the capture rate of 95% throughout start-up and shut-down. Solvent inventory is provided to ensure supply of lean amine for treatment throughout the start-up sequence until the regenerator can take over supply of lean amine. Once the regenerator supply is established, rich amine is worked off within the constraints of circulating pump sizing and stripper performance.

Estimated solvent volume is therefore given conservatively by providing hold-up to provide treatment at the solvent design rate (i.e. approximately 1500kg/s) for the full start-up time. Given the hot start-up time of 81 minutes for the standard configuration, the worst-case extra hold-up time required is calculated as:

$$Standard\ configuration\ solvent\ storage = 30\ mins\ (in\ one\ tank)$$

$$Start-up\ time = 81\ mins$$

$$Inventory\ requirement\ for\ startup = 81\ mins\ at\ 1500\frac{kg}{s}, or\ 7{,}290{,}000\ kg$$

$$Density\ of\ lean\ amine = 1099\frac{kg}{m^3}, \therefore\ inventory\ for\ start-up = 6{,}633m^3$$

6633m³ storage includes the 30-minute storage provided in the standard configuration (2456m³, net increment for start-up is therefore 4177m³). Cost estimates for buffering the hot start and cold start options (169 mins per Section 9.2.6) are given in Table 21, comprising the cost of the tanks and solvent only, assuming a stainless steel 316-grade tank (see Appendix D).

Table 21. Additional amine storage volume calculation for design amine circulation rate of 1500kg/s, density 1099kg/m³, increment on 30 minutes storage provided by the standard configuration (2456m³), dedicated lean and rich storage for start-up

Solvent hold-up basis	Lean tank volume, m^3	Lean tank cost, £2018	Rich tank volume, m^3	Rich tank cost, £2018	Extra amine inventory, £2018	Cost increment for start-up storage, £2018
Un-improved, 30 mins	2,456	£155,000	N/A	N/A	N/A	-
81 mins, hot starts	6,633	£325,000	6,633	£325,000	£2,332,273	£2,982,273

Solvent hold-up basis	Lean tank volume, m^3	Lean tank cost, £$_{2018}$	Rich tank volume, m^3	Rich tank cost, £$_{2018}$	Extra amine inventory, £$_{2018}$	Cost increment for start-up storage, £$_{2018}$
169 mins, cold starts	18,840	£807,000	18,840	£807,000	£9,148,184	£10,762,184

Note that these cost estimates have not considered the other incremental cost effects from increased storage inventory e.g. instrumentation, piping and bund size. The cost differential on these options has been assumed to be negligible as the primary cost driver is clearly the solvent inventory. For the tank cost estimates, uncertainty in the cost estimates presented above is relatively low, the amine storage tanks would have similar metallurgy and design as that required for demineralised water. Costs are readily available for stainless steel tanks of the given sizes and some savings may be found if lower cost material selection is specified (e.g. glass reinforced plastics).

9.3.3.3 Working off rich inventory following completion of start-up

Working off the rich solvent inventory built up during start-up will clearly require supplementary energy to the normal heat consumption and can be estimated from the quantity of CO_2 held up in the solvent. The CO_2 hold-up is itself calculated from the total quantity of CO_2 produced by the GT during the full start-up time (thus giving the quantity of buffered CO_2 in storage), at 95% capture basis and the regenerator specific steam consumption. Note that the working off procedure would be carried out during full normal operation (i.e. by definition after start-up is complete), the full 336MW.th for 95% capture of 85kg/s CO2 into the plant would be assumed to be available, or 4.2MJ.th/t$CO_{2\ product}$). For a cold start:

$$Quantity\ of\ CO_2\ held\ in\ solvent = \ 493t\ total\ from\ GT\ per\ , \times\ 95\%\ capture \approx 468tCO_2$$

$$4.2MJ\ steam\ per\ tCO_{2\ product} \times 468tCO_2\ to\ work\ off \approx 1970\ MJ$$

Therefore, for a cold start, approximately 1970MJ of heat would be required from steam to work off all the CO_2 inventory built up during start-up. This energy will have to be provided alongside the normal regeneration heat input required by the reboiler. From the Basis for Design for this study (Ref. 2), the design margin applied on throughput in the capture plant is approximately 7% i.e. the reference flow from the GT is approximately 1020kg/s. However, the PCC plant mass balance has been carried out to treat 1100kg/s total flue gas. The normal heat consumption of the process for a flue gas of 1020kg/s would be approximately 312MW.th steam, leaving approximately 24MW.th design margin in the reboiler, plus the associated hydraulic margins in the regenerator system. Using the identified headroom of 24MW.th steam in normal operation, the built-up CO_2 would be expected to be worked off over 82 seconds:

$$\frac{1970\ MJ}{24\ MW.th} = 82\ seconds$$

Utilising the full design margin in the process would be an extreme scenario, dropping net cycle efficiency by up to 0.5 percentage points. It is likely that a more gradual blending would be pursued with a lower instantaneous penalty on a real plant and more immediately, on the amine circulation pumps. However, by inspection, the blending of the rich amine inventory would still be expected to be achieved within one hour and would not affect decisions regarding plant minimum up-time as the full solvent hold-up would be fully regenerated.

Note that the storage options incur a delayed 1970MJ regeneration requirement which must be repaid once the cold start-up is complete. In a hot start, the equivalent delayed penalty is approximately 1411MJ based on total 355tCO_2 to work off, see Table 11.

9.3.3.4 Combination with segregated inventory improvement

Evaluation of the solvent inventory options noted that storage can be readily combined with the segregated inventory improvement option and it is expected that projects given a start-up capture target may seek to deploy combinations of both. Therefore, using segregated inventory (detail in Section 9.3.2) in combination with start-up storage has been considered and the corresponding stripper start-up times given as 37 mins and 82 mins for hot and cold starts, respectively, see Table 22.

Table 22. Storage cost increment in combination with segregated inventory allowing faster starts of 37 mins and 82 mins for hot and cold, respectively

Scenario description	Lean tank volume, m^3	Lean tank cost, £2018	Rich tank volume, m^3	Rich tank cost, £2018	Cost of additional amine, £2018	Cost above base case, £2018
Base case	2,456	£155,000	N/A	N/A	-	-
Hot start 37 mins	3,030m³	£180,000	3,030	£180,000	£320,499	£680,499
Cold start 82 mins	6,715m³	£330,000	6,715	£330,000	£2,378,059	£3,038,059

Note that the cost estimates given for deploying start-up storage together with segregated inventory have not considered the increment on control and hydraulic system complexity to deliver the switch-over from segregated to circulating mode. This area would be worth investigating on individual projects with dynamic simulation to consider the bottlenecks for a specific design and determine whether any further optimisation is possible. The findings from such a study would be specific to that project, although some generally applicable knowledge transfer may be possible between projects.

9.3.3.5 Amine storage option conclusions

The solvent storage requirement for achieving 95% capture during start-up was calculated as 51 mins or 139 mins to cover hot or cold starts, respectively. The volume would be in addition to the 30 mins of hold-up taken to be part of the reference configuration. By providing the extra hold-up, the plant would be expected to achieve 95% capture throughout start-up, buffering CO_2 in the solvent inventory for working off later once the start-up is complete. The time required for working off the solvent is expected to be less than one hour, depending on the rate at which the operator chose to blend rich start-up solvent into the stripper. The limit of the stripper and reboiler system itself to accept extra solvent was found to be approximately 2 mins, though in reality, the rate at which the circulation pumps could drive the rich inventory from storage would not allow such a fast transfer. Costs for the storage tanks and solvent inventory have been estimated as approximately £3,000,000 to £11,000,000, excluding pumping reconfiguration, foundations, bunds, pipework or other project works.

Projects considering start-up storage will likely also consider some means of segregating inventory for start-up optimisation, so the two options have also been considered together. The additional solvent inventory in this case was found to be approximately 7 mins to cover hot starts or 52 mins for cold starts. The costs for solvent inventory optimised by combination with segregated start-up have been estimated as £700,000 to £3,100,000 for tanks plus solvent approximately, excluding pumping reconfiguration, process instrumentation and controls, foundations, bunds, pipework or any other project works.

9.3.4 Improvement configuration 3 – heat storage

9.3.4.1 Introduction

The second configuration variant considered was the storage of thermal energy for instant availability to pre-heat the regenerator column and reboiler. This configuration would allow reboiler pre-heating to occur prior to steam availability from the HRSG, with the steam extraction taking over as soon as steam is available. Depending on the means of storage, the store could also be charged prior to power plant shut-down and continue reboiler operation to strip amine of residual flue gas. During periods of high renewable generation to the grid (coincident with times when the CCGT is likely not operating, by definition), one means may be to top the thermal store using an electric coil from the grid which would be relatively low in carbon intensity at that time. The storage unit would use hot oil to provide heat to the reboiler as the primary source of thermal energy. In case the heat storage at 130°C and required volume was found to be impractical for the hot oil storage tank, a separate backup hot water store option would be considered instead of the hot oil store if required.

This option would address the first and fourth main constraint of the Standard CCUS process: allowing heat to be readily available from the beginning of the start-up process and during the shut-down process. As this option would require a large working volume on the order of 10,000m^3 depending on the selected configuration and reservoir type (hot oil or water), there is a greater commercial risk than solvent storage. Relatively few projects have been deployed at such scale and temperature level. However, a review by TES in 2016[10] found at least one hot water thermal energy store of comparable scale in operation for district heating at Friedrichshafen, Germany. Further, the TES review found a general correlation for declining costs per unit volume as overall

[10] Evidence Gathering: Thermal Energy Storage (TES) Technologies, 2016, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final__1_.pdf

installed volume increased. The technological risk of deploying a thermal energy store is low as the theory is well-defined[11], sharing design with the district heating industry.

9.3.4.2 Description

Given a worst case requirement of 1,100GJ to start the amine reboiler (calculated in Section 9.2.4), indicative sizing for a thermal energy store was carried out based on typical heat transfer fluid characteristics, as shown in Table 23.

Table 23. Typical oil characteristics

Parameter	Value	Units
Density	930	kg/m^3
Heat capacity	1.95	kJ/kg.K

Source: https://www.therminol.com/sites/therminol/files/documents/TF-8695_Therminol-66_Technical_Bulletin.pdf at approximately 130°C storage temperature

Temperature parameters used to inform the hold-up calculation include the starting temperature in the hot oil store and temperature drop: 140°C and 10°C respectively. The final temperature of the vessel would be 130°C and therefore meet the criteria in the Design Basis (Ref. 2) for 5°C minimum temperature difference between the store and the reboiler. The resulting hold-up was then calculated as:

$$Mass\ of\ oil = \frac{Input\ thermal\ energy\ required}{Heat\ capacity\ of\ oil \times Temperature\ drop} = \frac{1{,}100{,}000{,}000\ kJ}{1.95\frac{kJ}{kg.K} \times 10K} = 56{,}410{,}256 kg, or$$

$$Volume\ of\ oil = \frac{56{,}410{,}256 kg}{930\frac{kg}{m^3}} = 60{,}656 m^3$$

60,656m³ of storage would be expected to be required for this scenario which would be an order of magnitude larger than the largest existing current Tank Thermal Energy Store (TTES)[12] at 5,700m³. Note also that the largest existing TTES stores hot water at 95°C rather than oil at 140°C, without the additional heat losses introduced through insulation.

Another variant of this improvement configuration was considered in terms of storing a fraction of the start-up heat requirement in a hot water TTES. Based on the properties of water and heat transfer basis of 95°C hot side to 90°C, the calculated hold-up requirement was:

$$Mass\ of\ water = \frac{1{,}100{,}000{,}000}{4.18\frac{kJ}{kg.K} \times 5K} = 52{,}631{,}579 kg, or$$

$$Volume\ of\ water = \frac{52{,}631{,}579 kg}{1{,}000\frac{kg}{m^3}} = 52{,}631 m^3$$

The water option would be comparable in volume to the hot oil option: 52,631m³ and 60,656m³, respectively. A concept cost estimate (Appendix D) has been carried out according to a review of existing Thermal Energy Storage (TES) facilities for district heating[13]. The estimated cost for deploying tank thermal energy store was taken as the upper bound of Figure 2 in the Evidence Gathering report: €150/m³. This figure was reported in 2012 and has been escalated to approximately £$_{2018}$124/m³ according to the latest Chemical Engineering Plant Index (CEPCI)[14].

The preliminary cost of deploying either a water or oil thermal storage option is therefore calculated as shown in Table 24 below. Estimated costs of £6,600,000-£7,600,000 are comparable to the larger lean amine storage options once solvent supply costs are included and within the same order of magnitude as the other improvement configuration options.

[11] A Comprehensive Review of Thermal Energy Storage, Sarbu and Sebarchievici, Sustainability, January 2018
[12] The future of Thermal Energy Storage in the UK Energy System; UKERC; 2014; http://www.ukerc.ac.uk/asset/82664E2B-6533-4019-BF5140CEB7B9894D/
[13] Evidence Gathering: Thermal Energy Storage (TES) Technologies; BEIS; 2016; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final__1_.pdf
[14] Annual CEPCI reported as 584.6 in 2012 and 603.1; https://www.chemengonline.com/tag/cepci/

Table 24. Thermal store options cost calculations

Thermal Store Option	Volume of store, m^3	High-level cost estimate for store, $£_{2018}$
Oil at 130°C	60,656	£7,612,333
Water at 95°C	52,631	£6,605,247

9.3.4.3 Uncertainties

There is significant uncertainty in the cost of deploying Thermal Energy Storage (TES) at the scale that would be necessary to store enough heat to pre-heat the reboiler. A figure of $€_{2016}$150/m³ according to a 2016 Evidence Gathering report for BEIS. This is at the top end of the range the authors expected for the largest thermal stores (on the order of 10,000m³). Reductions on the €150/m³ cost rate are not expected due to the novelty behind the store size. Multiple smaller units in parallel may be required to meet the volume demand of 52,631m³-60,656m³ thermal storage if a specially designed tank was not considered. For reference, the largest standard size of storage tank for crude oil is approximately 24,000m³ gross volume, the plant may require up to 3 tanks in parallel without going out to a specialist design.

9.3.4.4 Combination with segregated inventory improvement

The heat storage requirement can be reduced by combination with segregated inventory, reducing the pre-heat requirement to 220GJ per Section 9.3.2.3. Table 25 summarises the results of the store volume and cost calculation using this reduced energy requirement. Reducing the pre-heat energy storage requirement would reduce the expected cost to approximately £1.5 million for either oil or water. However, the heat store requirement would still be significant (10,526m³ or 12,131m³ for oil and water, respectively) which must be accommodated on-site in an insulated storage tank.

Table 25. Thermal store options cost calculations for the combined improvement option

Thermal Store Option	Volume of store, m^3	High-level cost estimate for store, $£_{2018}$
Oil at 130°C	12,131	£1,522,467
Water at 95°C	10,526	£1,331,049

9.3.5 Improvement configuration 4 – steam cycle improvements

9.3.5.1 Introduction

The initial proposal for this study was to consider a third option combining both amine and heat storage to optimise the sizing of both options. However, this was superseded by investigation of fast starting steam cycle technology which would significantly reduce the time lag before steam can be extracted to the PCC plant.

Fast-starting steam cycle technologies include:

- Operational procedures such as carrying out the combustion path purge at shut-down instead of start-up
- Feedback control and automatic adjustment of the gas turbine inlet guide vanes at start-up
- Once-through high-pressure boiler technology such as the Benson Boiler equipment (as originally installed in the UK at Cottam)[15], allowing supercritical steam through the boiler and significantly increased allowable start-up steam cycle warm-up rates

Fast steam cycle starting technologies have the potential to impose extra fatigue on the steam cycle, with the connection between the high-pressure drum (for a fast drum boiler) and its steam riser being the component at most risk of failure in work by Foster Wheeler America[16]. The same report also proposed advanced plant controls to mitigate the impact on component life. Another report by VPI[17] proposed a full inspection and monitoring program based on condition modelling for fast starting and cycling CCGT based on adapting sub-critical HRSG for fast starts. Sufficient measures to mitigate any impact on steam cycle lifetime are therefore expected to be available such that the net penalty in plant life for fast starting would be likely to be negligible. Note that a supercritical once-through boiler such as the Benson technology would avoid the high-pressure drum and therefore stress issue altogether, albeit imposing stricter water quality and operating procedure requirements than drum boilers.

[15] UK sites with Benson Boilers include: Cottam; Lagange; Severn Power; Keadby 2 https://assets.new.siemens.com/siemens/assets/api/uuid:a10a1319-3b9a-4265-bcd2-f95addd4aa1e/version:1560384111/references-firedbensonsg-20180305.pdf
[16] Fast Start HRSG Life-Cycle Optimization; Power; 2013; https://www.powermag.com/fast-start-hrsg-life-cycle-optimization/
[17] Economic Operation of Fast-Starting HRSGs; Power; 2010; https://www.powermag.com/economic-operation-of-fast-starting-hrsgs/

Alternative means of improving the steam cycle response and therefore PCC plant start-up time particularly during the cold start include diverting bypass steam into the amine reboiler. The bypass steam is normally dumped into the condenser and the heat rejected until steam quality is acceptable to use in the ST. However, the amine reboiler minimum requires only LP-grade steam. Therefore, the PCC plant can utilise heat that would otherwise be wasted into the condenser during start-up, completing the PCC start-up significantly sooner particularly in a cold start scenario. However, the diverted steam will be of continuously increasing quality during start-up, imposing requirements on let-down to LP to protect against introducing supercritical steam into a low--pressure system. The steam must also be appropriately de-superheated to avoid overheating the reboiler and amine inventory.

The impacts of using fast starting steam cycle options have been considered at a high level for Benson boiler technology and steam diversion, as well as in combination with the segregated amine inventory option.

9.3.5.2 Description: Benson boiler

For the fast steam cycle start-up improvement variant, credit was taken for specific fast-starting steam extraction (such as Benson boiler technology or other improvements specifically prioritising fast start of the steam cycle). Some slowdown in the start-up procedure of the steam turbine to facilitate early steam extraction would be expected. However, this slowdown would likely be relatively small and it is worth noting that the HRSG has significant excess heat which is otherwise dumped into the condenser during start-up. Fast start steam extraction technology improvements for the PCC plant comprise:

- Reduced lag time to approximately 40% of base case configuration for both cold and hot starts, as indicated possible for starting best-in-class fast-starting boilers[18].
- Increased steam availability, taking credit for steam extraction for the PCC plant being prioritised and therefore full steam extraction being available immediately following lag time.

The improved start-up performance of the fast-starting steam cycle is shown in Table 26 below. The lag time after NTS for steam extraction in the standard configuration is approximately 25 and 60 minutes for hot and cold starts respectively (as shown in Section 9.2.6). Technology such as the Benson boiler would reduce the extraction time to 40% of the base case i.e. 10 and 24 minutes for both starts, respectively. Both hot and cold starts would then be followed by approximately 55 minutes of active heating time at 336MW.th, as calculated in Section 9.2.6. For cold starts, it is assumed that the full extraction rate of 336MW.th could be provided compared to an initial partial extraction in the standard configuration of 168MW.th (50%).

Table 26. Stripper start-up time calculations with fast steam cycle start

Start type	Lag time post-NTS	Extraction duration	Extraction rate	Total start-up time post-NTS
Hot start	10 mins	55 mins	336 MW.th	65 mins
Cold start	24 mins	55 mins	336 MW.th	79 mins

9.3.5.3 Description: steam diversion

The steam diversion option would connect by a take-off valve on the HP bypass line and require controls to be put in place for the rising upstream steam quality during start-up. Measures could include multiple parallel control valves of dissimilar trim sizes to cover the range of conditions encountered or other split-range control measures. This option would require rigorous analysis to ensure adequate safeguarding measures are put in place to protect the low-pressure equipment in the amine plant.

Once the steam cycle start-up is complete, steam extraction should switch over to the normal operating extraction point i.e. the IP/LP cross-over as prolonged operation on HP steam let-down would be inefficient for the plant.

Alternative means could be an arrangement with an intermediate back-pressure turbine such as investigated by Bechtel for Loy Yang A[19]. Under such an arrangement, steam extraction for the PCC plant would always be via the main ST HP bypass, with the intermediate back-pressure turbine also bypassed during start-up, with expansion through the back-pressure turbine once start-up is complete. Clearly, an additional turbine and generating equipment would be required in this scenario compared to the standard configuration and any other improvement configuration which would introduce cost and complexity. However, the incremental costs would likely be partly offset by less onerous extraction connection works required. In particular, the HP bypass line is

[18] https://www.acboilers.com/en/wp-content/uploads/2012/10/Heat-Recovery-Steam-Generators-for-large-combined-cycle-plants1.pdf
[19] Retrofitting an Australian brown coal power station with post-combustion carbon capture; Bechtel; 2018; http://www.co2crc.com.au/wp-content/uploads/2018/10/Retrofitting_Australian_Power_Station_with_PCC.pdf

more likely to be easily accessible on existing plants than the IP/LP cross-over. Existing plants considering retrofit of PCC may see more benefit from this option (providing suitable location can be provided for the back-pressure turbine).

Steam diversion would be of most benefit in cold starts when the standard configuration plant considered in this study would require approximately 60 minutes to begin steam extraction from the IP/LP cross-over. Diversion of some steam into pre-heating the amine reboiler could likely begin at approximately 25 minutes when the GT is held at 50% load for steam cycle heating. During the 35-minute long period from 25 minutes post-NTS to IP/LP cross-over extraction from the ST, the heat output from the GT and taken up by the HRSG would be:

$$GT\ exhaust\ @\ 50\%\ load = 680\frac{kg}{s}\,at\ 670°C,$$

$$HRSG\ exhaust = 680\frac{kg}{s}\ at\ 118°C\ and,$$

$$average\ flue\ gas\ C_P\ in\ the\ HRSG = 1.14\frac{kJ}{kg.K}$$

$$Q = 680\frac{kg}{s} \times 1.14\frac{kJ}{kg.K} \times (670°C - 118°C) \approx 428\ MW.th$$

$$35\ minutes\ at\ 428\ MW.th = 898\ GJ$$

The heat input to the HRSG during this period is approximately 898GJ and the estimated heat consumption to start the standard configuration amine plant is approximately 1100GJ, or a further 8 minutes of heating in the reboiler at 428MW.th. Clearly, this option is worth investigating in detail on an individual project basis for the potential to start the PCC plant purely on excess waste heat rather than waiting for the ST to come online and using energy that could be used for generating electricity. This option would potentially require over-sizing of the reboiler system to allow for increased steam flow at start-up (normal heat consumption in the reboiler is 336MW.th so approximately 30% overdesign on steam flow would be required).

Hot starts would not see such a dramatic improvement with steam diversion: the predicted delay before steam extraction from the IP/LP cross-over in the standard configuration in a hot start scenario without using bypass steam is already only 25 minutes. Reduction of the lag time would still be followed by active heating time and give smaller relative improvement than for cold starts. Without building a dedicated margin in the reboiler to accept extra steam for start-up, both hot and cold starts would require approximately 55 minutes of active heating time. It follows that in either hot or cold start, the PCC plant utilising steam diversion but without additional steam capacity would be ready within 79 mins after NTS (see Table 26).

9.3.5.4 Combination: Benson boiler with segregated amine inventory

As with the other improvement options, the optimised non-recirculating amine inventory can be combined with the fast-starting steam cycle technology to further optimise the start-up time.

Using the method presented above, the calculated extraction duration for the combined fast steam cycle option is shown below based on the stripper pre-heat energy requirement for the optimised inventory (220GJ) and full steam extraction.

$$Extraction\ duration = \frac{220{,}000MJ}{336MW.th} = 655s = 11mins$$

The stripper start-up time summary for the combined option is shown in Table 27, with the total start-up time for both start types reduced by 44 minutes.

Table 27. Stripper start-up time calculations with fast steam cycle start and optimised inventory

Start type	Lag time post-NTS, mins	Extraction duration, mins	Extraction rate, MW.th	Total start-up time post-NTS, mins
Hot start	10	11	336	21
Cold start	24	11	336	35

9.3.5.5 Fast starting steam cycle conclusions

The power CCUS plant start-up times for the scenarios shown in Table 26 and Table 27 range between 21 minutes for a hot start with segregated, optimised amine inventory at start and 79 minutes for cold start in the default, circulating mode at start. Clearly, significant reduction in start-up time of the CCS plant would be expected with the deployment of fast steam cycle starting technology over the base case (37-169 mins, respectively, see Table 10). With fast-start steam extraction, the PCC plant start-up process to reach steady-state regeneration and 95% capture would be expected to keep up with the power plant start-up.

High-level cost data for deploying once-through boiler technology is readily available from Thermoflow, estimated to be up to approximately £1,000,000 greater than a drum boiler per CCGT train (see Appendix D). This cost would be expected to allow economies elsewhere in the power plant and overall the power plant capital cost difference between once-through and drum boiler technology is expected to be negligible.

Costs of implementing steam diversion on its own have not been investigated, the required degree of over-design in the amine reboiler system and preceding engineering studies to confirm process details are a potential area for further study.

Current generating assets operating within the top half of the merit table have start times within the range of 55-80 minutes, based on discussion during a recent Open Access forum hosted by the UKCCSRC[20]. Therefore, a modern plant equipped with fast starting steam technology will be expected to operate in the top half of the merit order in all cases. Further, with some CCS process control optimisation to segregate the amine inventories or some extra storage for start-up, the plant would be expected to be ready with 95% capture and operate at or near the top of the merit order.

9.3.6 Other improvement options not considered in detail

Other options for improving start-up and shut-down behaviour of PCC plant include fitting auxiliary gas-fired or electric heaters to heat the solvent in advance of start-up.

Gas-fired auxiliary heaters were excluded early in this study as being unlikely to be considered compliant with guidance on Best Available Techniques (BAT) for Large Combustion Plants. A case could be made for a BAT-compliant auxiliary heater used only for pre-heating the solvent before transitioning to steam extraction; if the heater exhaust was also connected to the absorber and emissions captured. This idea has not been tested in any planning applications at time of writing and was not considered in detail given that several other options were identified which would not be expected to be challenged on BAT.

An electrical auxiliary heater is worth noting as a further alternative option. Provided the necessary safeguarding on surface temperatures is put in place to protect the solvent from localised overheating, an electrical heater could be used to warm up the solvent ready for capture within the start-up process of the power plant. The heater would run when the power plant is offline i.e. when the majority of generation supplying the grid is from renewables so the carbon intensity of pre-heating with an electrical heater would likely be low.

[20] Notes taken during Open-access PCC Discussion, 19th March 2020, UKCCSRC

10. Conclusions

10.1 Standard configuration performance

From modelling the standard configuration of the PCC plant within Thermoflow and ProMax during transient phases, the following conclusions relating to the various performance indicators can be found.

10.1.1 Start-up and shut-down times

The standard configuration post-combustion capture plant designed for 95% capture was found to finish the start-up process within approximately 81 to 169 minutes for hot and cold starts, respectively (as shown in Table 10). For the power plant itself, start times would be expected to be within 30 minutes to 200 minutes for hot and cold starts, respectively. Note that, for the cold start, the PCC plant completing its start-up cycle and producing steady-state 95% capture within 169 minutes means the PCC plant start-up and pre-heating can be completed up to 31 minutes earlier than the power plant (which still requires ongoing heating until the 200 minute mark), due to extended time at part load in the gas turbine for reboiler heating.

10.1.2 Minimum up-time and down-time

As discussed in the Literature Review (Appendix A), the minimum plant up-time and down-time are economically-driven decisions, made by the operator based on their cost-benefit judgement of shutting down (and increasing start-up cost as well as increasing component fatigue). It is expected that an operator would only be inclined to shut down if they expected a minimum down-time of at least 2 hours.

Minimum up-time once started is also primarily an economic decision – an operator would normally prefer not to incur a start if they could not forecast at least 2 hours of operation in the case of a hot start or 4 hours 40 minutes of operation for a cold start. The durations of minimum up-time stated are based on an unabated plant. The times associated with an abated plant are expected to be similar as a similar regime is followed.

10.1.3 Carbon dioxide capture rates and residual emissions during start-up and shut-down

Capture rates during start-up have been estimated as 99% initially, falling to effectively 0% for a cold start, as shown by the blue line in Figure 4. Residual CO_2 emissions have been calculated as 336tCO_2 during the cold start. Overall capture rate for a cold start has been estimated as approximately 32%. The standard configuration presents a scenario where a PCC plant has been designed without any measures to maintain capture rates throughout start-up. The standard configuration is therefore a general worst-case scenario considering the degree to which an un-optimised plant might fail to meet the target of 95% capture rate during start-up and shut-down.

For a hot start, the minimum expected capture rate is approximately 10% at approximately 81 minutes. Overall emissions during a hot start were estimated as 213tCO_2 and correspond to an overall capture rate of 40%.

The standard configuration CCGT with PCC would be expected to shut down within 45 minutes as described in Table 4. Emissions expected during the shut-down process were estimated as 47t CO2 total over a shut-down. However, snapshots 1 and 2 happen while some steam is likely to still be available for extraction. Therefore, credit has been taken during shut-down for the first 29.1t (sum of Snapshot 1 and 2) of captured CO_2 to not contribute to accumulation in the amine following shut-down.

Snapshot 3 is therefore the only period of expected CO_2 accumulation in the solvent inventory, a total of 27.9t which corresponds to 635kmol of CO_2 or an increment of 0.04mol/mol to loading. Preliminary analysis of the stripper performance at part-load has found that operating with an increased stripper back-pressure of approximately 3.1bar allowed for a reboiler temperature of 137°C and lean amine production at 0.21 mol/mol during the 30 minutes preceding a shut-down to build up sufficient over-stripped amine and allow the plant to complete the shut-down with amine at 0.25mol/mol loading.

10.1.4 Minimum stable generation

Minimum stable generation within environmental compliance limits for modern H-Class CCGT is driven by combustor technology and can be as low as 25% on the gas turbine for those deploying sequential combustors. Annular and can-annular combustors are limited to approximately 33%-50% turndown on the GT for steady lean burn at minimum emissions-compliant load.

10.1.5 Associated costs

Fuel consumption during hot and cold starts has been estimated as approximately 122t (5,680GJ) and 276t (12,841GJ), respectively.

10.1.6 Gross and net thermal efficiency

The standard configuration plant has an estimated thermal efficiency of approximately 61% net (LHV) prior to PCC (Table 6). With 95% PCC, the net efficiency is expected to drop to approximately 52% net (LHV). Gross efficiency for the standard configuration at the site conditions has been estimated as approximately 57% (LHV) at the generator terminals with 95% capture.

10.2 Performance with improvement configurations

The PCC plant performance with the four different improvement configurations, as well as the combination options examined, are detailed below. Comparisons between the improved configurations and to the standard configuration are made throughout to clearly identify the impact of the options introduced. The improvement configurations each consider how a real plant might be designed to meet the capture rate target at start-up as well as normal operation, with each option being contrasted against the standard configuration to highlight the main differences.

Note that the options considered in this study do not themselves interfere with the ability of the power plant to operate flexibly and are only ways to improve start-up and shut-down performance of the PCC plant. Once operating, the power plant would still be able to operate flexibly (e.g. with ramp rates), with the PCC plant following as an ongoing steam and auxiliary power consumer. In fact, the deployment of additional amine storage option for flexible operation would be expected to somewhat enhance the ability of the power plant with PCC to operate flexibly by shifting some regeneration to periods of low electricity cost, giving an extra degree of freedom for the operator to follow any variable electricity price.

10.2.1 Configuration 1 – segregated amine inventory

The first configuration variant considered was the de-coupling of the amine inventory for absorption and for stripper start-up. This option would require bypass of the lean-rich cross-exchanger on the absorber side during start-up and allow maximum lean solvent inventory to be stored in the absorber side of the PCC plant. It follows that this option allows the minimum inventory in the stripper to facilitate initial pre-heating of the stripper column, cross-exchanger and associated piping. This method was found to reduce the stripper start times for both hot and cold starts by approximately 50%, leading to 37 mins and 82 mins, respectively.

Note that this option did not maintain 95% capture throughout start-up. The overall capture rate in a hot start with segregated inventory was estimated as 87%. However, this option requires no major new equipment, only modifications to piping and instrumentation to facilitate the proposed mode of operation. It is anticipated that PCC plant design for flexibility would incorporate a combination of the options proposed in this report and this option has the potential to be combined with each of the other options to reduce the active heating time of the stripper..

10.2.2 Configuration 2 – dedicated lean and rich amine storage

This improvement option would replace the single 2,456m³ tank in the standard configuration with two tanks of 6,633m³, providing an additional 51 minutes of net amine circulation at start-up, with volume to store the rich amine without recirculating.

Corresponding cold start inventory requirements were for an additional 139 minutes of circulation, provided as a lean storage tank of 18,840m³ and rich amine storage tank (also 18,840m³) operating once-through from lean to rich storage at start-up. The tanks would then switch to holding rich amine in the rich tank, blending stored rich amine into the stripper feed at a controlled rate. At the same time, the lean amine tank could be either bypassed, or flowed through by the regenerated lean amine from the stripper depending on the particular configuration chosen. Other configurations could potentially remove the rich amine tank or seek to optimise inventory usage further, contingent on more sophisticated process control measures. It is expected that these tanks would be welded stainless steel and cost in the order of £495,000-£1,459,000 for hot and cold start basis per CCUS train respectively. The estimate cost of the additional solvent will cost in the region of £2,300,000 to cover capture during hot starts and £9,100,000 for cold starts.

Providing the additional amine storage inventory would allow the plant to continue generating low-carbon electricity with no decrease in capture rate throughout the start, depending on whether the capacity is available to treat throughout the cold start or only for hot starts.

Additional amine storage would allow 95% capture to be maintained through the plant start, with residual emissions calculated as approximately 17.7tCO_2 to 24.6tCO_2 for hot and cold starts, respectively.

By combining this improvement option with segregated inventory, the required increment on amine volume for start-up is significantly reduced, as are the associated costs of the tanks and additional solvent. The resultant amine tank sizes for hot and cold start for the combined option were 574m^3 and 4,259m^3 respectively. Applying the same cost estimate assumptions as before, the tanks would cost approximately £205,000-£505,000 for hot and cold start basis per CCUS train respectively. The required additional solvent in the PCC plant will cost in the region of £300,000-£2,400,000 for hot and cold starts respectively.

Clearly a trade-off exists between a developer seeking to cover capture during hot starts and the extra investment required to also cover cold starts. Given that a plant running at baseload would only be expected to have up to 20 cold starts per year, a developer may choose to install storage to cover capture during hot starts only. This would be a commercial decision driven by the cost of residual emissions and the number of cold starts. For example, a two-shifting plant may run 271 starts per year (of which approximately 50-55 may be cold starts). In this event, the incremental cost of emissions over the lifetime of the plant may drive the decision towards covering cold starts as well. Detailed commercial modelling will be required particularly given the expectation at time of writing for the first PCC power plants to initially run mostly baseload and eventually transition to the more flexible modes to work around growing renewables.

Solvent storage could be added later in the life of a plant when justified by operating economics, provided some provisions were made to do so when the plant is designed. These measures include reserving plot space for future operational rich amine storage (minimal pre-investment), and/or over-sizing the lean amine storage tank to allow additional inventory to be stored later (without purchasing the start-up inventory until required).

10.2.3 Configuration 3 – heat storage

Preliminary sizing estimated that 60,656m^3 of storage would be expected to be required for a hot oil thermal store to provide sufficient heat to start the amine reboiler, which would be an order of magnitude larger than the largest existing current Tank Thermal Energy Store (TTES)[21] at 5,700m^3. Note also that the largest existing TTES stores hot water at 95°C rather than oil at 140°C, without the additional heat losses which can only be partially mitigated by insulation.

A cost estimation of required storage tanks can be found using the unit prices of the largest existing TTES and scaled up to the appropriate dimensions. Based on a reported unit cost value of €150/m^3 in 2012, the estimated cost for the oil and water thermal store was approximately £7,600,000 and £6,600,000 respectively.

Storing heat would allow the plant to maintain 95% capture and therefore residual emissions rates would be approximately 17.7tCO_2 to 24.6tCO_2 for hot and cold starts, respectively, depending on the storage inventory basis.

Combining the thermal energy store improvement option with the non-recirculating inventory reduces the required volume of the water or oil store significantly. This is due to reduced stripper pre-heat requirement (1,100GJ down to 220GJ) as a result of the optimised level of inventory. For the thermal store using oil at 130^{o}C, the required volume of the store is 12,131m^3 with a high-level cost estimate of approximately £1,500,000. For the store using water at 95^{o}C, the required volume of the store is 10,526m^3 with a high-level cost estimate of approximately £1,300,000.

10.2.4 Configuration 4 – fast starting steam cycle technology

The power CCUS plant start-up times for the standard inventory shown in Table 26 range between 65 and 79 minutes for a hot and cold start respectively. Clearly, significant reduction in start-up time of the CCS plant would be expected with the deployment of fast steam cycle starting technology over the standard case (37-169 mins, respectively, see Table 10). With fast-start steam extraction, the PCC plant start-up process to reach steady-state regeneration and 95% capture would be expected to keep up with the power plant start-up.

[21] The future of Thermal Energy Storage in the UK Energy System; UKERC; 2014; http://www.ukerc.ac.uk/asset/82664E2B-6533-4019-BF5140CEB7B9894D/

For the combined improvement option with non-recirculating inventory, the total start-up times for both hot and cold starts reduce by 44 minutes due to the reduced amine inventory in the stripper decreasing the overall duration of extraction. Therefore, for this configuration the total start-up time for a hot and cold start is 21 and 35 minutes respectively.

High-level cost data for deploying once-through boiler technology is readily available from Thermoflow, estimated to be up to approximately £1,000,000 greater than a drum boiler per CCGT train. This cost would be expected to allow economies elsewhere in the power plant and overall the power plant capital cost difference between once-through and drum boiler technology is expected to be negligible.

Costs of implementing steam diversion on its own have not been investigated, the required degree of over-design in the amine reboiler system and preceding engineering studies to confirm process details are worth further study.

Current generating assets operating within the top half of the merit table have start times within the range of 55-80 minutes, according to discussion during a recent Open Access forum hosted by the UKCCSRC. Therefore, a modern plant equipped with fast starting steam technology will be expected to operate in the top half of the merit order in all cases. Further, with some CCS process control optimisation to segregate the amine inventories or some extra storage for start-up, the plant would be expected to be ready with 95% capture and operate at or near the top of the merit order.

10.3 Overall study conclusions

All the improvement options considered have been found to effectively decouple the power plant from the PCC plant and allow the whole complex to maintain 95% capture through start-up and shut-down events, with the exception of segregated amine inventory alone (87% overall start-up capture). There are no incremental impacts expected on the overall process during normal operation and no strong reasons to prefer one option over another. The estimated costs to implement any of the flexibility improvement options identified are within the same order of magnitude. Therefore, the configuration of process options will likely be site- and project-specific rather than converging on any single approach and indeed most likely to tend towards a combination of options. For example, a fast-starting steam cycle (which would likely be an advantage in the current market even without PCC) would be complemented by segregated amine inventory and some additional dedicated start-up storage if found necessary during engineering work. This option would likely give a PCC power plant ready to respond quickly to grid demand, starting quickly and maintaining high capture rates through the start-up, operating phase and shut-down phases.

10.4 Further work

A future phase of development of this study should consider transient behaviour to optimise the process design including any start-up/shut-down improvement options being considered, as well as various combinations of improvement configurations. Once process parameters have been selected in detail, dynamic analysis of the integrated power CCUS facility would likely find significant savings possible from removing overly conservative assumptions. For this dynamic analysis, required parameters will include:

- Line sizing
- Column inventory estimates
- Preliminary process control valve specification
- Process control philosophy
- Pump and compressor preliminary specification

The above information would be expected to be available part-way through the Front End Engineering Design (FEED) of a power CCUS project, in which case, this study could be used to inform the activities to be carried out in a dynamic analysis towards the end of FEED.

Further work considering the steam heat extraction available at part load could also consider reducing the degree of conservatism in the cold start time calculation which likely underestimates the quantity of steam that could be made available for extraction to the steam cycle.

Appendix A – Literature Review

Start-up and Shut-down Times of Power CCUS Facilities

Literature Review

Department of Business, Energy & Industrial Strategy

1 April 2020

Quality information

Prepared by	Checked by	Verified by	Approved by
Klim MacKenzie Senior Process Engineer	Andy Cross Project Manager	Andy Cross Project Manager	David Hope Technical Director, Power & Energy

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Prepared for:

Department of Business, Energy & Industrial Strategy

Prepared by:

Klim MacKenzie
Senior Process Engineer
M: +447384819409
E: klim.mackenzie@aecom.com

AECOM Infrastructure & Environment UK Limited
3rd Floor, Portwall Place
Portwall Lane
Bristol BS1 6NA
United Kingdom

T: +44 117 901 7000
aecom.com

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1. Abbreviations

ITT - Invitation to Tender

BREF - Best Available Techniques Reference Document

CCGT - Combined Cycle Gas Turbine

CCS - Carbon Capture and Storage

CCUS - Carbon Capture utilisation and Storage

DLN - Dry Low NO_x

HP - High Pressure

LCP - Large Construction Plant

SS - Single Shaft

2. Introduction

The following literature review has been prepared to support the Start-up and Shut-down Times of Power CCUS Facilities project. The final literature review is intended to be presented in the final report for this project.

The literature review considers the research questions posed in the Invitation to Tender (ITT):

1. How do unabated Combined Cycle Gas Turbine (CCGT) and “standard configuration” post-combustion Carbon Capture Utilisation and Storage (CCUS) power plants perform?
2. What is the best available evidence on the start-up and shut-down times associated with alternative configurations and/or operating strategies for CCUS power plants?
3. Based on a qualitative assessment, what three alternative configurations are best suited for further analysis, based on:
    a. Their ability to improve the start-up times of ‘standard configuration’ power CCUS facilities without significantly impacting the power generation and CO_2 capture rate
    b. The engineering and cost challenges associated involved in either newly building such facilities or retro-fitting ‘standard configuration’ power + CCUS stations to incorporate the alternative configurations and operating strategies
4. Based on metrics such as time, CO_2 vented, total cost etc., how would the selected alternative configurations perform in relation to the parameters identified in the first question?

3. Literature Review

3.1 How do unabated CCGT and 'standard' CCGT+CCUS plants perform?

3.1.1 Full system start-up and shut-down times

Start-up of unabated CCGT and model-based optimisation of the start-up time has shown that significant start-up time savings are available if feedback control is used from the steam cycle to the gas turbine (Nannarone & Klein, 2019). The absolute start times for the un-optimised CCGT plant used as the reference values for cold and warm starts were 247 mins and 75 mins respectively. The authors found three main benefits from their optimised start-up model which were verified on the real site being modelled:

- 187 mins (32.5% reduction) and 48 mins (31.8% reduction) total start time for cold and warm starts, respectively, due to optimal inlet guide vane positioning
- 47.0% and 32.4% reduction in overall fuel consumption for cold and warm starts, respectively, due to reduced gas turbine ramp rate to follow maximum heat uptake by the steam cycle
- Approximately 10% reduction in maximum stress on the HP steam turbine rotor during both cold and warm starts

The reference start times used in this study are within the upper end of the range for start times reported in an overall review (Parsons Brinckerhoff, 2014), given in Table 1.

Table 1. Indicative start-up times from notice to synch through to full load

Start Type	Technology type	Full start time (mins)
Hot start	Existing gas CCGT	55 – 95
Warm start	Existing gas CCGT	95+
Cold start	Existing gas CCGT	105 - 255

Source: (Parsons Brinckerhoff, 2014)

Note that the differences between the gas turbine considered in the optimisation paper and modern H-class equipment may allow for higher ramping and steam turbine heating rates than existing equipment. For example, Siemens' H-class SGT5-8000H allows for 500MW within 30 mins in a fast start mode (Siemens, 2019). In addition to advancements in the operation of gas turbine, steam turbines and heat recovery steam generators (HRSG) are also being developed with advanced fast-start capabilities to improve the speed within the steam cycle. Some of the potential improvements as identified by Siemen's Flex-Power services include starting the gas and steam turbine in parallel (co-start), modified pre-warming concept for faster cold starts and advanced HRSG design with the water-steam separation split into two stages.

CCGT integrated with post-combustion CCS plant has been investigated (Ceccarelli, et al., 2014) based on a CCGT with 350MW export capacity and 90% CO_2 abatement. The authors based their study on introducing flue gas to the amine absorber only once steam was available for heating the amine reboiler. Until reboiler steady operation is achieved (90 mins after gas turbine start), the CCGT was run un-abated, causing approximately 170 to 180 tons of unabated CO_2 to be emitted for the hot and cold starts, respectively.

The authors concluded that the amine system itself has a fast response to flue gas flow and concentration. However, the amine system depends on the availability of lean amine in the system, whether from the circulating lean solvent inventory or from the regenerator. The availability of lean amine is therefore key to reducing unabated CO_2 losses.

Dynamic simulations of the start-up of a coal-fired power plant with post-combustion amine carbon capture plant have been carried out (Marx-Schubach & Schmitz, 2018), investigating the impact of steam availability at different power plant generating rates. The authors found a significant increase from 30 mins to 184 mins for power plant export rates of 100% and 15%, respectively. The scenario in this study evaluated the introduction of flue gas into the absorber as soon as the packing was wetted without delaying until the regenerator reboiler reached operating temperature. The start-up time was therefore considered from the start of the boiler firing until steady-state 90% abatement was reached. The minimum allowable turndown of CCGT plants while maintaining NO_X compliance is between 30% and 50% depending on combustor technology (see Section 3.1.5), in comparison to 15% turndown for the coal plant studied. Therefore, the lack of steam would not be expected to be so substantial when starting a CCGT to minimum load than starting a coal plant to minimum load.

As well as reviewing the start-up process of CCGTs, previously papers mentioned also investigate the shut-down process. (Ceccarelli, et al., 2014) examines an example shut-down sequence based on the analysis of CCGT power plant operational data over 2011. Here the total length of the time for shut-down is approximately 22 minutes with both the steam and gas turbine simultaneously starting their separate unloading process. This duration is consistent with the work from (Mertens, et al., 2016), analysing the complete start-up and shut-down process of a CCGT plant where a time of approximately 30 minutes was found through modelling. In addition, recent trials of the Forutuna CCGT unit at Stadtwerke Düsseldorf Lausward site in Germany was able to achieve a shut-down of approximately 25 minutes using this simultaneous turbine shut-down technique (Modern Power Systems, 2016).

3.1.2 Start-up and shut-down costs

A unit commitment model was developed to forecast start-up costs of the thermal power plant mix in Germany (Schill, et al., 2016) under German Grid data for 2010, as well as forecasts for increasing renewables in 2020 and 2030. The authors found that CCGT starts rose by approximately 10% between 2010 and 2030. This rise has been attributed mainly to:

- A change in the forecast thermal portfolio with CCGT balancing a substantial part of renewables fluctuation (increasing number of starts)
- CCGT replacing outgoing nuclear, coal and lignite generation (increasing number of starts)
- Overall general increase in unit block size (decreasing number of starts)

The CCGT annual start-up costs were estimated at approximately €60,000 per 500MW block in 2010, rising to approximately €70,000 for a 500MW block in 2030. This rise is mainly driven by an increase in prices for fuel and CO_2 certificates. Over the same period, start-up costs for CCGT are expected to rise from 1.3% of total variable costs in 2010 to 1.7% in 2030. The annual start-up cost per 500MW block from 2010 would be equivalent to approximately £57,000 in 2019.

Note that the authors did not consider the real reduction in plant thermal efficiency at part-load. As a result, real plants shutting down completely rather than operating at part-load during some marginal demand periods may underestimate the cycling requirement. On the other hand, electricity import and export rates have been considered to be fixed between 2010 and 2030, while the impact of demand-side response has been ignored by the authors. Both could significantly overestimate the residual peak demand for CCGT.

Start-up costs have been considered as part of overall plant costs to calculate CCGT plant revenues in the day-ahead market (Hentschel, et al., 2016). A fuel price of 27.6€/MWh and CO_2 certificate price from 2014 of 5.42€/t were used as the input cost variables within this study. These figures for fuel price and CO_2 certificate price are equivalent to £23.7/MWh and £4.65/t respectively for 2019 prices. The authors separated start-ups costs into:

- Fuel consumption, CO_2 emissions and auxiliary supplies costs (direct start-up costs: 5€/ΔMW)
- Capital replacement costs and maintenance due to start-up (indirect start-up costs: 40€/ΔMW)
- Increment on forced outages (0.35h of outage on an averaged annual basis accrued per start)
- Capital replacement and maintenance related to load following (ramping costs: 0.5€/ΔMW)
- Cost of decreased operating thermal efficiency away from design point (efficiency costs: %-points/cycle)

The authors based their cost estimates on cycling cost data from (NREL, 2012). An estimation for the fuel consumption for a start-up and shut-down process for H-class configurations were presented in (LeighFisher Ltd., 2016). Table 2 presents the various fuel consumptions within this report, however only warm and hot starts were captured. These figures appear to be conservative and modern plant should require less time (and therefore fuel) to either start or stop.

Table 2. Average fuel consumption of a H-class CCGT for start-up and shut-down processes

Process	Fuel Consumption (GJ/MWe at base load)
Warm Start	5.30
Hot Start	3.65
Shut-down	2.28

Source: (LeighFisher Ltd., 2016)

3.1.3 Minimum up-time and down-time

Papers on CCGT up-time and down-time include (Schroder, et al., 2013), (Schill, et al., 2016) and (Gonzalez-Salazar, et al., 2018). The authors concur that up-time and down-time values are driven by economic decisions (e.g. to avoid unnecessary wear and tear) rather than some aspect of the physical plant. All three papers concur approximately 2 hours as an average minimum down-time value.

Minimum up-time is given by the sum of the start-up time, ramping period to dispatch and ramping down to shut-down, as estimated by (Gonzalez-Salazar, et al., 2018). The total minimum operating cycle time was estimated as 2 hours and approximately 4.7 hours approximately for warm and cold starts, respectively.

3.1.4 Ramp rates

The ramp rates for modern H-class CCGTs based on the specification of various manufacturers have been given in Table 3.

Table 3. H-class CCGT ramp rates

Manufacturer	Configuration	Installed power (MW)	Ramp rate (MW/min)	Reference
GE	1x1 9HA (SS)	661 – 838	65 – 88	(GE, 2019)
GE	2x1 9HA	1324 – 1680	120 – 140	(GE, 2019)
Siemens	1x1 9000HL (SS)	870	85 (GT ramp rate)	(Siemens, 2020)
Siemens	2x1 9000HL	1740	85 (GT ramp rate)	(Siemens, 2020)
MHPS	1x1 M701JAC (SS)	818	66 (GT ramp rate)	(MHPS, 2015)

Typical CCGTs currently in use have the ability to ramp up at a rate of 8%/min based on the findings of (Brasington, 2012). However, further review and prediction of future advances in ramp rates has been the subject of work by (Gonzalez-Salazar, et al., 2018). The authors estimated approximately 10(% of Full Load)/min as a future ramp rate for CCGT based on F-class technology which is consistent with the manufacturer data available for H-class in Table 3 above.

As investigated by (Ceccarelli, et al., 2014) and (Domenichini, et al., 2013), the ramp rate of CCGT with post-combustion CCUS is expected to be the same as unabated CCGT. Fast lean amine flow control can follow ramping flue gas rates. On the other hand, the corresponding change in steam demand in the reboiler is relatively slow, depending on rich amine loading. Thus, the power plant and absorber are fast-acting while the reboiler and steam extraction follow at some delay. Due to the delayed effect on steam flow, no effect is expected on the ramp rate capacity of the power plant itself – the amine plant response will lag behind any significant ramping event and catch up. It is worth noting that there will be a trade-off in overall generation when extracting steam away from the steam turbine cycle to the reboiler during the start-up. This has been considered by including steam extraction to the amine reboiler in the power plant mass balance.

Another paper considering dynamic simulation of CCGT with PCC investigated rapid, high-amplitude modulation of the steam extraction valve to attempt to closely couple the PCC plant to the CCGT (Rua, et al., 2020). The authors in that paper concluded that operating the PCC plant would not impose any restriction on the power plant being able to ramp its load rate. This is intuitive, however, the means by which the authors tested response on the integrated plant – rapid, high-amplitude modulation of the steam extraction valve – are not representative of how any real plant would be operated. Real plant would likely control steam extraction with feed-forward control or slow-acting feedback control (as acknowledged by the authors), or simply a look-up table with corresponding steam extraction settings, taking advantage of the significant inertia available in:

- Amine inventory, allowing gradual response from the stripper in response to rising loadings
- Thermal mass in the reboiler and stripper column inventories

These two sources of delay would allow the operator to respond slowly to varying demand for solvent regeneration while still closely meeting a flue gas specification. The model presented in this paper appears to instead be analogous to an improperly tuned controller attempting to respond quickly to a slow-acting system.

3.1.5 CO_2 capture rates and residual emissions

(Ceccarelli, et al., 2014) estimated approximately 170 and 185 tons of CO_2 emitted during start-up of their 350MW CCGT abated plant for hot and cold starts, respectively. Note that the difference in emissions was an artefact of the experimental set-up the authors selected for their study by considering two potential amine solvent loadings at start-up (0.4 mol/mol and 0.5 mol/mol for hot and cold starts, respectively). The higher initial solvent loading at cold start must be worked off to achieve the steady-state operational lean solvent loading (0.26 mol/mol), hence the increased start-up emissions. Real plants would normally be expected to over-strip their amine in the time preceding a shut-down and use the extra-lean amine to absorb residual emissions during planned shut-down to end with their desired lean amine loading. There should not normally be any reason for a plant to shut down and re-start with highly loaded amine inventory. The only exceptions to this would be following a process trip or emergency shut-down but those shut-downs would be relatively rapid and unlikely to cause significant build-up of CO_2 from residual fuel gas in the amine inventory.

CO_2 emissions during start-up are a function of the time taken for start-up and the total fuel consumed by the gas turbine. Clearly, improvements in either would decrease overall CO_2 emissions. Processes such as optimised start-up procedures (Nannarone & Klein, 2019) as discussed in Section 3.1.1 will have a proportional effect on CO_2 emissions.

All the main equipment manufacturers supply units that comply with the LCP BREF at steady-state operation. However, during start-up and shut-down, these limits do not apply and higher emissions are allowed. One review presented the start-up and shut-down emissions for power plant as factors of steady-state operation (Obaid, et al., 2017). This review considered 11 sources including applications for CCGT, OCGT, reciprocating engines and CHP. The authors then reported start-up and shut-down emissions as multiples of steady-state emissions, irrespective of the variable used in each source as summarised in Table 4.

Table 4. Normalised emissions as multiples of steady-state emissions (= 1) for power generating facilities

Contaminant	Start-up emissions	Shut-down emissions
NO_X	0.47 – 16.67	1.13 – 9.26
CO	2.08 – 158.85	3.09 – 51.85

Source: (Obaid, et al., 2017)

A more directly applicable review of NO_X and CO emissions during start-up considered an hourly integral approach with CCGT start-up and shut-down emissions to be measured in the stack (Macak, 2005). The authors then considered the implications of averaging these emissions out to overall quantities on a 24-hour average basis for a plant carrying out a single shift. Table 5 states the peak emissions found from this study for both NOx and CO contaminants measured in particles per million by volume (dry basis) (ppmvd) for a reference oxygen content within the fuel.

Table 5. CCGT peak emissions during start-up and shutdown

Contaminant	Start-up peak	Shut-down peak
NO_X	55 ppmvd @ 15% O_2	25 ppmvd @ 15% O_2
CO	250 ppmvd @ 15% O_2	125 ppmvd @ 15% O_2

Source: (Macak, 2005)

As the modern H-Class CCGT start time is rapid with some heat being available in the HRSG soon after ignition, SCR temperatures should also be achieved soon after start-up.

3.1.6 Minimum stable generation

The minimum generation compliant with emissions limits are given in Table 6 based on the specification from various CCGT manufacturers.

Table 6. H-class CCGT minimum generation rates compliant with emissions

Manufacturer	Model	Minimum turndown	Reference
GE	7HA.03	30% gas turbine	(GE, 2020)
GE	9HA	33% (1x1 configuration) 15% (2x1 configuration)	(GE, 2019)
Siemens	9000HL	50%	(Siemens, 2020)
MHPS	M701J	50%	(MHPS, 2015)
Ansaldo	GT36	30%	(Ansaldo, 2020)

A comparison between the minimum turndown for CCGTs with and without CCS was presented in (Domenichini, et al., 2013). To ensure a minimum environmental load for the combined-cycle of 40-50% (net power output), a minimum turndown of 30-40% GT load was stated in which aligns with the manufacturers data presented above. For the CCGT with CCS, the minimum load for the post-combustion unit is 30% with the CO_2 compressor limited to 70% turndown.

3.1.7 Gross and net thermal efficiency

A significant number of papers have researched and analysed the effect on the overall efficiency of the CCGT plant with and without CCUS. Findings from several papers identified that typical unabated CCGT plants have a net efficiency of approximately 55-58% while the inclusion of carbon capture within a CCGT plant results in a reduction in efficiency of 8-12% (Soltani, et al., 2017) (Fernandez, et al., 2014) (Amrollahi, et al., 2012).

The recent Cost and Performance Baseline for Fossil Energy Plants report compared the performance of different fossil fuel power plant with and without carbon capture (National Energy Technology Laboratory, 2019). The CCGT plant considered in this report had a multi-shaft configuration with two state-of-the-art 2017 F-class GTGs, two HRSGs, and one STG. Following thorough analysis, it was found that the unabated CCGT plant had a net efficiency of 59.4% (LHV basis) while the efficiency of the CCGT+CCUS plant decreased to 52.8%. These figures are consistent with the findings from (Wood, 2018) where the average efficiency for an unabated CCGT and a CCGT with CCS was 59.0% and 52.0% respectively. This provides a realistic performance indicator for the current available technology on the market.

The primary cause of this efficiency reduction was the additional energy required for solvent regeneration, followed by CO_2 compression and other auxiliary energy consumption (Linnenberg, et al., 2012). Using simulations developed within the ASPEN RateSep framework, the solvent regeneration energy of MEA (with a lean amine load of 0.22mol/mol) represented approximately 60% of the additional energy consumption for the capture process (Kothandaraman, et al., 2009).

Along with the loss of generation due to steam extraction directly impacting the plant's performance, the efficiency is also affected indirectly through the loss of generation. As steam is required during the capture process, there is reduction in the power output from the plant's steam cycle which has a negative effect on the plant's thermal efficiency. This can be seen from the NETL results as the steam turbine power output reduces by 50MWe, resulting in a reduction of 7% to the total net power output.

3.2 Flexible operation of post-combustion CCS

To consider ways to improve the flexibility of a CCGT with post-combustion CCS, the following criteria must be the primary considerations of the configuration options in this study:

- Ability to improve on the start-up times of standard CCGT+CCS power plants
- Engineering and cost challenges associated involved in either newly-built such facilities or retrofitting standard CCGT+CCS are feasible

Most research investigating the flexibility of carbon capture technologies for fossil-fuelled power plants focus on the economics and costs associated with operating the plant, benefiting from the variable electricity price pattern. Research relating to the duration of start-up and shutdown of these plants, however, is limited.

A paper written in 2004 first mentioned the premise of using solvent storage as a possible method to develop a flexible power plant with CCS (Gibbins & Crane, 2004). It was found this configuration has the potential to save 6-7% in electricity costs during the plant's operation. Another paper demonstrated that incorporating solvent storage could save approximately 5.07% of the operating costs compared to the reference case using a capture plant simulated using the software g-PROMS (Zaman & Lee, 2015). This figure is dependent on the solvent storage capacity of the selected tank. More recent research concluded that this method of flexibility, along with exhaust gas venting, could result in an increased profit of 0-35% depending on the regenerator design and solvent storage capacity (Oates, et al., 2014). Although the exhaust gas venting or bypass option repeatedly appears within the literature for CCS flexibility, this option is only economically viable depending on how the electricity price fluctuates and how stringent the future carbon intensity policy is (MacDowell & Shah, 2014) (Spitz, et al., 2019). This is also concluded by (Chalmers, et al., 2009) which states that solvent storage methods are a useful method when strict emission regulations are imposed. From these papers, using additional solvent storage has been identified as a viable and effective option in both flexibility scenarios from a cost and timesaving viewpoint, especially when the cost of emitting increases.

The Shell dynamic simulation study (Ceccarelli, et al., 2014) (also reviewed in Section 3.1.1) considered improving start-up times. One of the improvement options included an auxiliary boiler to supply steam sooner than would be available from the steam cycle. The authors considered that the use of an auxiliary boiler would provide steam for the CCS plant approximately 30 minutes earlier than would be available from the steam turbine, thus reducing typical start-up CO_2 emissions from 180 tons to 110 tons per cold start. Note that the authors made no attempt to calculate or mitigate the emissions from the auxiliary boiler during this period.

Models of flexible operation of CCGT with amine CCS have been presented by (Mechleri, et al., 2017). The authors considered an MEA-based capture process with three possible approaches for improved flexible operation with respect to simply load-following CCGT based on Siemens SGT5-4000F with 90% abatement. Note that the system examined by the authors appears to be a non-standard 1 x 3 arrangement with 1 gas turbine feeding into 3 steam turbines (net generating capacity of 421 MWe unabated, 395 MWe abated). The flexibility improvement approaches were:

- Online solvent storage for both lean and rich amine to balance variable regeneration rates (reduced during peak electricity price periods)
- Partial venting of exhaust gas during peak electricity prices (21% of gas flow) with subsequent increased capture to provide 90% time-averaged capture over 24 hours
- Variable solvent regeneration, allowing CO_2 to accumulate in the solvent during peak electricity price hours (with increased lean amine loading) followed by off-peak increased regeneration duty

The above flexibility approaches were considered specifically for their potential to maximise plant short run marginal cost as would be the dominant financial decision-making process during a substantial fraction of any plant operating life. The authors briefly mentioned shut-down in terms of a financial decision as part of the short run marginal cost decision but did not review the amine unit performance characteristics during start-up or shut-down.

(Marx-Schubach & Schmitz, 2018) examined improving the dynamic start-up performance of the amine CCS process. The authors assembled a dynamic simulation which was validated against a pilot plant in Heilbronn, Germany. Their simulation considered the impact of varying solvent flowrate at start-up in order to minimise start-up time and found two counter-acting processes:

- Minimising solvent inventory in the stripper during start-up allows the start-up time to be reduced as less mass must be heated to achieve boil-up in the reboiler
- Maximising solvent inventory during start-up allows the absorber to capture more CO_2 while the stripper is starting up and therefore maximum treatment capacity

The validation step of this paper showed a close match to the experimental data for the dynamic behaviour of the process. However, a significant over-estimate of the actual absorption rate was seen for the model: the pilot plant experienced a minimum instantaneous absorption of approximately 27% before recovering once the regenerator started while the simulation predicted a minimum of 40%. The authors attributed the error to the use of simplified equilibrium modelling for the absorber and stripper as well as potential for faulty instrument readings in the pilot plant during start-up. A minor drawback of the use of solvent storage was also identified within this paper regarding the need for additional solvent regeneration after the initial start-up for the next one. This is a factor that should be considered in estimating the associated costs to gain a more realistic value for the real-life plant operation.

Another option for optimising the start-up and shut-down performance of the CCS plant would be to store heat while the plant is offline. The heat could then be drawn down for instant heat at start-up, without waiting for steam from the steam turbine. Thermal energy storage has been reviewed in general (Sarbu & Sebarchievici, 2018) (Delta Energy & Environment Ltd, 2016). The full start-up energy and temperature requirements in the stripper would not be met by a hot water storage approach (storing at 95°C) due to the high reboiler temperature requirement of 120-130°C. One alternative method for storing heat could be to store hot regenerated amine in a dedicated insulated tank which can be supplied to the stripper at start-up, removing the requirement to heat from ambient. This technique would only be effective in a short shutdown scenario though unless supplementary electrical heating was also included.

The temperature requirement for reaching the stripper operating temperature could be met by hot oil storage. Another aim of this study is to consider the size of hot oil storage required for delivering the required quantity of heat (potentially on the order of 326GJ) based on a comparable 875MW coal power plant as determined by (Marx-Schubach & Schmitz, 2018).

3.3 Amine choice selection

MEA was chosen as the solvent for this study given the breadth of literature available for benchmarking. Particularly worth noting is an open-access FEED study written by Bechtel for Karsto (Bechtel, 2009). This study has been based on 30wt% MEA, published by the UKCCSRC in redacted form following the expiry of confidentiality agreements. It is noted that Bechtel do not appear to have optimised for maximum capture or flexible operation but it presents the most complete set of real engineering design data in the open domain for post-combustion capture with amine.

3.4 Steam cycle performance

Modern developments in achieving fast start of CCGT have been targeted at improving the flexibility of the steam cycle, given the gas turbine response rate in simple cycle appears to be fast enough to meet any requirement posed. Steam cycle improvements to reduce start times include:

- Operational procedures such as carrying the combustion path purge at shut-down instead of start-up (supported by positive isolation of the fuel gas line to ensure no leakage)
- Feedback control and automatic adjustment of the gas turbine inlet guide vanes at start-up

- Once-through high-pressure boiler technology such as the Cottam Benson Boiler equipment, allowing supercritical steam through the boiler and significantly increased allowable start-up steam cycle warm-up rates

Fast steam cycle starting technologies have the potential to impose extra fatigue on the steam cycle, with the connection between the high-pressure drum and its steam riser being the component at most risk of failure (Foster Wheeler America, 2013). The same report also proposed advanced plant controls to mitigate the impact on component life. Another report by VPI (VPI, 2010) proposed a full inspection and monitoring program based on condition modelling for fast starting and cycling CCGT. Sufficient measures to mitigate any impact on steam cycle lifetime are therefore expected to be available to rule the net penalty in plant life for fast starting negligible.

The benefits of this technology would allow:

- Reduced lag time to approximately 40% of base case for both cold and hot starts, as indicated possible for starting best-in-class fast-starting boilers[1].
- Increased steam availability, taking credit for steam extraction for the PCC plant being prioritised and therefore full steam extraction being available immediately following lag time.

Given that overall project cost implications for installing fast starting steam cycles should be negligible and the significant potential reduction on start times, this option was evaluated as one of the improvement configuration variants.

This option would require a vertical HRSG as opposed to the more normal horizontal arrangement considered for flue gas extraction which will have a non-negligible effect on the ducting for the flue gas.

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Appendix B – Basis of Design

Imagine it.
Delivered.

Start-up and Shut-down times of power CCUS facilities

Basis of Design

Department for Business, Energy & Industrial Strategy

1 April 2020

Quality information

Prepared by	Checked by	Verified by	Approved by
Jamie Calvert Graduate Engineer	Klim MacKenzie Senior Process Engineer	Andy Cross Project Manager	David Hope Technical Director, Power & Energy

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Prepared for:

The Department for Business, Energy & Industrial Strategy

Prepared by:

Jamie Calvert
Graduate Engineer

AECOM Limited
3rd Floor, Portwall Place
Portwall Lane
Bristol BS1 6NA
United Kingdom

T: +44 117 901 7000
aecom.com

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1. Introduction

1.1 Purpose

This document is a high-level Basis of Design for the base configuration of a modern Closed Cycle Gas Turbine (CCGT) power plant with and without standard post-combustion carbon capture (PCC) to provide reference performance definitions required for Engineering Modelling work to be undertaken. The performance of the base configuration during the transient period of the plant's operation (i.e. start-up, shut-down and ramping) will be compared later against different potential PCC improvement configurations.

1.2 Scope

The chosen configuration of the standard unabated CCGT plant has the following characteristics:

- Gas inlet to the two Combined Cycle Gas Turbine (CCGT) trains of Siemens SGT5-9000HL for an unabated export capacity of approximately 1,740MW at International Standards Organisation (ISO) conditions. 9000HL units have been used for the calculations carried out in this study as a typical example of modern H-Class CCGT. However, suitable design margins were added in the concept design work (notably for the carbon capture plant) to ensure a technology-neutral basis for the prime mover;
- Two (1 x 1) CCGT H-Class trains – Estimated capacity of approximately 1,672 MW at site conditions (at the generator terminals), each consisting of:
  - 1 Gas Turbines (GT) - Nominal capacity approximately 593 MW at ISO conditions;
  - 1 Heat Recovery Steam Generators (HSRG), configured as 3-pressure cycle with reheat and flue gas ducting connection to enable Post-Combustion Capture (PCC), horizontal layout to enable ducting connection;
  - 1 Steam Turbine (ST) - Nominal capacity approximately 277 MW at ISO conditions, condensing;
- Flue gas treatment, with Selective Catalytic Reduction (SCR), for NO_x removal.

Addition of 95% PCC to each train of CCGT plant reduces the export capacity to approximately 1.4GW total. Additional equipment comprises:

- Axial fan blowers to overcome pressure losses through the gas treatment path (approximately 90mbar);
- Direct Contact Cooler (DCC) circulating caustic solution for capturing residual contaminants (mainly NO_x and residual SO_2) and cooling the flue gas for absorption;
- 35wt% MEA-based CO_2 capture system to reduce plant total CO_2 emissions during steady-state operation by 95%, comprising:
  - Absorber with water wash section for entrained amine removal;
  - Regenerator operating at approximately 2.2bara and 125°C to regenerate amine from 0.45mol/mol loading to 0.25mol/mol as a semi-optimised loading profile for energy efficiency;
  - Amine rich/lean cross-exchanger of plate-and-frame type;
  - Circulating amine and water pumps;
  - Heat exchangers for heat rejection to site cooling water circuit;
  - Site cooling water circuit along with heat rejection method (mechanical draft cooling towers, shared with the power plant);
  - Lean amine storage tank for draining during shut-down;
  - CO_2 compression and dehydration train for export at 150bara;

1 x 1 configuration was selected for the CCGT over 2 x 1 mainly due to alignment with the European market and previous work in the Energy Technologies Institute (ETI) Generic Business Case study[1]. Reference information

[1] Thermal Power with CCS; ETI; 2017; https://www.eti.co.uk/programmes/carbon-capture-storage/thermal-power-with-ccs

was more readily available in the Literature Review to compare performance for 1 x 1 over 2 x 1, particularly with open-art MEA-based PCC. In addition, some small benefits have been noted for:

- improved efficiency of 0.05-0.1% for 1x1;
- Higher overall output capacity by approximately 0.08% at base load;
- Lower auxiliary power consumption

Selective Catalytic Reduction (SCR) was included in all designs to reduce NO_x by 90% as SCR is now common on modern H-Class CCGT to meet emissions performance guarantees in normal operation.

Ancillary equipment such as the reclaiming unit and the amine make-up rate are to be calculated as nominal flows but are not expected to have an effect on the start-up or shut-down operation of the process.

2. Abbreviations

The following abbreviations have been used within this document.

Abbreviation	Description
CCGT	Combined Cycle Gas Turbine (Gas Turbine + Steam Turbine)
CCS	Carbon Capture and Storage
CWS	Cooling Water Supply
CWR	Cooling Water Return
DCC	Direct Contact Condenser
GW	Giga watts
GT	Gas Turbine
HHV	Higher Heating Value
HSRG	Heat Recovery Steam Generator
LHV	Lower Heating Value
mbar	Millibar
MW	Mega watts
PCC	Post-combustion Carbon Capture
ppmv	Parts per million by volume
Ppmvd	Parts per million by volume, dry basis (i.e. excluding diluting contribution of water molecules)
RH	Relative Humidity
SCR	Selective Catalytic Reduction
ST	Steam Turbine
WN	Wobbe Number

3. Design Conditions

3.1 Plant Location and Site Condition

The site is assumed to be a coastal, greenfield location situated in the North East of England and will be assumed to be obstruction free, both under and above ground, without the need for any special civil works. The altitude of the site is assumed to be 10m above sea level.

3.2 Plant Operating Conditions

The following ambient conditions marked (*) shall be considered reference conditions for the plant performance modelling.

Table 1. Ambient conditions for chosen site location

Ambient Condition	Value
Atmospheric Pressure, mbar	1013 (*)
Relative Humidity, %	80 (average) (*) 100 (maximum) 10 (minimum)
Ambient Temperatures, °C	9 (average) (*) 30 (maximum) -10 (minimum)

Source: Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology – Basis of Design

3.3 Carbon Dioxide Capture Rate

For the carbon dioxide abated case, the target carbon capture level within the normal operation envelope for this facility will be at least 95%, defined as:

$$CO_2\ Capture\ Rate\ (\%) = \frac{100 \times (Mass\ of\ CO_2\ in\ flue\ gas\ exiting\ HRSG - Mass\ of\ CO_2\ from\ absorber\ to\ stack)}{Mass\ of\ CO_2\ in\ flue\ gas\ exiting\ HRSG}$$

This capture rate is to be on a steady-state operation basis. The purpose of this study is to consider the capture rate (according to the formula above) during start-up and shut-down operations.

3.4 Feedstock and Utility Specifications

The streams available at the plant battery limits are the following:

- High pressure natural gas
- Cooling and plant make-up water
- Carbon dioxide product

3.4.1 Natural Gas

The fuel gas composition, shown in Table 2, has been used within the engineering model for natural gas, which meets the UK National Grid Gas specification, shown in Table 3.

Table 2. Natural Gas Composition

Constituent	% Volume (4 significant figures)
Nitrogen, N_2	0.8887
Carbon Dioxide, CO_2	1.997
Methane, CH_4	88.87
Ethane, C_2H_6	6.989
Propane, C_3H_8	0.9985
N-Butane, C_4H_{10}	0.09985
N-Pentane, C_5H_{12}	0.009985
Hydrogen, H_2	0.1495
Oxygen, O_2	0.001315
Hydrogen Sulphide, H_2S	7.837×10^{-5}

Source: BEIS CCUS Start-up times Fuel Gas Composition Calculation

Table 3. National Grid Specification with value used within the model

Characteristic	UK National Grid	Value Used
H2S Content	Not more than 5 mg/m^3	3 ppm (molar)
Total Sulphur Content	Not more than 50 mg/m^3	40 mg/m^3
Hydrogen Content	Not more than 0.1% (molar)	0.1% (molar)
Oxygen Content	Not more than 0.001% (molar)	0.001% (molar)
Hydrocarbon Dewpoint	Not more than -2°C, at any pressure up to 85 bar(g)	<-2°C
Water Dewpoint	Not more than -10°C, at 85 bar(g) (or the actual delivery pressure)	<-10°C
Supply Temperature	Between 1°C and 38°C	9.0°C
Supply Pressure	Not specified	70.0 bar(a)
Volumetric Lower Heating value (LHV), @ 25°C	Not specified	34.22 MJ/m^3
Volumetric Higher Heating Value (HHV), @ 25°C	Between 36.9 MJ/m^3 and 42.3 MJ/m^3 (at standard temperature and pressure)	37.88 MJ/m^3
Total LHV + Sensible Heat @ 9°C	Not specified	46.49 MJ/kg
Wobbe Index	Between 48.14 MJ/m^3 and 51.41 MJ/m^3 (at standard temperature and pressure)	48.86 MJ/m^3
Contaminants	Gas shall not contain solid or liquid material which may interfere with the integrity or operation of pipes or any gas appliance within the meaning of the Regulation 2(1) of the Gas Safety (Use of) Regulations 1998 that a consumer could reasonably be expected to operate.	

Source: Gas Safety (Management) Regulations 1996, Schedule 3, Part I; Values used based on Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology – Basis of Design

3.4.2 Cooling water

Heat rejection for the combined power plant and CCS plant will, as a default, be provided through mechanical draft wet cooling towers. Dry air condensers were considered and represent a more conservative option for the cooling demand, as well as posing lower net water consumption. However, dry air condensers would impose a significant efficiency penalty in summer conditions on the steam cycle operation. Therefore, mechanical draft cooling towers (wet or hybrid type) are more appropriate for the power plant. It is sensible to combine the overall site cooling requirements into one overall heat rejection system. Thus, the CCS plant will add a cooling load on the towers in addition to the power plant. The design conditions of the mechanical draught wet cooling towers are shown in Table 4.

Table 4. Plant cooling water conditions

Cooling Water Condition	Value
Approach Temperature, ºC	7
Cooling Water Supply (CWS), ºC	14
Temperature Rise, ºC	11

Source: Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology – Basis of Design

3.4.3 Carbon Dioxide Product Quality

CO_2 product specification at the pipeline entrance taken as a conservative estimate of other open literature data:

Table 5. CO_2 product specification

CO_2 product specification	Value	Comments
Pressure	150bar	Conservative estimate, Peterhead was only 120bar
Temperature	25°C	
Flowrate	Approximately 5400t/d	To be confirmed by this study
Water	≤50 ppmv	
Oxygen	≤5ppmv	
Volatile components	≤0.6%vol	
Hydrogen	≤0.3%vol	

Source: Peterhead CCS project

3.5 Environmental Emission Basis

The overall gaseous basis and unabated reduction effectiveness for this study is presented in Table 6 for nitrogen oxide (NOx) and carbon monoxide (CO) emissions.

Table 6. Emission parameters for CCGT plant

Emission Parameter	Value
NOx Produced, ppmvd @ 15% O_2 content	25
NOx Reduction Effectiveness, %	90
CO Produced, ppmvd @ 15% O_2 content	10

Source: H-Class High Performance Siemens Gas Turbine SGT-8000H series (2011)

The values stated in Table 6 relate to the emissions produced after the power plant has successfully completed the start-up process and the plant is running at normal operation.

3.6 CCS Plant Design (see simplified PFD)

To gain a detailed insight of the start-up and shut-down process, key snapshots of the different steady-state stages during each process will be simulated using the model. The key equipment design parameters are required as inputs within the CCS model and these are defined in the subsequent sections along with the outline of both the start-up and shut-down processes. The design point for the net CO_2 absorption rate for the CCS model will be 95wt%.

3.6.1 Flue Gas and Blower Design Basis

The design parameters for the flue gas entering the CCS plant and the required blower are presented in Table 7 with the value for abated flue gas target temperature defined to ensure adequate buoyancy of the gas.

Table 7. Flue gas and boiler parameters

Design Parameter	Value
Flue Gas Temperature from HRSG to Gas-gas Exchanger, °C	80 (tbc)
Gas-gas Exchanger Temperature Approach, °C	20
Abated Flue Gas Target Temperature, °C	60 (tbc)
Blower Pressure Rise, mbar	90 (tbc)

3.6.2 Solvent Design Basis

In line with typical MEA operating parameters, it is proposed to set the amine CCS plant parameters according to Table 8.

Table 8. CCS solvent parameters

Solvent Parameter	Value
MEA Concentration, wt %	30
Lean Loading, mol/mol	0.2
Rich Loading, mol/mol	0.45-0.5 (tbc)

Energy requirements for solvent regeneration and energy release during absorption to be calculated by rate-based kinetic equations from the rigorous Mass + Transfer column model in ProMax.

3.6.3 Absorber Design Basis

Table 9 defines the design parameters relating to the absorber and the typical column values. The temperature of the flue gas from the direct contact condenser (DCC) to the absorber is defined by the saturation temperature to keep water balance neutral within the DCC. A margin of 8°C has been applied to the lean amine temperature to prevent condensation or fogging from the saturated vapour contacting the cooler amine.

Table 9. Absorber temperature and column parameters

Absorber Parameter	Value
Flue Gas Temperature from DCC to Absorber, °C	35 (tbc)
Lean Amine Temperature to Absorber, °C	43 (tbc)
Intercooler Temperature Approach to CWS, °C	5*
Flood, %	80
Structured Packing	Sulzer Mellapak® 250.Y metal
System Factor	0.8

**Note – intercooler requirement to be confirmed during simulation from actual absorber temperature bulge.*

A water wash section is provided in the top packed section to reduce emissions of amine in flue gas and therefore to air. This system is to be set as a circulating flow which would be determined experimentally (outside scope of project) to maintain emissions to air (mainly ammonia) within limits. Nominal flowrate to be set for this study to meet the water top up requirements and recover entrained amine, to be calculated by the make-up blocks in ProMax.

Structured packing is necessary in the absorber for minimum vapour-side pressure drop, thus allowing minimum column diameter. Trays are not a practical option for the absorber (aside from the difficulties of manufacturing large-diameter trays).

3.6.4 Stripper Design Basis

The design parameters of the stripper are presented in Table 10, with the reboiler operating temperature to be determined from the modelling simulation. After this value has been determined the rich amine temperature can be defined, as this is approximately 2°C below the reboiler operating temperature.

Table 10. Stripper temperature and column parameters

Stripper Parameter	Value
Rich Amine approach temperature in cross-exchanger, °C	5°C
Reboiler Operating Temperature, °C	125
Operating Pressure, bara	2.2
Flood, %	80
Packing type	Intalox 50X
System Factor	0.8

For this study, lean vapour recompression or any other proprietary energy efficiency improvements will not be considered as they are deemed to be outside of this scope of work.

Intalox saddles of 50mm size have been specified as a typical low pressure drop solution which allows for a minimum column diameter over trays.

3.6.5 Exchangers design basis

The outline heat exchanger specifications will be based on the values presented in Table 11 for the various types. The values stated offer an optimistic design for the shell-and-tube and plate-and-frame heat exchanger types.

Table 11. Heat exchanger specification parameters

Heat Exchanger Parameter	Value
F_t correction factor	>0.8
Temperature Approach for Shell-and-tube Type, °C,	5
Temperature Approach for Plate-and-frame Type, °C	2

3.6.6 Pumps design basis

Pump duty to be estimated based on shaft work required with corrections for efficiencies. Mechanical efficiencies to be used are: 0.8 for large amine pumps, 0.75 for small pumps. In addition, all pumps will apply 0.99 electrical efficiency.

3.6.7 Compressor design basis

The design parameters for the compressor are presented in Table 12, with the number of stages and corresponding average pressure ratio to be confirmed later.

Table 12. Compressor parameters

Compressor Parameter	Value
Export Pressure, bar	150
Number of Centrifugal Stages	8 (tbc)
Average Pressure Ratio	1.8 (tbc)

The use of two (2) trains at 50% may be necessary due to the high flow rate through the compressor. This arrangement would be more suitable for operating efficiently at part-load than operating one (1) train at 100%. However, as compressors are not expected to be one of the limiting steps in flexible plant operation, mechanical compressor specification will not be carried out in this study.

3.6.8 Reclaimer design basis

Reclaiming for MEA carried out on-line with a slip-stream of lean amine from the stripper bottoms. The reclaiming process rate will be experimentally derived, nominally set to approximately 2% of total lean amine stream mass flow based on typical values recommended by reclaiming vendors. Of the 2% processed in the reclaimer, at least 95% is expected to be recovered back into lean amine. Therefore, the fresh amine make-up rate is approximately 0.1% of the total lean amine circulating flowrate. This flow has been set as a high-level figure to include both degradation and other amine losses, given that reclaimer operation would not be expected to be required at start-up or shut-down.

3.7 CCS Plant Snapshots

The process of both start-up and shut-down of the CCS plant have been broken down into the key events with the timings and flowrate data defined. This helps to separate the transient profile into smaller periods to focus on during further analysis. The following subsections present a summary of the snapshots identified for both the start-up and shut-down process.

3.7.1 CCS Plant Start-up Snapshots

The start-up procedure for the CCGT with post-combustion CCS can be separated into five key stages which are presented in Table 13.

The process is initiated after receiving a notice to synchronise from the ESO (Snapshot Number 0). Assuming the various checks are performed on the power plant to ensure the GT and ST's auxiliary systems are operational and release criteria are satisfied, the auxiliary motor is switched on to begin to drive the GT shaft. This allows ambient air to vent through the HRSG to remove any residual combustible gases if not already done in the previous shut-down process.

The next stage is initiated when ignition is triggered, resulting in the first firing of the GT (Snapshot Number 1). This is achieved by opening the fuel stop valve of the combustion chamber while the starting motor increases the GT shaft speed further to approximately 1,600rpm. Within the ST, the high and medium-pressure bypass valves open when ignition occurs to ensure that is a suitable pressure gradient in the high-pressure circuit. Internal temperatures within the ST and HRSG will gradually increase which is important to limit the thermal stresses throughout the process. The motor is then disconnected to allow the GT to reach the synchronisation speed of the grid and is now producing net mechanical power. The GT is ramped up at a specified constant rate to 50% of its full load after the minimum operating pressure has been reached and held at these conditions (Snapshot Number 2).

At this point in the process, the HRSG will have warmed sufficiently, reached the minimum operating pressure and have stabilised drum levels. Once the required steam parameters are met with the first high pressure steam admitted to the ST, the ST begins to start and ramps up to full speed to synchronise with the grid. A significant period in the start-up process is then required to increase the ST load and to allow all the available steam to be routed through the ST following the bypass valves closing. Once the steam conditions at crossover between the intermediate and low-pressure turbines are sufficient, the steam can be extracted and used for the solvent regeneration needs in the PCC process (Snapshot Number 3).

The final stage of the start-up process is to increase the load of the entire plant to full capacity (Snapshot Number 4). This represents the performance of the power plant at its design baseload conditions with the entire start-up process taking 30 and 200 minutes for hot co-starts and cold starts respectively.

Flue gas flowrates to be determined by calculation for the off-design flow cases from the power plant model if not already given, and specific start-up times to be confirmed. The start-up times provided in the table below are used as a reference based on current CCGT technologies available, for instance fast hot co-start technologies.

Table 13. Snapshots of flue gas flowrate to CCS plant during start-up, starting at time = 0

Description	Snapshot No.	Time for hot / cold start, min	Flowrate, kg/s
Notice to synch, start-up sweep	0 (initial)	0	Nil
First firing, NSNL	1	5 / 15	Minimum turndown
Ramping up, 50% full load	2	20 / 25	To be determined by model
Steam export	3	25 / 100	To be determined by model
Full load	4	30 / 200	1000 kg/s

Source: Gas Turbines: A handbook of air, land and sea applications (2nd Ed., 2014) – C. Soares; Strategies for Integration of Advanced Gas and Steam Turbines in Power Generation Application – J. Zachary

3.7.2 CCS Plant Shut-down Snapshots

As with the start-up process, the shut-down sequence can be separated into five key stages with a number of steady-state snapshots identified.

The shut-down of the plant is initiated following the order from the control centre while the plant is operating at full load (Snapshot Number 4). After this, both the GT and ST begin to ramp-down and reduce their load simultaneously. As the combined-cycle load reaches approximately 30% of its full load, the load of the GT and ST is briefly held at a constant value (Snapshot Number 5). At this point the steam conditions are assumed to be no longer sufficient for extraction to the CCS process and the steam is stopped from flowing to the reboiler.

Following this stage of the plant's shut-down process, the ST completes the remainder of its shut-down by reducing its load to zero (Snapshot Number 6). This is achieved by the main steam valves rapidly closing to disconnect the HRSG and ST while the excess steam is discharged through bypass valves. This excess steam can be used within the PCC plant to continue some solvent regeneration once the steam turbine is no longer available and maintain lean solvent loading for the next start-up.

After the load of the ST is reduced completely and the ST is decoupled, the GT completes the remainder of its shut-down. The ST bypass valves are closed to ensure a fixed standby pressure is maintained. The decoupling of the ST means that the speed of ST gradually reduces until being recoupled back to the GT shaft just after the plant load is zero. After approximately 10 minutes of steadily ramping down the GT, the load of the GT is held at 5% of its full load to allow the power generator to split from the system (Snapshot Number 7).

The remaining time of the shut-down process is to remove the final load from the plant and to decouple the GT shaft, allowing its speed and temperature to reduce gradually. After the load of the plant is zero, the shut-down process is complete (Snapshot Number 8).

As with the start-up process, the flue gas flowrates will be determined by the power plant model, with the specific shut-down times to be confirmed. These times are taken from the available knowledge of the process breakdown for a typical shut-down of current CCGTs used today.

Table 14. Snapshots of flue gas flowrate to CCS plant during shut-down, starting at time = 0

Description	Snapshot No.	Time for shut-down, min	Flowrate, kg/s
Initiate unit shutdown at full load	4 (initial)	0	1000 kg/s
Ramping down, 30% full load	5	5	To be determined by model
ST complete shutdown	6	15	To be determined by model
GT load hold, 5% full load	7	30	To be determined by model
No plant load	8	45	Nil

3.8 Improvement configurations

3.8.1 Option 1 – amine storage (see simplified PFD)

Volume of amine inventory in the absorber system to be determined from sum of (see simplified PFD):

$$Column\ sump\ inventory + margin\ for\ piping\ and\ equipment\ + amine\ tank\ volume = Absorber\ system\ inventory$$

The margin for piping and equipment has been taken conservatively as 2% of the column sump volume to account for the small yet non-negligible effect of hold-up volume. A greater margin would increase the effective available solvent inventory for buffering CO_2 and therefore maintaining a minimum quantity of estimated margin presents a conservative design basis.

The column sump volume has been estimated based on an estimate of 5 minutes residence time at full solvent flow in the sump for process safety time. Preliminary estimates for the solvent flowrate are based on the CCS plant capture design basis of 95% capture of approximately 6,000 t/d (as a steady-state operating rate) and a mass ratio of 20:1 rich solvent stream total mass flow: CO_2 mass flow in incoming flue gas stream. The final flows are to be calculated from the ProMax flowsheet.

$$95\%\ capture\ of\ total\ CO_2\ mass\ flow = 95\% \times \frac{6000t\ CO_2\ from\ CCGT}{d} \approx\ 5700\frac{t}{d}\ , or, 240\frac{t}{hr}$$

$$\frac{rich\ stream\ mass\ flow}{captured\ CO_2} = \frac{20}{1}, rich\ stream\ mass\ flow = 240 \times 20 = 4800\frac{t}{hr},$$

Approximately 4,800 t/hr represents the total flowrate of the rich stream including amine, water and absorbed CO_2. The actual process flow of circulating lean amine used in the design was 1500kg/s or 5400t/hr. The value of the rich stream will be used to calculate the volume of hold-up with a density of approximately 1,099kg/m³ (35% MEA loaded with 0.45 mol/mol CO_2), giving:

$$5400\frac{t}{hr} \times\ 5\ min\ residence\ time\ \times \frac{1}{1.099\frac{t}{m^3}} \approx 409\ m^3$$

The absorber flow cross-sectional area and therefore the level in the sump will be determined from the column sizing following the ProMax simulation to confirm 5 minutes hold up represents a reasonable estimate for the sump level.

The required amine tank volume is to be determined from the required extra inventory volume to continue 95% absorption during start-up and shut-down transients without exceeding the maximum rich amine loading allowed by the vapour-liquid equilibrium. The volume of the amine storage tank supplied as part of normal operation is not considered in this calculation as the normal amine storage tank is designed only for slow top-up of amine losses in the system with nominal volume and pumping rates.

3.8.1.1 Calculating required solvent volume

Solvent required inventory given as the sum of the integrals under the capture graph during start-up and shut-down events. During each snapshot, emissions rate from CCGT is taken as fixed. The rates are conservatively set as:

- Final, maximum emissions at the end of each snapshot for start-up, taking no credit for lower emissions at the start of every interval or ramping up through,

- Initial, maximum emissions at the start of each snapshot for shut-down.

The mass of CO_2 to be captured during any one snapshot during either start-up or shut-down is therefore simplified to the flue gas (and CO_2 concentration) rate into the CCS plant, multiplied by the duration of the snapshot. The total start-up or shut-down transient CO_2 to be absorbed is then given by the sum of each integral.

In addition, the following simplifying assumptions are necessary:

- Absorber intercooling through the cooling water system is available to maintain the temperature profile in the absorber during the transients. This assumption is to be tested by calculating the maximum heat rejection rate required from the absorber and determining whether the heat rejection exceeds the normal operating capacity of the intercooler.
- Circulation pumps can deliver the required rate of amine to the absorber without delay for each snapshot.
- Amine loading starts at the lean loading and incrementally rises during each snapshot by the absorbed CO_2 quantity during the snapshot, determining the settle-out amine loading.

3.8.2 Option 2 – heat storage (see simplified PFD)

3.8.2.1 Stripper system column and fittings mass calculation

The stripper column preliminary wall thickness will be calculated based on the stress imposed by a full internal vacuum during steam out, which is normally greater than would have been required for the maximum allowable internal working pressure. The thickness will be calculated according to:

$$P_c = 2E_Y\left(\frac{t}{D_0}\right)^3, where:$$

$$P_C = buckling\ pressure, MPa$$

$$D_0 = external\ diameter\ (to\ be\ determined), m$$

$$t = wall\ thickness, m$$

$$E_y = Young's\ modulus, MPa$$

The total approximate mass of the steel column and fittings will then be calculated based on the volume for a thin-walled cylinder, given by the annular area multiplied by the column height:

$$Volume = Area \times height$$

$$Area = \pi \times (R^2 - r^2):$$

In addition to the preliminary weight for the steel vessel, above, the mass of amine in the stripper system will be taken as 30 minutes of process time and mass calculated as for the absorber. In addition, 2% margin will be applied for both amine and steel to account for other fittings in the system.

3.8.2.2 Estimating reboiler start-up heat requirement and time

The total energy input, Q, required to the reboiler for achieving stripping is given by:

$$Q = \left(m_m C_{P,m} + m_a C_{P,a}\right)\Delta T, where:$$

$$m_m = mass\ of\ metal, kg$$

$$C_{P,m} = Specific\ heat\ capacity\ of\ metal, \frac{kJ}{kg}.K$$

$$m_a = mass\ of\ amine, kg$$

$$C_{P,a} = Specific\ heat\ capacity\ of\ amine, \frac{kJ}{kg}.K$$

$$\Delta T = temperature\ difference\ from\ ambient\ to\ minimum\ reboiler\ operation, K$$

The minimum reboiler operating temperature is to be determined from the ProMax flowsheet as the condition for minimum stable stripping. Initially, this is conservatively set as the normal reboiler operating temperature of approximately 126°C with the ambient temperature set as 9°C based on the Plant Operating Conditions.

The heat input from starting the steam flow is determined by numerical integration across the start-up snapshots. The steam flow rate available for extraction during each snapshot is taken as the mean of the flowrates available at the start and end of each snapshot:

$$\dot{m}_{steam}\ for\ snapshot = \frac{\dot{m}_{steam}\ at\ start\ of\ snapshot + \dot{m}_{steam} at\ end\ of\ snapshot}{2}$$

The proposed basis is less conservative than restricting steam extraction during each snapshot to the flow available at the start of that snapshot. However, the more conservative approach would simply shift the steam flow available for each snapshot over to the next. It is therefore considered more appropriate to consider the gradual ramping of steam availability during start-up for this study.

The heat supplied by the steam flow during each snapshot integral is used to increment the total heat supplied to the reboiler from ambient temperature to the minimum reboiler operational temperature:

$$Q_{steam} = \dot{m}_{steam} for\ snapshot \times L\ \times snapshot\ duration, where:$$

$$L = latent\ heat\ for\ saturated\ steam, kJ/kg$$

The time for starting the reboiler, $time_{reboiler}$ is given as the sum of heat delivered to the reboiler during each start-up snapshot followed by the residual time required to achieve minimum reboiler operating temperature at full extraction rate.

3.8.2.3 Thermal store sizing – Option 2a hot oil

The thermal store sizing improvement option will be based on an insulated stratified storage tank holding hot oil nominally at 125°C – temperature difference in coil to reboiler minimum temperature is 5°C. The energy content of the hot oil store is set as the residual reboiler energy requirement, considering:

- Buffering capacity in the absorber system and any steam already supplied from the HRSG and;
- Any steam already supplied as a result of the HRSG start-up snapshots

The above parameters are determined from considering the progression of snapshots for the CCGT, absorber system and regenerator system without passing amine between the two columns.

The volume of the hot oil store is to be determined from the energy requirement for the process, plus 10% margin for losses to the environment during storage.

3.8.2.4 Thermal store sizing – Option 2b hot water

In the event the required hot oil storage volume is found to be impracticable, a standby option with hot water is to be considered on the stripper amine recirculation line. The hot water store in this case would operate at approximately 95°C and be designed to raise a temperature of 90°C in the reboiler during start-up.

3.8.3 Option 3 – combination

The combined amine and heat storage option will seek to use synergy between the equipment deployed for each option. Equipment is to be designed according to the same basis as each individual option with reduced amine buffer volume taking credit for shorter stripper start-up time and vice versa.

Appendix A Simplified PFD

A.1 Overall Process Flowsheet

See attached.

A.2 Improvement option 1 – amine storage

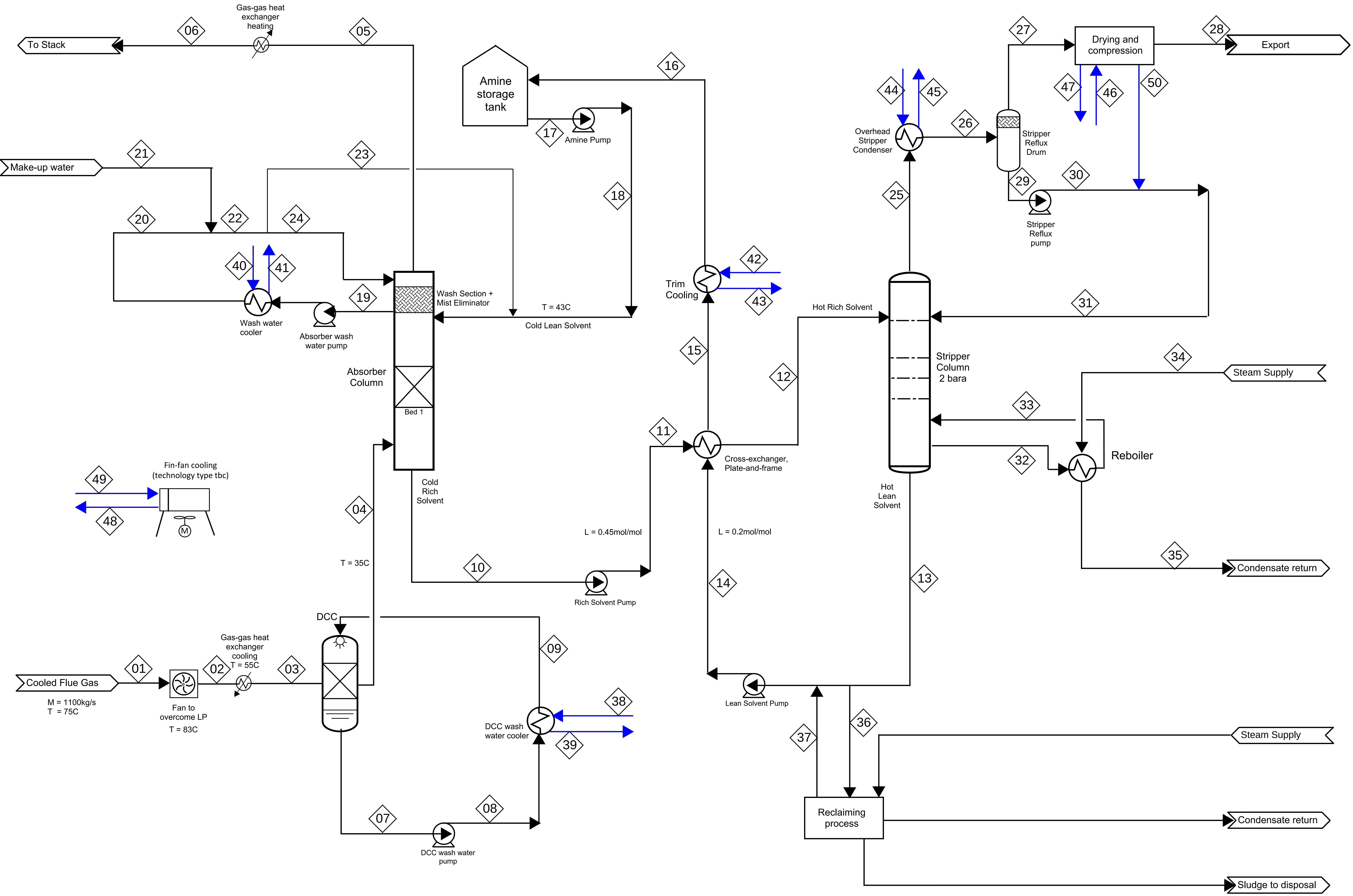
See attached.

A.3 Improvement options 2a and 2b

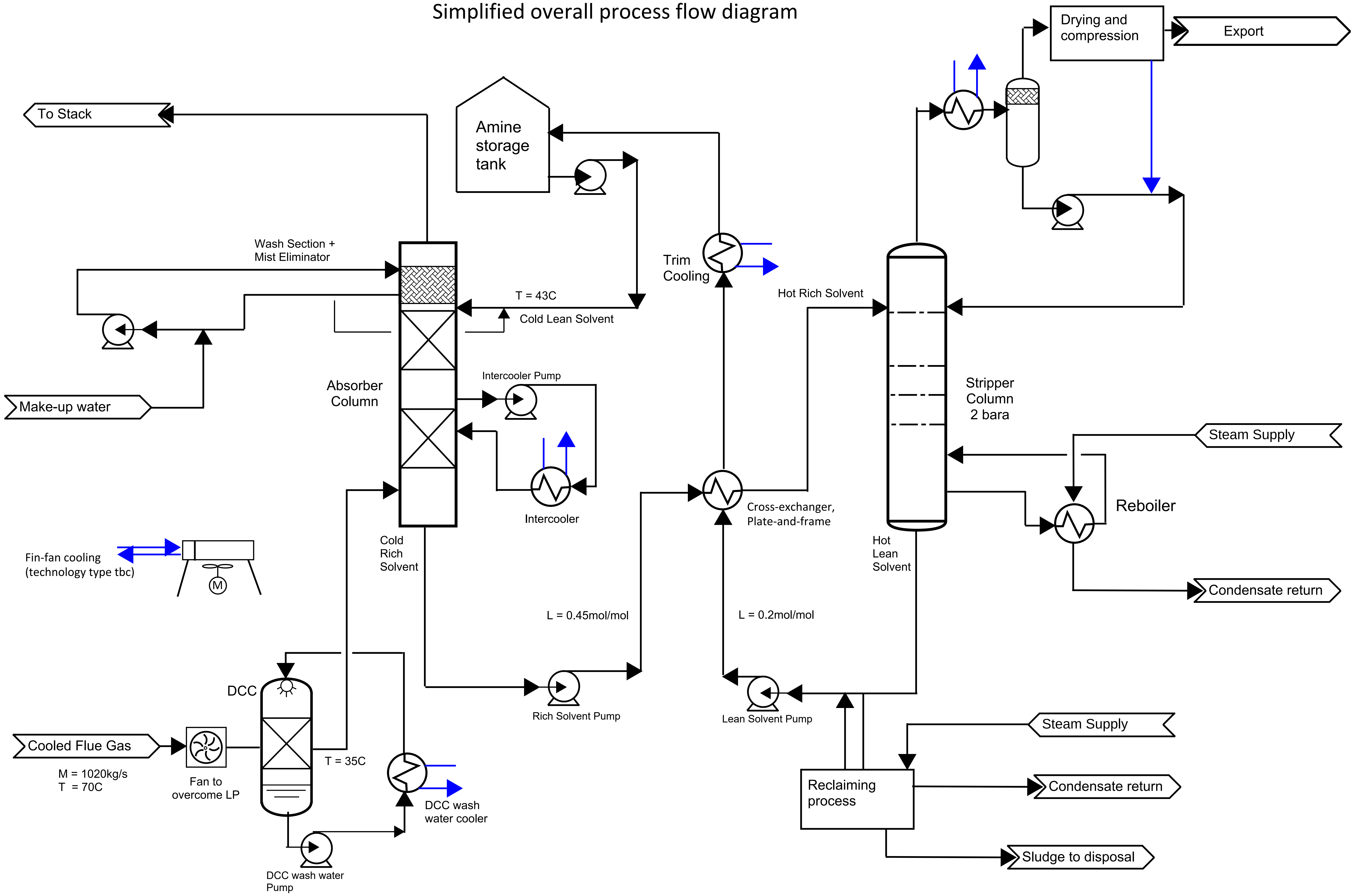
See attached.

Appendix C – Process Flow Diagrams

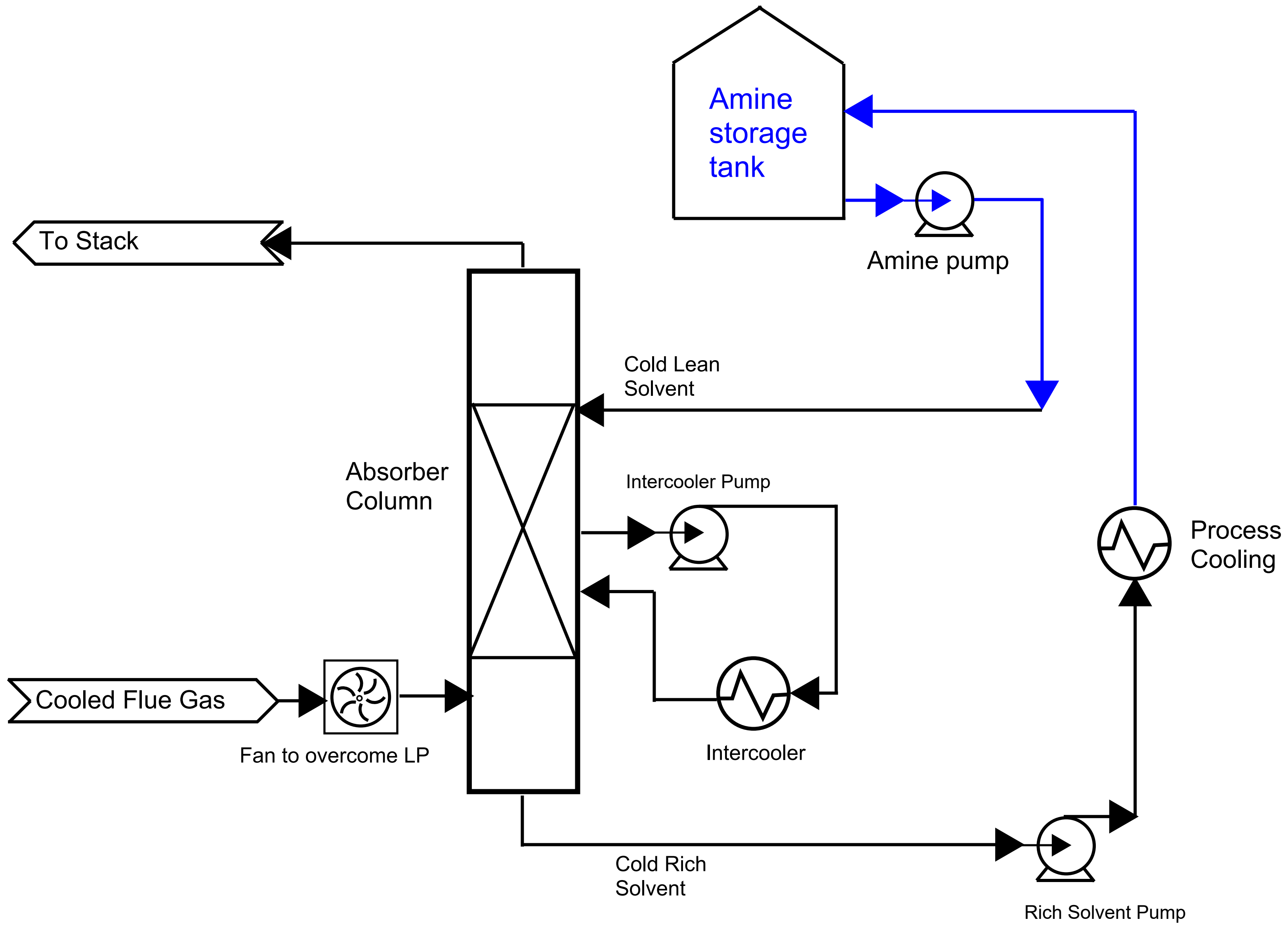
Simplified overall process flow diagram with process stream labels



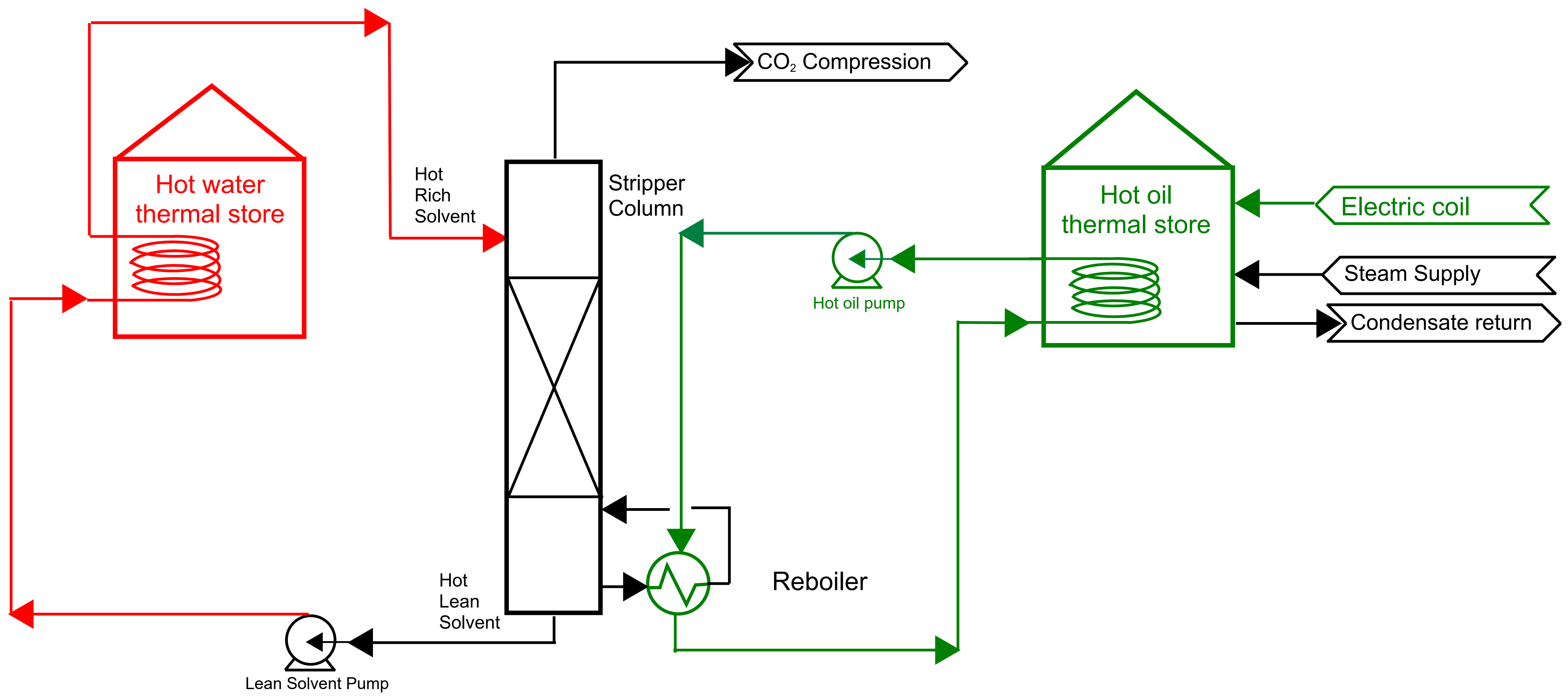
Simplified overall process flow diagram



Improvement configuration 1 - Storage of amine



Improvement configuration 2a and 2b - Storage of heat



Appendix D – Cost Breakdown Spreadsheet

AECOM			Revision Table				
	CLIENT:	BEIS	**REV**	**DATE**	**BY**	**CHK.**	**APP.**
	PROJECT:	Start-up and Shut-down times of power CCUS facilities	1	6.3.20	KM	JC	AC
			2	1.4.20	JC	KM	AC
	LOCATION:	UK	3	22.4.20	JC	KM	AC

CALCULATION TITLE: **Cost Breakdown Calculations**

DESCRIPTION: Cost estimation for the base case and two inventory scenarios

Amine storage tanks

Reference price list for the various amine tank sizes

Amine tank volume (m3)	Amine tank cost (£)	Cost basis
2,456	155,000	316L stainless steel tank cost only, no inventory costs included
3,030	180,000	
6,633	325,000	
6,715	330,000	
18,840	807,000	

Associated storage tank costs for the different scenarios

Scenario Description	Lean tank volume (m^3)	Lean tank cost (£)	Rich tank volume (m^3)	Rich tank cost (£)	Total tank cost (£)	Cost above base case (£)
Base case	2,456	155,000	N/A	0	155,000	0
Config. 2, hot start	6,633	325,000	6,633	325,000	650,000	495,000
Config. 2, cold start	18,840	807,000	18,840	807,000	1,614,000	1,459,000
Config. 1+2, hot start	3,030	180,000	3,030	180,000	360,000	205,000
Config. 1+2, cold start	6,715	330,000	6,715	330,000	660,000	505,000

Additional amine required

MEA cost variables	Values
Historic cost of monoethanolamine (MEA) in NOK/t in 2008 - Ref. 1	14310
Annual CEPCI reported in 2008 - Ref. 2	575.4
Annual CEPCI reported in 2018 - Ref. 2	603.1
Exchange rate used from NOK to £ from 2008 - Ref.3	0.0968
Estimated cost of monoethanolamine in £/t in 2018*	1451.61

* Cost estimate cross checked against historic internal project cost database

MEA properties	Values
Density of MEA solvent (35%wt) in kg/m^3	1099.00

Scenario Description	Add. solvent required (m^3)	Add. solvent required (t)	MEA required (35%wt) (t)	Add. solvent cost (£)
Config. 2, hot start	4,177	4,591	1,607	2,332,273
Config. 2, cold start	16,384	18,006	6,302	9,148,184
Config. 1+2, hot start	574	631	221	320,499
Config. 1+2, cold start	4,259	4,681	1,638	2,378,059

Thermal energy storage tanks

Heat transfer fluid properties for oil and water

Fluid	Density (kg/m3)	Heat capacity (kJ/kg.K)	Reboiler energy requirement (GJ)	Temp. change (K)	Required mass (tonnes)	Required volume (m3)
Oil	930	1.95	1100	10	56,410	60,656
Water	1000	4.18	1100	5	52,632	52,632

Thermal energy storage tank cost variables	Values
Estimated cost of thermal energy storage tank €/m³ in 2012 - Ref. 1	150
Annual CEPCI reported in 2012 - Ref. 2	584.6
Annual CEPCI reported in 2018 - Ref. 2	603.1
Exchange rate used from € to £ from 2012 - Ref.3	0.80
Estimated cost of thermal energy storage tank £/m³ in 2018	124.00

Fluid	Required volume (m3)	Storage cost estimate (£)
Oil	60,656	7,521,344
Water	52,632	6,526,295

Boilers

Values collected from Thermoflow for two different HRSG and boiler configurations

HRSG and Boiler Configuration	Equipment cost (£M)	Contractor's internal power plant cost (£M)
Horizontal HRSG with standard boiler	5	270
Vertical HRSG with once-through boiler	6	270

References

1. CO2 Capture Facility at Kårstø, Norway; Bechtel; FEED Study Report; https://ukccsrc.ac.uk/sites/default/files/documents/news/Karsto-FEED-Study-Report-Redacted-Updated-comp.pdf; accessed Mar 2020

2. Annual CEPCI reported in 2008, 2012 and 2018; https://www.chemengonline.com/tag/cepci/

3. Yearl Average Rates, https://www.ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/; accessed Mar 2020

4. Evidence Gathering: Thermal Energy Storage (TES) Technologies, 2016, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final__1_.pdf

5. Euro (EUR) to British pound sterling (GBP) average annual exchange rate from 1999 to 2019, https://www.statista.com/statistics/412806/euro-to-gbp-average-annual-exchange-rate/

Appendix E – Heat Mass Balance Sheets

AECOM	CLIENT: BEIS	606-CA-001				
	PROJECT: Start-up and Shut-down times of power CCUS facilities	REV	DATE	BY	CHK.	APP.
	LOCATION: UK					
		1	6.3.20	KM	JC	AC

CALCULATION TITLE: **Heat and Material Balance**

DESCRIPTION: Heat and material balance output

Inputs

1. BEIS CCS model 20-03-06b.pmx
2. Basis of Design Draft Rev 1
3. Reference CCGT 9000HL with CCS NTS Gas Composition LP steam.gtm

Notes

1. Flow basis for flue gas scaled up from calculated GT flow of 1020kg/s. 5% margin added and rounded up to 1100kg/s flue gas flow.
2. Column flood limit taken as 80% and system factor 0.8
3. Low lean approach to equilibrium in the absorber top section (14%) indicates higher capture rate would be available with increased packing height and the system is not lean-pinched

Key results

Reboiler duty	336	MW.th
Lean amine loading	0.25	mol/mol
Rich amine loading	0.46	mol/mol
Stripper overhead pressure	2.2	bara
Lean amine total stream circulation rate	1500	kg/s
Overall CO2 capture rate	95.5	%
Treated flue gas temperature to stack	70	°C
Heat rejection load in cooling towers	469	MW.th
CCS plant total power consumption (exc cooling towers)	39.2	MW.e

Process Stream		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
Description	Fluid:	Flue gas	Flue gas	Flue gas	Flue gas	Treated flue gas	Heated treated flue gas	DCC wash water	DCC wash water	DCC wash water	Cold rich solvent	Cold rich solvent	Hot rich solvent	Hot lean solvent	Hot lean solvent	Cold lean solvent	Cold lean solvent
	From:	HRSG	Booster fan	Gas-gas heat exchanger	DCC	Absorber column (Overhead)	Gas-gas heat exchanger	DCC	DCC wash water pump	DCC wash water cooler	Absorber column (Sump)	Rich solvent pump	Cross-exchanger (plate-and-frame)	Stripper column (Sump)	Lean solvent pump	Cross-exchanger (plate-and-frame)	Trim cooling heat exchanger
	To:	Booster fan	Gas-gas heat exchanger	DCC	Absorber column	Gas-gas heat exchanger	Stack	DCC wash water pump	DCC wash water cooler	DCC	Rich solvent pump	Cross-exchanger (plate-and-frame)	Stripper column	Lean solvent pump	Cross-exchanger (plate-and-frame)	Trim cooling heat exchanger	Amine storage tank
Mol%																	
Nitrogen	%	73.83	73.83	73.83	77.47	80.90	80.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oxygen	%	10.37	10.37	10.37	10.88	11.36	11.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	%	4.87	4.87	4.87	5.11	0.24	0.24	0.02	0.02	0.02	6.74	6.74	6.74	3.80	3.80	3.80	0.16
Water	%	10.06	10.06	10.06	5.62	6.53	6.53	99.97	99.97	99.97	78.57	78.57	78.57	81.05	81.05	81.05	99.84
Argon	%	0.86	0.86	0.86	0.90	0.94	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEA	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.69	14.69	14.69	15.15	15.15	15.15	0.00
CO	%	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	%	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molar Flow																	
Nitrogen	kmol/h	103314.61	103314.61	103314.61	103314.56	103313.06	103313.06	1.45	1.40	1.40	1.50	1.50	1.50	0.00	0.00	0.00	0.00
Oxygen	kmol/h	14509.38	14509.38	14509.38	14509.36	14508.94	14508.94	0.39	0.37	0.37	0.42	0.42	0.42	0.00	0.00	0.00	0.00
CO2	kmol/h	6813.95	6813.95	6813.95	6812.92	308.03	308.03	28.89	27.85	27.85	14187.61	14187.61	14187.61	7754.79	7754.79	7754.79	0.48
Water	kmol/h	14075.64	14075.64	14075.64	7500.15	8344.02	8344.02	190324.46	183748.98	183748.98	165344.57	165344.57	165344.57	165308.90	165308.90	165308.90	300.98
Argon	kmol/h	1203.28	1203.28	1203.28	1203.28	1203.25	1203.25	0.03	0.03	0.03	0.04	0.04	0.04	0.00	0.00	0.00	0.00
MEA	kmol/h	0.00	0.00	0.00	0.00	0.91	0.91	0.00	0.00	0.00	30903.16	30903.16	30903.16	30903.17	30903.17	30903.17	0.00
CO	kmol/h	15.67	15.67	15.67	15.67	15.67	15.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	kmol/h	4.51	4.51	4.51	4.51	4.50	4.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	kmol/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	kmol/h	1.29	1.29	1.29	0.34	0.34	0.34	26.32	25.38	25.38	0.34	0.34	0.34	0.34	0.34	0.34	0.00
Mass %																	
Nitrogen	%	73.07	73.07	73.07	75.33	81.04	81.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oxygen	%	11.72	11.72	11.72	12.08	13.00	13.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	%	7.57	7.57	7.57	7.80	0.38	0.38	0.04	0.04	0.04	11.37	11.37	11.37	6.55	6.55	6.55	0.39
Water	%	6.40	6.40	6.40	3.52	4.21	4.21	99.95	99.95	99.95	54.25	54.25	54.25	57.19	57.19	57.19	99.61
Argon	%	1.21	1.21	1.21	1.25	1.35	1.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEA	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34.38	34.38	34.38	36.25	36.25	36.25	0.00
CO	%	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	%	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	%	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mass Flow																	
Nitrogen	kg/s	803.9	803.9	803.9	803.9	803.9	803.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	kg/s	129.0	129.0	129.0	129.0	129.0	129.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO2	kg/s	83.3	83.3	83.3	83.3	3.8	3.8	0.4	0.3	0.3	173.4	173.4	173.4	94.8	94.8	94.8	0.0
Water	kg/s	70.4	70.4	70.4	37.5	41.8	41.8	952.4	919.5	919.5	827.4	827.4	827.4	827.2	827.2	827.2	1.5
Argon	kg/s	13.4	13.4	13.4	13.4	13.4	13.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MEA	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	524.4	524.4	524.4	524.4	524.4	524.4	0.0
CO	kg/s	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N2O	kg/s	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO2	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ammonia	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Property	**Units**																
Temperature	°C	74	85	55	36	38	71	47	47	21	40	40	120	126	126	44	35
Pressure	bar	1.01	1.10	1.08	1.08	1.04	1.02	1.08	6.00	5.30	1.18	7.18	6.18	2.21	10.00	9.00	3.53
Mole Fraction Vapour	%	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0
Mass Fraction Vapour	%	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0
Molecular Weight	kg/kmol	28.3	28.3	28.3	28.8	28.0	28.0	18.0	18.0	18.0	26.1	26.1	26.1	25.5	25.5	25.5	18.1
Mass Density	kg/m^3	1.0	1.0	1.1	1.2	1.1	1.0	988.7	988.7	997.8	1156.3	1156.4	1133.7	1069.6	1069.6	1105.3	994.2
Molar Flow	kmol/h	139938.3	139938.3	139938.3	133360.8	127698.7	127698.7	190381.6	183804.0	183804.0	210437.6	210437.6	210437.6	203967.2	203967.2	203967.2	301.5
Mass Flow	kg/s	1100.2	1100.2	1100.2	1067.3	992.0	992.0	952.9	920.0	920.0	1525.2	1525.2	1525.2	1446.4	1446.4	1446.4	1.5
Vapour vol. flow	m^3/h	3998752.9	3782387.4	3533105.0	3176943.0	3184841.4	3594898.7	3469.8	3349.7	3319.4	4748.6	4748.4	4843.2	4868.4	4868.1	4710.8	5.5
Liquid Vol. flow	m^3/h	3998752.9	3782387.4	3533105.0	3176943.0	3184841.4	3594898.7	3469.8	3349.7	3319.4	4748.6	4748.4	4843.2	4868.4	4868.1	4710.8	5.5
Normal vap vol flow	Nm^3/h	3136572.2	3136572.2	3136572.2	2989143.7	2862234.2	2862234.2	4267204.8	4119776.3	4119776.3	4716741.4	4716741.4	4716741.4	4571712.9	4571712.9	4571712.9	6756.9

Process Stream		17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Description	Fluid:	Cold lean solvent	Cold lean solvent	Absorber wash water	Absorber wash water	Wash water Make-up	Absorber wash water	Amine make-up	Absorber wash water	Stripper overhead	Stripper overhead	Wet CO_2 vapour	CO_2 Product	Stripper reflux	Stripper reflux	Stripper reflux	Reboiler feed
	From:	Amine storage tank	Amine pump	Absorber column (Wash bed)	Absorber wash water cooler	Make-up water supply	Absorber wash water cooler	Absorber wash water stream	Absorber wash water cooler	Stripper column (Overhead)	Overhead stripper condenser	Stripper reflux drum	Drying and compression unit	Stripper reflux drum	Stripper reflux pump	Stripper reflux pump	Stripper column
	To:	Amine pump	Absorber column (Bed 1)	Absorber wash water cooler	Absorber column (Wash bed)	Absorber wash water stream	Absorber column (Wash bed)	Cold lean solvent stream	Absorber column (Wash bed)	Overhead stripper condenser	Stripper reflux drum	Drying and compression unit	CO_2 Export	Stripper reflux pump	Stripper column	Stripper column	Reboiler
Mol%																	
Nitrogen	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.00	0.00	0.00	0.00
Oxygen	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00
CO2	%	3.80	3.58	0.10	0.10	0.00	3.59	0.10	0.10	31.28	31.28	94.01	99.94	0.22	0.22	0.22	3.94
Water	%	81.05	82.00	99.59	99.59	100.00	82.11	99.59	99.60	68.61	68.61	5.96	0.03	99.62	99.62	99.62	82.70
Argon	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEA	%	15.15	14.41	0.30	0.30	0.00	14.30	0.30	0.30	0.10	0.10	0.00	0.00	0.15	0.15	0.15	13.36
CO	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molar Flow																	
Nitrogen	kmol/h	0.00	0.09	1.53	1.53	0.00	0.00	0.09	1.45	1.50	1.50	1.50	1.50	0.00	0.00	0.00	0.00
Oxygen	kmol/h	0.00	0.02	0.40	0.40	0.00	0.00	0.02	0.38	0.42	0.42	0.42	0.42	0.00	0.00	0.00	0.00
CO2	kmol/h	7754.73	7695.63	224.43	224.30	0.00	71.88	12.78	211.52	6464.22	6464.22	6433.55	6432.82	30.67	30.67	31.40	9158.67
Water	kmol/h	165309.86	176034.43	217049.32	217048.37	2523.82	1644.28	12368.86	207203.33	14178.80	14178.80	407.67	1.78	13771.14	13771.14	14143.14	192136.36
Argon	kmol/h	0.00	0.00	0.04	0.04	0.00	0.00	0.00	0.03	0.04	0.04	0.04	0.04	0.00	0.00	0.00	0.00
MEA	kmol/h	30903.16	30941.47	656.22	656.23	0.00	286.33	37.40	618.83	21.25	21.25	0.00	0.00	21.25	21.25	21.25	31034.36
CO	kmol/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	kmol/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	kmol/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	kmol/h	0.34	0.38	0.69	0.69	0.00	0.00	0.04	0.65	0.60	0.60	0.00	0.00	0.60	0.60	0.60	0.90
Mass %																	
Nitrogen	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
Oxygen	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	%	6.55	6.27	0.25	0.25	0.00	6.29	0.25	0.25	52.56	52.56	97.45	99.97	0.54	0.54	0.54	7.00
Water	%	57.19	58.73	98.74	98.74	100.00	58.92	98.74	98.75	47.19	47.19	2.53	0.01	98.94	98.94	98.96	60.09
Argon	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEA	%	36.25	35.00	1.01	1.01	0.00	34.79	1.01	1.00	0.24	0.24	0.00	0.00	0.52	0.52	0.50	32.91
CO	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mass Flow																	
Nitrogen	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO2	kg/s	94.8	94.1	2.7	2.7	0.0	0.9	0.2	2.6	79.0	79.0	78.6	78.6	0.4	0.4	0.4	112.0
Water	kg/s	827.3	880.9	1086.2	1086.2	12.6	8.2	61.9	1036.9	71.0	71.0	2.0	0.0	68.9	68.9	70.8	961.5
Argon	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MEA	kg/s	524.4	525.0	11.1	11.1	0.0	4.9	0.6	10.5	0.4	0.4	0.0	0.0	0.4	0.4	0.4	526.6
CO	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N2O	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO2	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ammonia	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Property	**Units**																
Temperature	°C	44	43	52	21	25	43	21	21	115	50	50	35	50	50	50	124
Pressure	bar	9.00	6.50	1.04	7.50	7.50	7.50	7.50	7.50	2.20	2.10	2.10	151.70	2.10	6.00	3.53	2.21
Mole Fraction Vapour	%	0	0	0	0	0	0	0	0	100	33	100	100	0	0	0	0
Mass Fraction Vapour	%	0	0	0	0	0	0	0	0	100	54	100	100	0	0	0	0
Molecular Weight	kg/kmol	25.5	25.2	18.2	18.2	18.0	25.1	18.2	18.2	26.2	26.2	42.5	44.0	18.1	18.1	18.1	24.8
Mass Density	kg/m^3	1105.3	1098.5	987.5	999.0	996.6	1098.0	999.0	999.0	1.8	6.2	3.3	793.8	988.8	988.9	989.0	594.3
Molar Flow	kmol/h	203968.1	214672.0	217932.6	217931.6	2523.8	2002.5	12419.2	208036.2	20666.8	20666.8	6843.2	6436.6	13823.7	13823.7	14196.4	232330.3
Mass Flow	kg/s	1446.4	1500.0	1100.1	1100.1	12.6	14.0	62.7	1050.0	150.4	150.4	80.7	78.7	69.7	69.7	71.5	1600.0
Vapour vol. flow	m^3/h	4710.9	4916.0	4010.4	3964.1	45.6	45.8	225.9	3783.8	299280.6	86984.4	86730.8	356.8	253.6	253.6	260.4	9692.7
Liquid Vol. flow	m^3/h	4710.9	4916.0	4010.4	3964.1	45.6	45.8	225.9	3783.8	299280.6	86984.4	86730.8	356.8	253.6	253.6	260.4	9692.7
Normal vap vol flow	Nm^3/h	4571733.0	4811650.4	4884733.8	4884709.7	56568.9	44884.0	278363.3	4662915.3	463225.7	463225.7	153382.8	144268.9	309842.9	309842.9	318197.5	5207442.3

Process Stream		33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Description	Fluid:	Reboiler boil-up	LP steam	LP condensate	Hot lean solvent	Hot lean solvent	Cooling water	Cooling water	Cooling water	Cooling water	Cooling water	Cooling water	Cooling water	Cooling water	Cooling water	Cooling water	Cooling water
	From:	Reboiler	LP-IP crossover	Reboiler	Hot lean solvent stream	Reclaimer	Cooling water supply	DCC wash water cooler	Cooling water supply	Absorber wash water cooler	Cooling water supply	Trim cooling heat exchanger	Cooling water supply	Overhead stripper condenser	Cooling water supply	Drying and compression unit	Cooling water return
	To:	Stripper column	Reboiler	HRSG condenser outlet	Reclaimer	Hot lean solvent stream	DCC wash water cooler	Cooling water return	Absorber wash water cooler	Cooling water return	Trim cooling heat exchanger	Cooling water return	Overhead stripper condenser	Cooling water return	Drying and compression unit	Cooling water return	Cooling towers
Mol%																	
Nitrogen	%	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oxygen	%	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	%	4.95	0.00	0.00	94.01	98.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	%	94.59	100.00	100.00	5.96	1.63	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Argon	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEA	%	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molar Flow																	
Nitrogen	kmol/h	0.00	0.00	0.00	1.50	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oxygen	kmol/h	0.00	0.00	0.00	0.42	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	kmol/h	1403.88	0.00	0.00	6433.55	6433.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	kmol/h	26827.46	30903.68	30903.68	407.67	106.69	436828.15	436828.15	621253.15	621253.15	4063.51	4063.51	769455.10	769455.10	190813.06	190813.06	2022412.98
Argon	kmol/h	0.00	0.00	0.00	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEA	kmol/h	131.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	kmol/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	kmol/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	kmol/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	kmol/h	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mass %																	
Nitrogen	%	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oxygen	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	%	11.17	0.00	0.00	97.45	99.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	%	87.38	100.00	100.00	2.53	0.67	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Argon	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEA	%	1.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N2O	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mass Flow																	
Nitrogen	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.0
Oxygen	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
CO2	kg/s	17.2	0.0	0.0	78.6	78.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
Water	kg/s	134.3	154.6	154.6	2.0	0.5	2186.0	2186.0	3108.9	3108.9	20.3	20.3	3850.5	3850.5	3437550.73	3437550.7	36434336.1
Argon	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
MEA	kg/s	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
CO	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
N2O	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
SO2	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
Ammonia	kg/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0	0.0
Property	**Units**																
Temperature	°C	126	139	135	95	35	14	25	14	25	14	25	14	25	14	25	14
Pressure	bar	2.21	3.50	8.00	3.78	5.80	6.00	5.30	6.00	5.50	6.00	5.00	6.00	5.30	6.00	5.30	3.60
Mole Fraction Vapour	%	100	100	0	100	99	0	0	0	0	0	0	0	0	0	0	0
Mass Fraction Vapour	%	100	100	0	100	100	0	0	0	0	0	0	0	0	0	0	0
Molecular Weight	kg/kmol	19.5	18.0	18.0	42.5	43.6	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Mass Density	kg/m^3	1.3	1.9	931.1	5.3	10.2	999.5	996.6	999.5	996.6	999.5	996.6	999.5	996.6	999.5	996.6	999.5
Molar Flow	kmol/h	28363.1	30903.7	30903.7	6843.2	6541.7	436828.2	436828.2	621253.2	621253.2	4063.5	4063.5	769455.1	769455.1	190813.1	190813.1	2022413.0
Mass Flow	kg/s	153.6	154.6	154.6	80.7	79.2	2186.0	2186.0	3108.9	3108.9	20.3	20.3	3850.5	3850.5	3437550.7	3437550.7	36434336.1
Vapour vol. flow	m^3/h	418933.1	295512.6	597.9	54827.6	27879.6	7873.6	7896.3	11197.8	11230.0	73.2	73.5	13869.1	13909.0	3439.3	3449.2	36454.1
Liquid Vol. flow	m^3/h	418933.1	295512.6	597.9	54827.6	27879.6	7873.6	7896.3	11197.8	11230.0	73.2	73.5	13869.1	13909.0	3439.3	3449.2	36454.1
Normal vap vol flow	Nm^3/h	635729.3	692673.8	692673.8	153382.8	146625.9	9791049.6	9791049.6	13924744.6	13924744.6	91079.4	91079.4	17246537.2	17246537.2	4276876.7	4276876.7	45330287.5

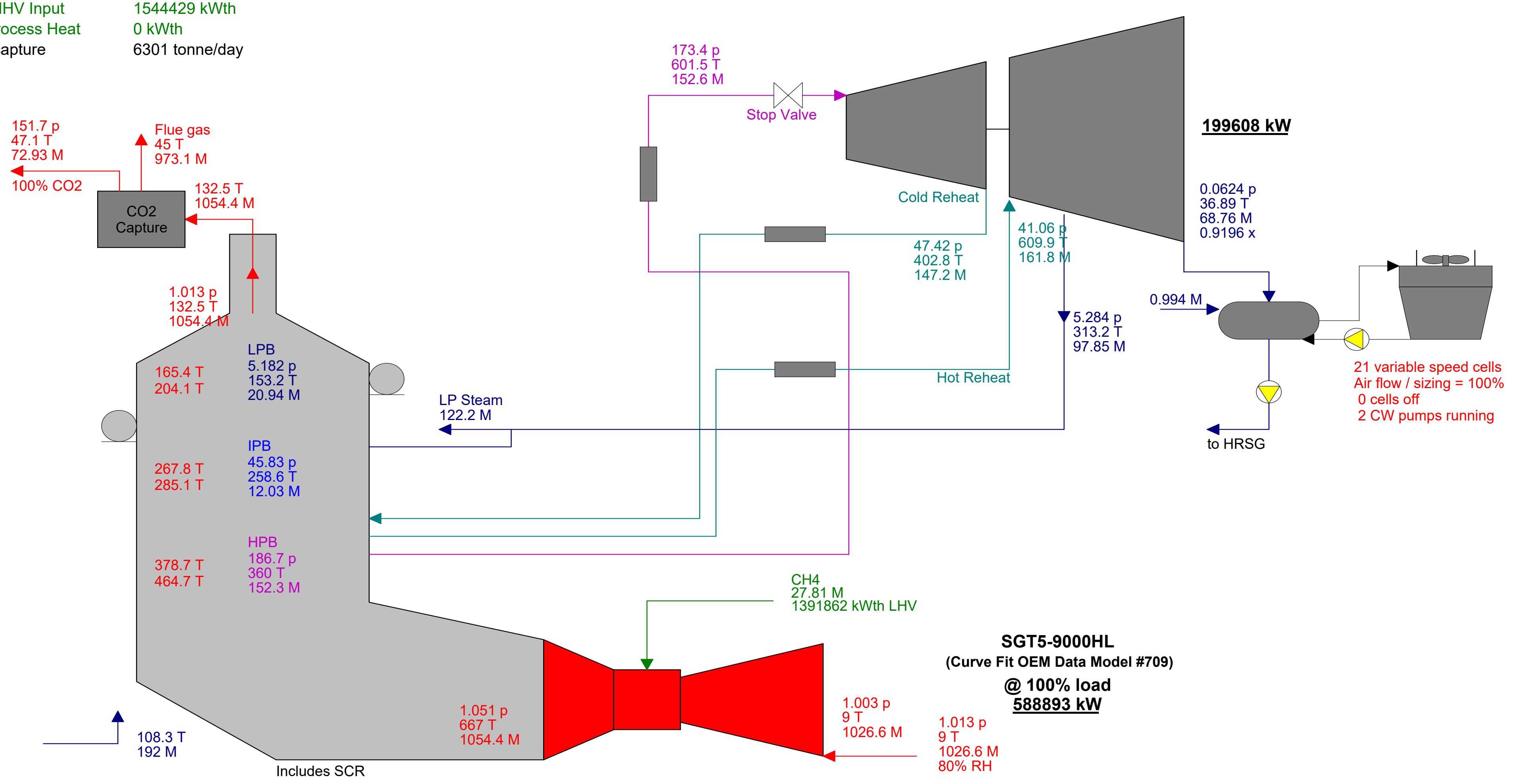
Process Stream		49	50
Description	Fluid:	Cooling water	Inter-stage liquid
	From:	Cooling towers	Drying and compression unit
	To:	Cooling water supply	Stripper reflux fluid stream
Mol%			
Nitrogen	%	0.00	0.00
Oxygen	%	0.00	0.00
CO2	%	0.00	0.20
Water	%	100.00	99.80
Argon	%	0.00	0.00
MEA	%	0.00	0.00
CO	%	0.00	0.00
N2O	%	0.00	0.00
SO2	%	0.00	0.00
Ammonia	%	0.00	0.00
Molar Flow			
Nitrogen	kmol/h	0.00	0.00
Oxygen	kmol/h	0.00	0.00
CO2	kmol/h	0.00	0.73
Water	kmol/h	30903.68	372.01
Argon	kmol/h	0.00	0.00
MEA	kmol/h	0.00	0.00
CO	kmol/h	0.00	0.00
N2O	kmol/h	0.00	0.00
SO2	kmol/h	0.00	0.00
Ammonia	kmol/h	0.00	0.00
Mass %			
Nitrogen	%	0.00	0.00
Oxygen	%	0.00	0.00
CO2	%	0.00	0.48
Water	%	100.00	99.52
Argon	%	0.00	0.00
MEA	%	0.00	0.00
CO	%	0.00	0.00
N2O	%	0.00	0.00
SO2	%	0.00	0.00
Ammonia	%	0.00	0.00
Mass Flow			
Nitrogen	kg/s	0.0	0.0
Oxygen	kg/s	0.0	0.0
CO2	kg/s	0.0	32.2
Water	kg/s	556738.4	6701.8
Argon	kg/s	0.0	0.0
MEA	kg/s	0.0	0.0
CO	kg/s	0.0	0.0
N2O	kg/s	0.0	0.0
SO2	kg/s	0.0	0.0
Ammonia	kg/s	0.0	0.0
Property	**Units**		
Temperature	°C	135	35
Pressure	bar	3.30	3.53
Mole Fraction Vapour	%	0	0
Mass Fraction Vapour	%	0	0
Molecular Weight	kg/kmol	18.0	18.1
Mass Density	kg/m^3	931.1	865.9
Molar Flow	kmol/h	30903.7	372.7
Mass Flow	kg/s	556738.4	6734.0
Vapour vol. flow	m^3/h	598.0	7.8
Liquid Vol. flow	m^3/h	598.0	7.8
Normal vap vol flow	Nm^3/h	692673.8	8354.6

Appendix F – Thermoflow Outputs

GT MASTER 29.0 AECOM

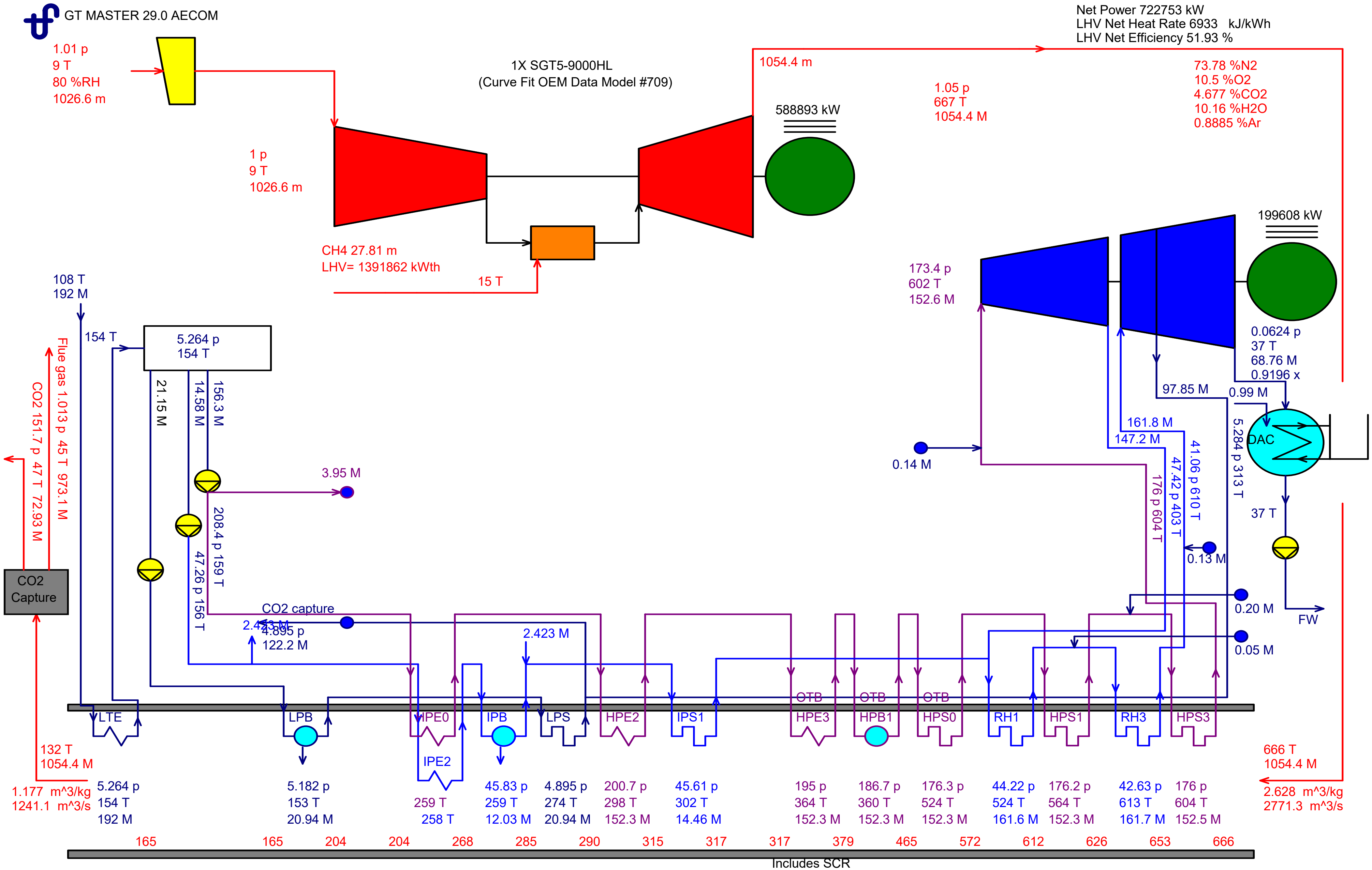
Gross Power	788501 kW
Net Power	722753 kW
Aux. & Losses	65748 kW
LHV Gross Heat Rate	6355 kJ/kWh
LHV Net Heat Rate	6933 kJ/kWh
LHV Gross Electric Eff.	56.65 %
LHV Net Electric Eff.	51.93 %
Fuel LHV Input	1391862 kWth
Fuel HHV Input	1544429 kWth
Net Process Heat	0 kWth
CO2 capture	6301 tonne/day

Ambient
1.013 P
9 T
80% RH
7.353 Twb



p [bar] T [C] M [kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 20:06:49 file=

GT MASTER 29.0 AECOM
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM



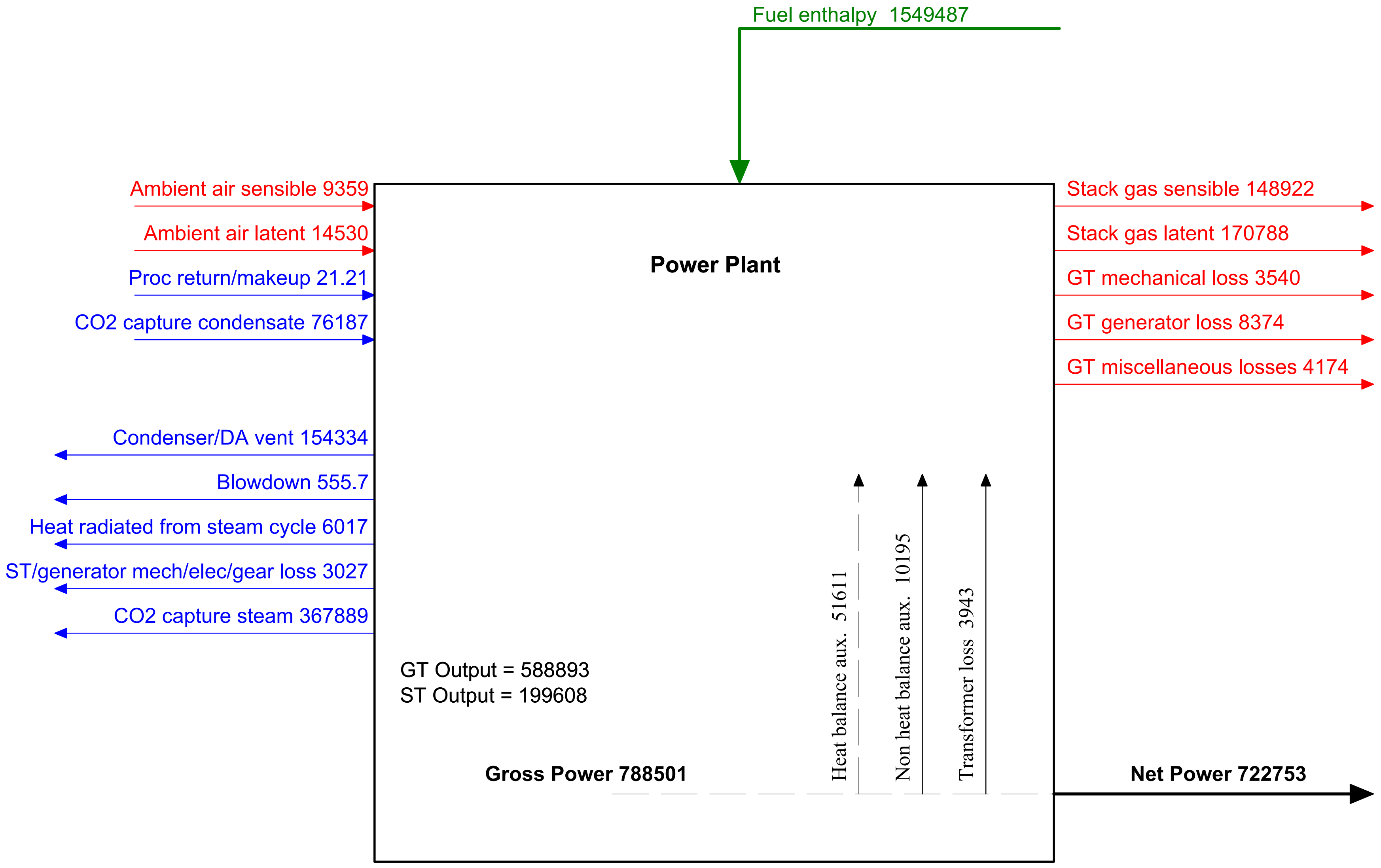
p[bar], T[C], M[kg/s], Steam Properties: IAPWS-IF97

1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Fuel chemical LHV input = 1391862 kW
Fuel chemical HHV input = 1544429 kW

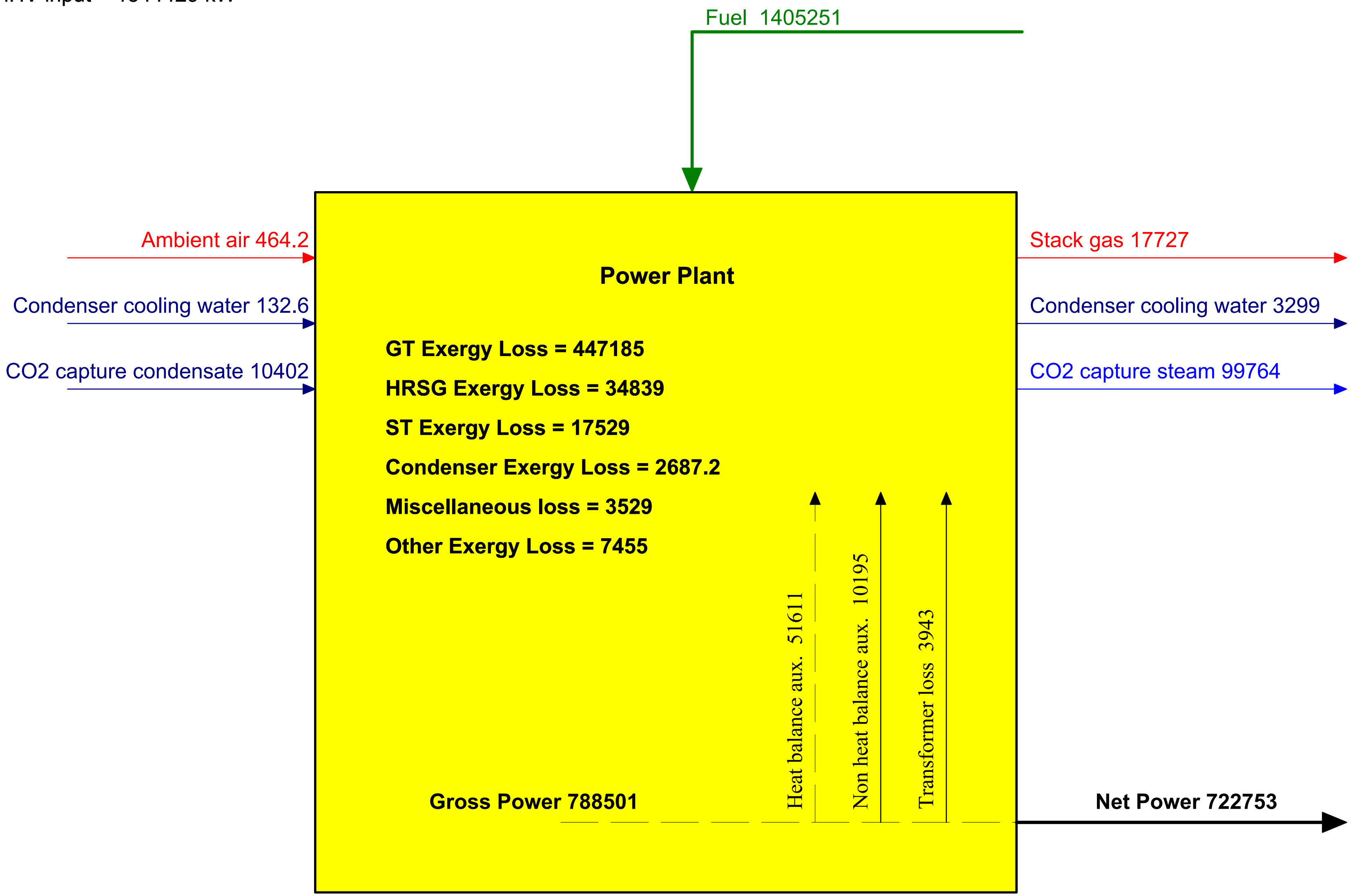
Power Plant Energy Flow Schematic [kW]



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Fuel exergy input = 1405251 kW
Fuel chemical LHV input = 1391862 kW
Fuel chemical HHV input = 1544429 kW

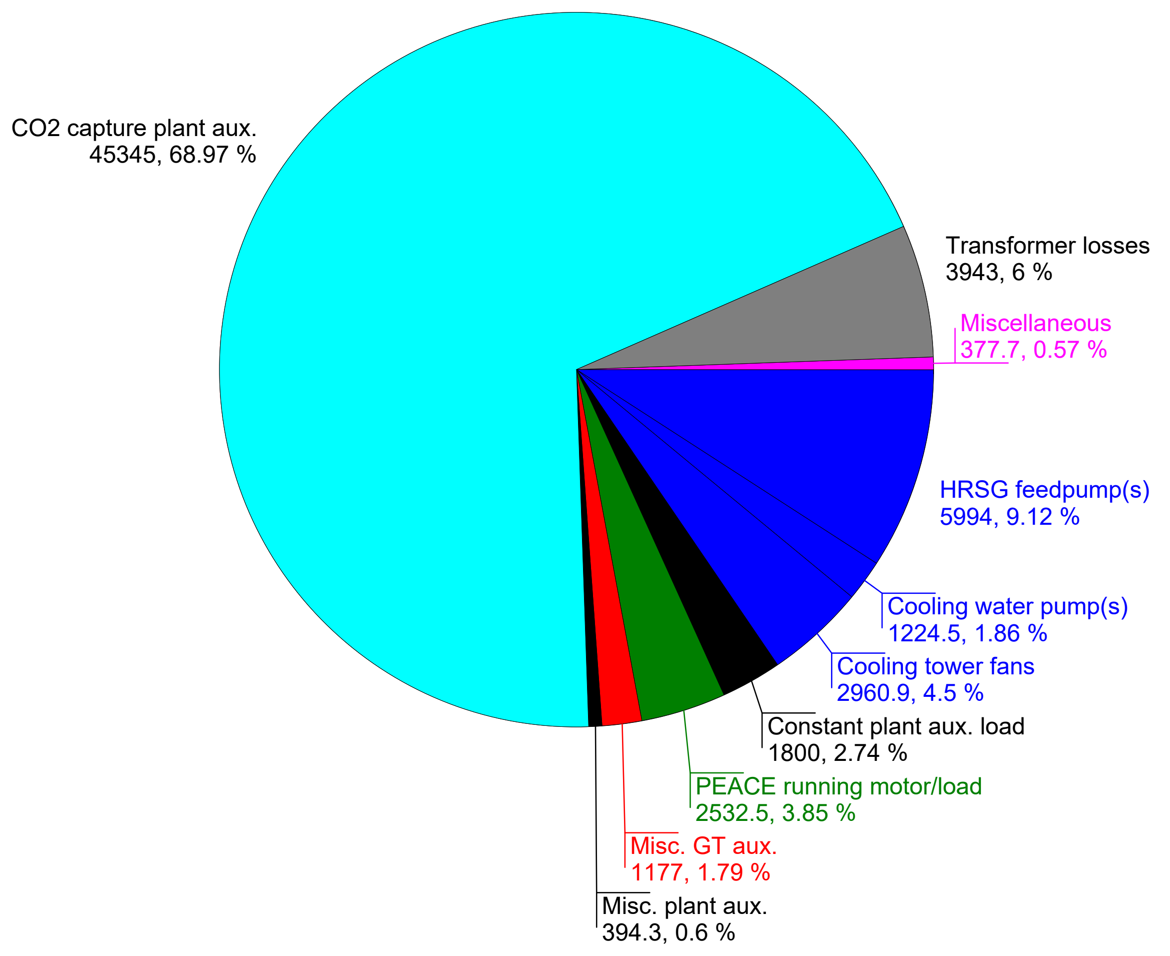
Power Plant Exergy Flow Schematic [kW]



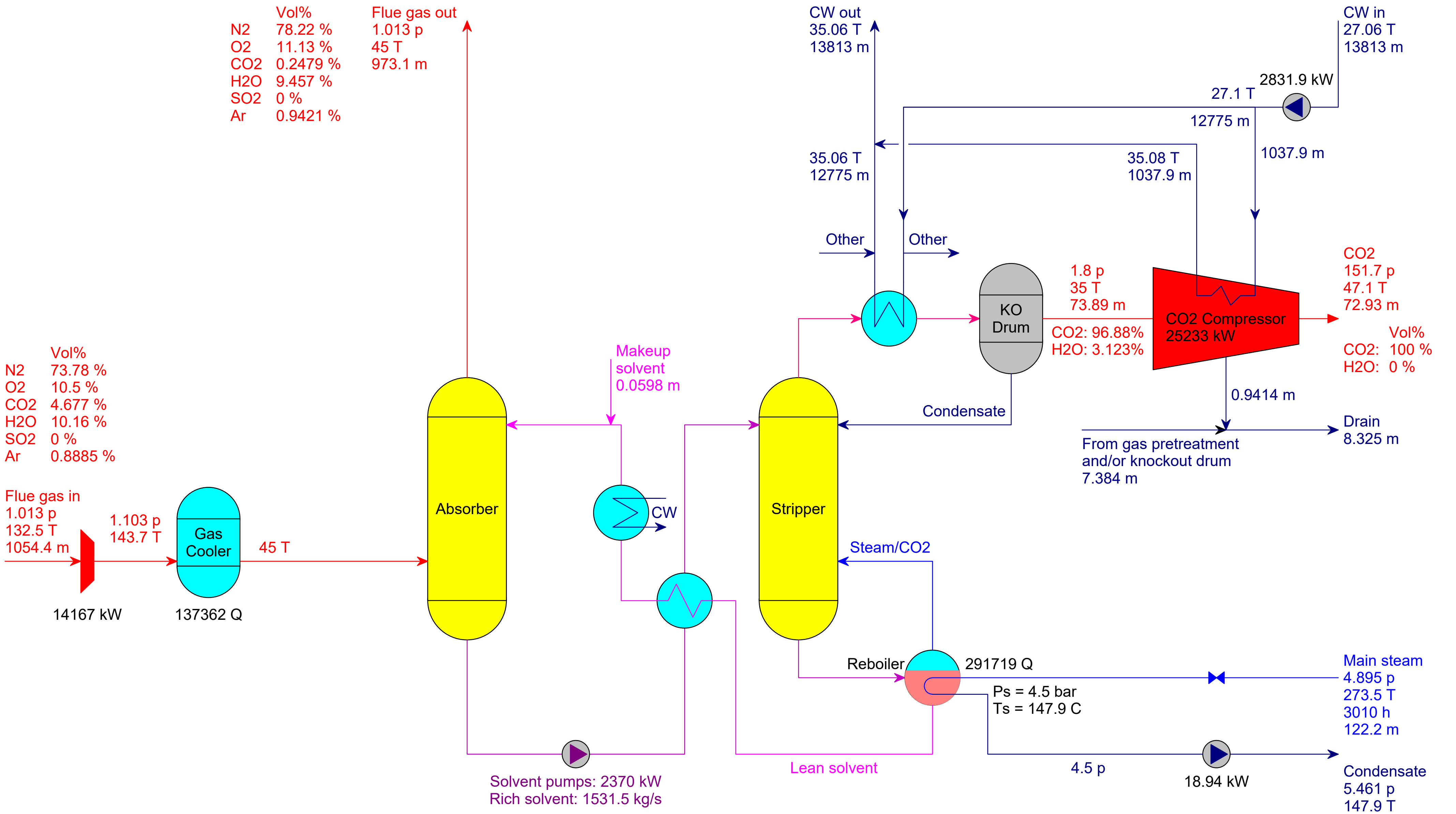
Reference: 1.013 bar, 25 C, water as vapor.

Auxiliaries & Losses [kW]

Total auxiliaries & transformer losses = 65748 kW



CO2 Capture Plant Flow Diagram

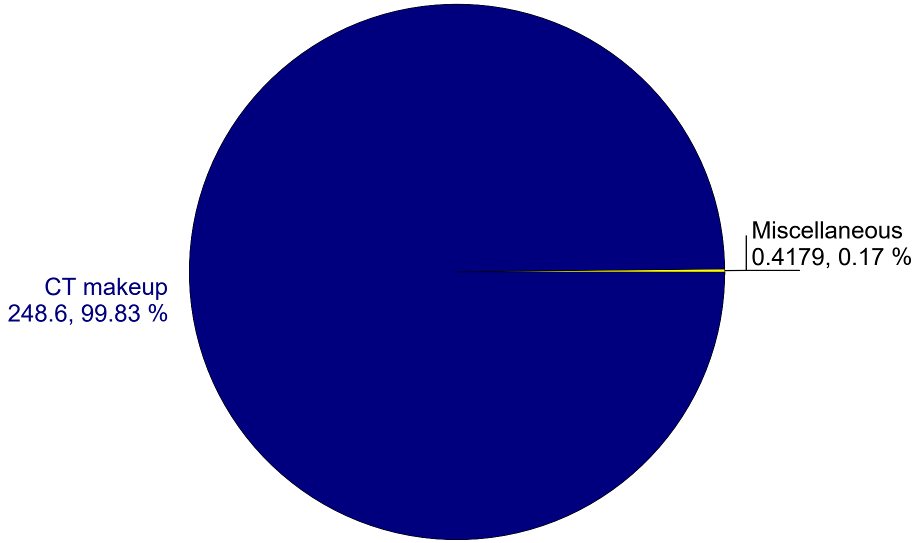


Process: Amine-based
CO2 capture: 72.93 kg/s, 6301 tonne/day
CO2 capture efficiency: 95 %
Heat input: 291719 kW, 291.7 MW, 4000 kJ/kg CO2
Total electrical power consumption: 45345 kW
Solvent consumption: 5.168 tonne/day

p[bar] T[C] h[kJ/kg] m[kg/s] Q[kW]

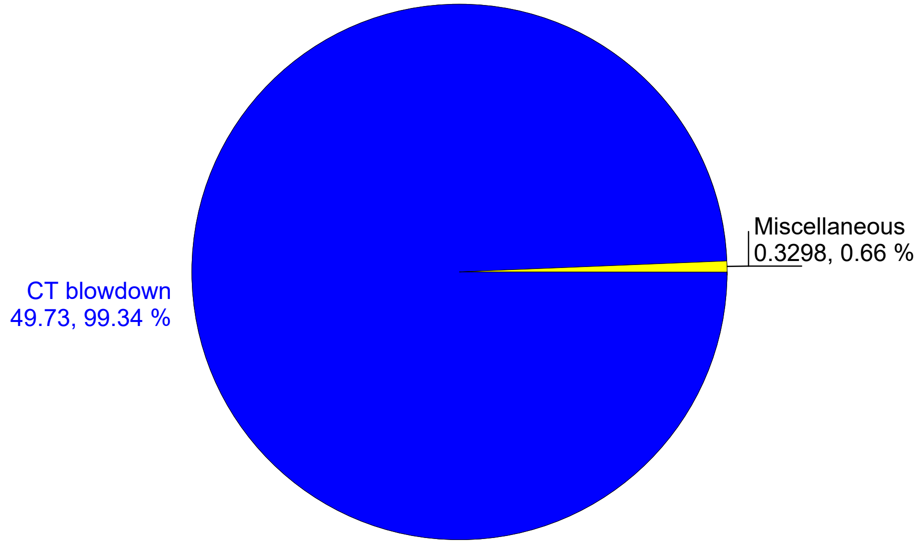
Plant Water Consumption [kg/s]

Plant water consumption = 249.1 kg/s

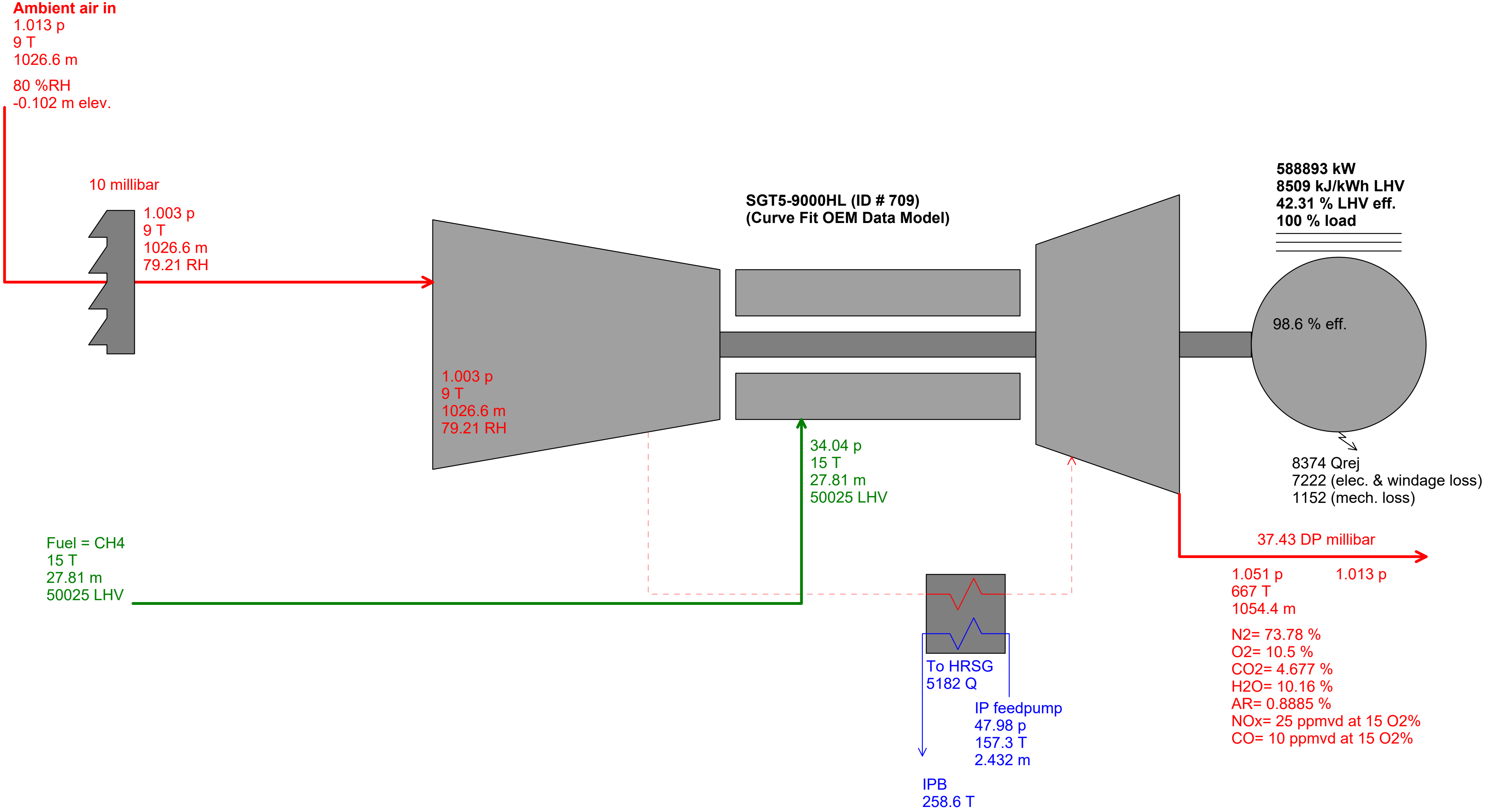


Plant Water Discharge [kg/s]

Plant water discharge = 50.06 kg/s

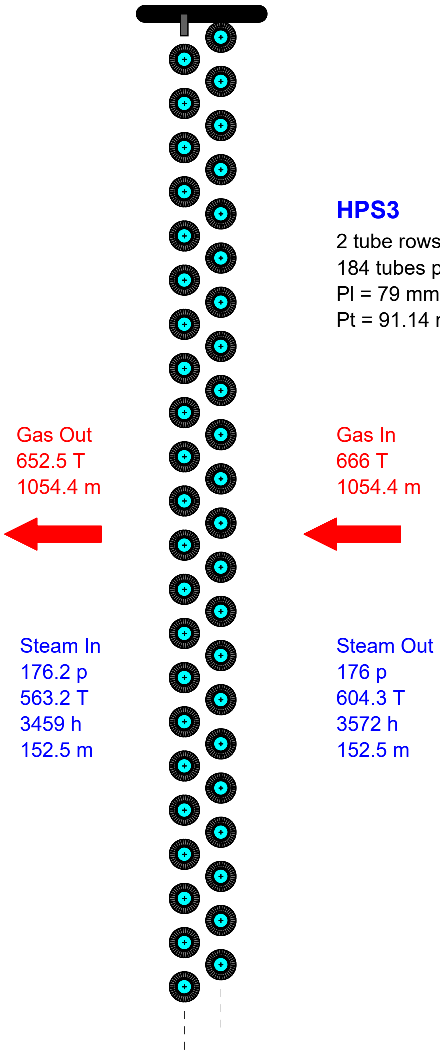


GT generator power = 588893 kW
GT Heat Rate @ gen term = 8509 kJ/kWh
GT efficiency @ gen term = 38.13% HHV = 42.31% LHV
GT @ 100 % rating



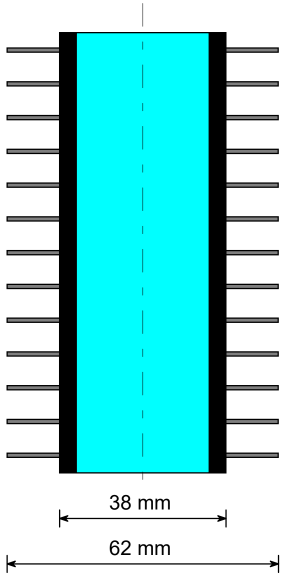
p[bar], T[C], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

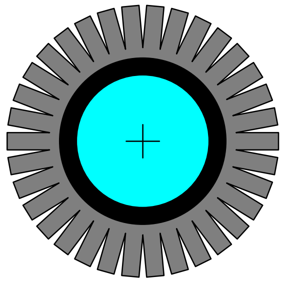
HPS3 Hardware Design



HPS3

2 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP304
Tube material	TP347HFG
Tube outer diameter	38 mm
Tube wall thickness	3.81 mm
Fin height	12 mm
Fin spacing	6.723 mm
Fin thickness	1 mm
Number of fins per meter	129.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4645 m^2
Maximum gas velocity	15.19 m/s
Gas pressure drop	0.5813 millibar
Steam side velocity	11.65 m/s
Steam side pressure drop	0.174 bar
Heat transfer from gas	17279 kW
Heat transfer to steam	17193 kW

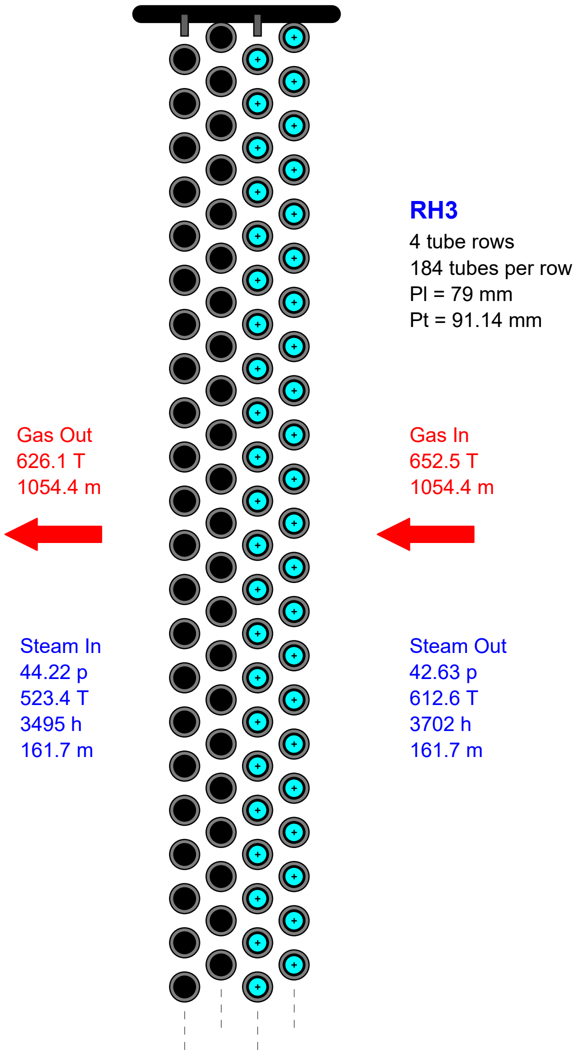
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

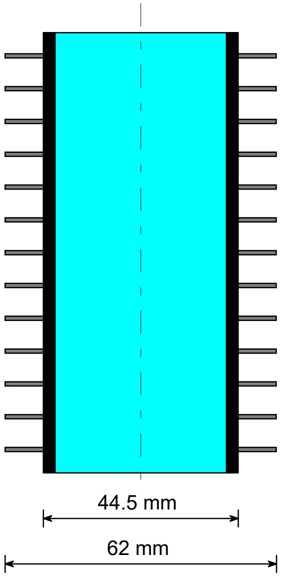
0 150 mm

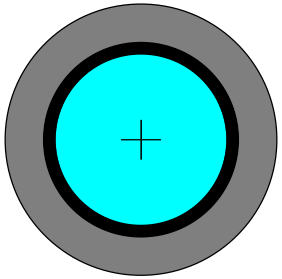
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS3
Date: 06/11/20	
Drawing No:	

RH3 Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	TP347HFG
Tube outer diameter	44.5 mm
Tube wall thickness	2.667 mm
Fin height	8.75 mm
Fin spacing	6.507 mm
Fin thickness	1 mm
Number of fins per meter	133.2
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	8064 m^2
Maximum gas velocity	16.79 m/s
Gas pressure drop	1.162 millibar
Steam side velocity	31.82 m/s
Steam side pressure drop	1.588 bar
Heat transfer from gas	33594 kW
Heat transfer to steam	33427 kW

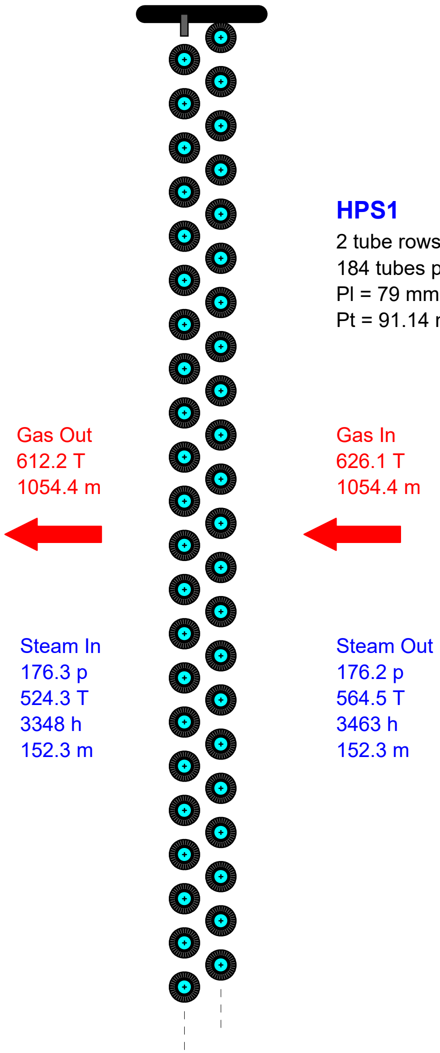
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

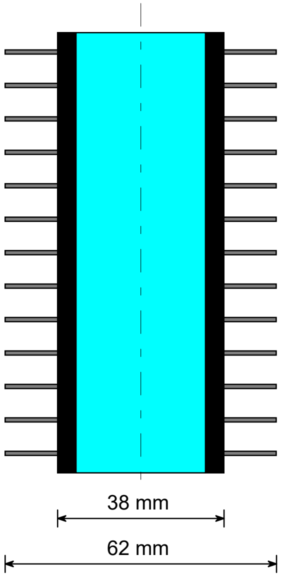
0 150 mm

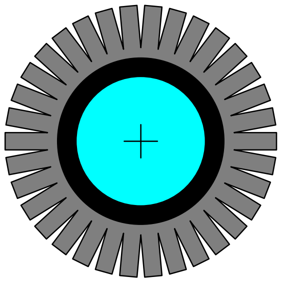
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH3
Date: 06/11/20	
Drawing No:	

HPS1 Hardware Design







Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T91
Tube outer diameter	38 mm
Tube wall thickness	4.191 mm
Fin height	12 mm
Fin spacing	6.65 mm
Fin thickness	1 mm
Number of fins per meter	130.7
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4680 m^2
Maximum gas velocity	14.55 m/s
Gas pressure drop	0.5532 millibar
Steam side velocity	11.38 m/s
Steam side pressure drop	0.1801 bar
Heat transfer from gas	17627 kW
Heat transfer to steam	17540 kW

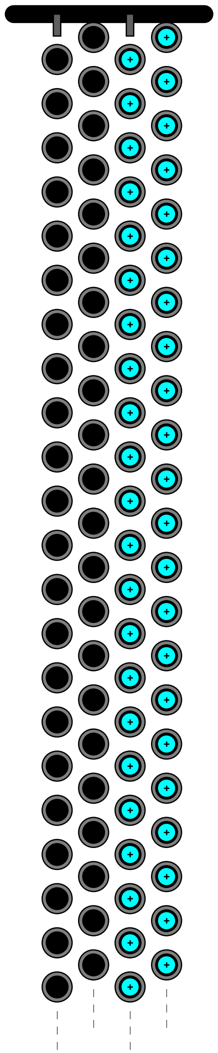
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS1
Date: 06/11/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

RH1 Hardware Design



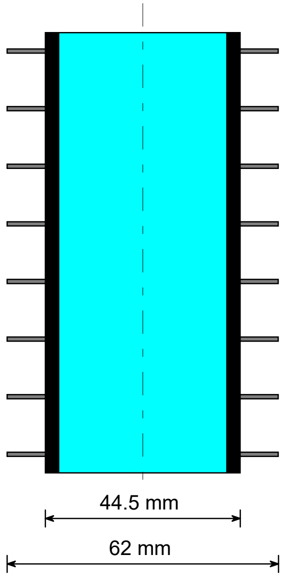
RH1
4 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

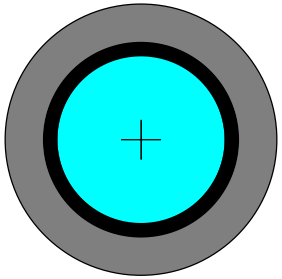
Gas Out
571.8 T
1054.4 m

Gas In
612.2 T
1054.4 m

Steam In
45.61 p
390.9 T
3182 h
161.6 m

Steam Out
44.22 p
523.7 T
3496 h
161.6 m





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T22
Tube outer diameter	44.5 mm
Tube wall thickness	3.048 mm
Fin height	8.75 mm
Fin spacing	12.19 mm
Fin thickness	1 mm
Number of fins per meter	75.8
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	5493 m^2
Maximum gas velocity	15.56 m/s
Gas pressure drop	0.8386 millibar
Steam side velocity	27.2 m/s
Steam side pressure drop	1.392 bar
Heat transfer from gas	50876 kW
Heat transfer to steam	50623 kW

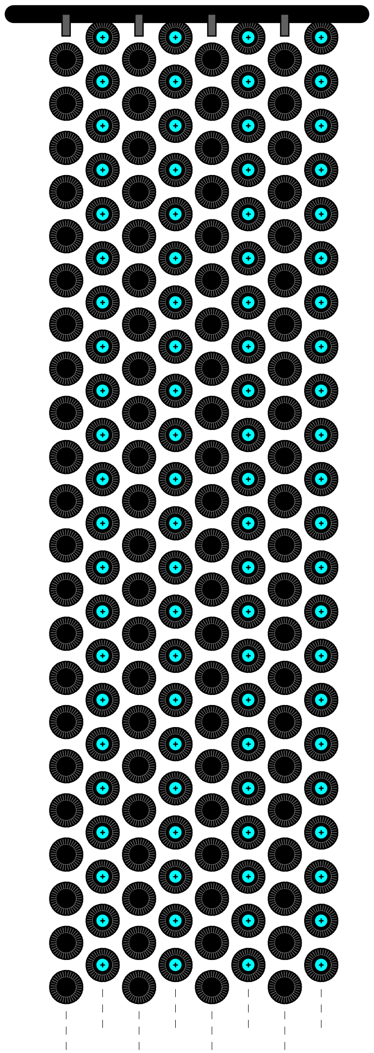
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH1
Date: 06/11/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

HPS0 (OTB) Hardware Design



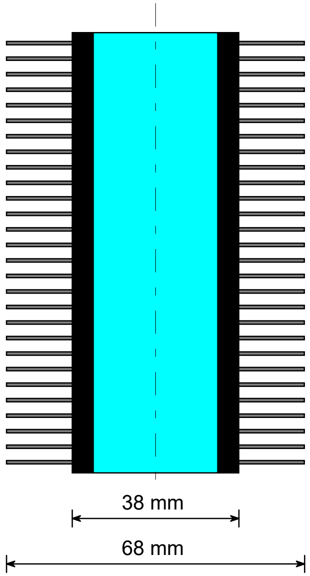
Gas Out
464.7 T
1054.4 m

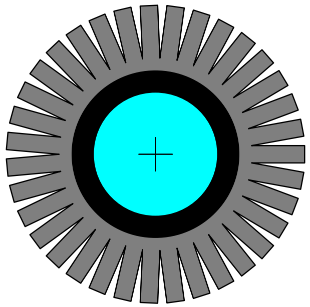
Steam In
186.7 p
360 T
2481.2 h
152.3 m

HPS0 (OTB)
7.746 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
571.8 T
1054.4 m

Steam Out
176.3 p
524.3 T
3348 h
152.3 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	7.746
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	42502 m^2
Maximum gas velocity	13.91 m/s
Gas pressure drop	3.388 millibar
Steam side velocity	18.38 m/s
Steam side pressure drop	10.34 bar
Heat transfer from gas	132672 kW
Heat transfer to steam	132012 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

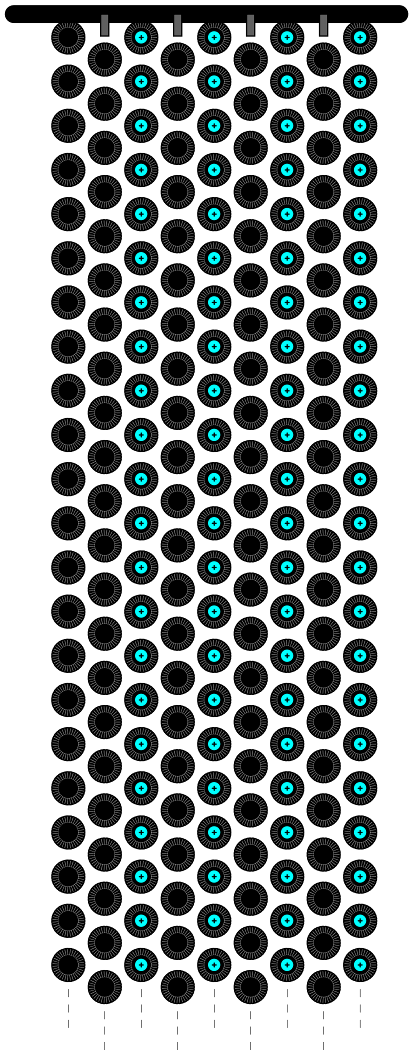
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS0 (OTB)
Date: 06/11/20	
Drawing No:	

HPB1 (OTB) Hardware Design

Gas Out
378.7 T
1054.4 m

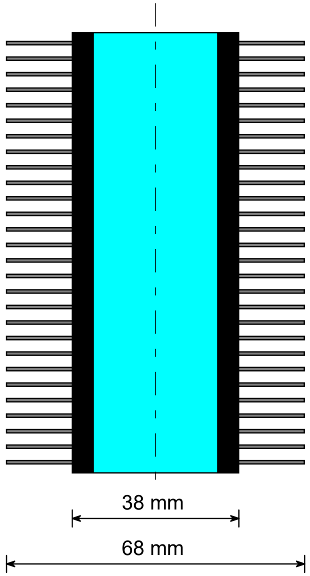
Water In
195.1 p
363.7 T
1801.5 h
152.3 m

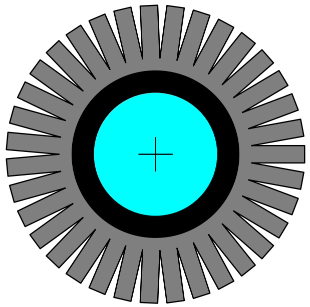


HPB1 (OTB)
8.579 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
464.7 T
1054.4 m

Steam Out
186.7 p
360 T
2481.2 h
152.3 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	8.579
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	47072 m^2
Maximum gas velocity	12.21 m/s
Gas pressure drop	3.218 millibar
Water side velocity	2.515 m/s
Water side pressure drop	8.359 bar
Heat transfer from gas	104060 kW
Heat transfer to steam/water	103542 kW

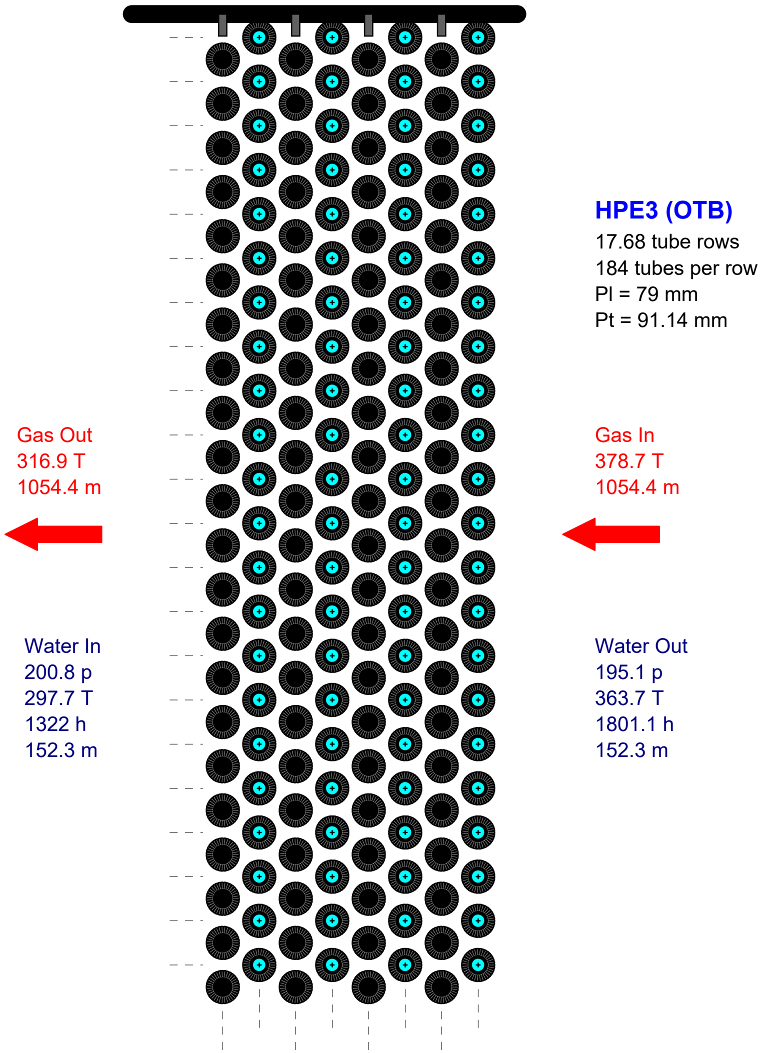
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

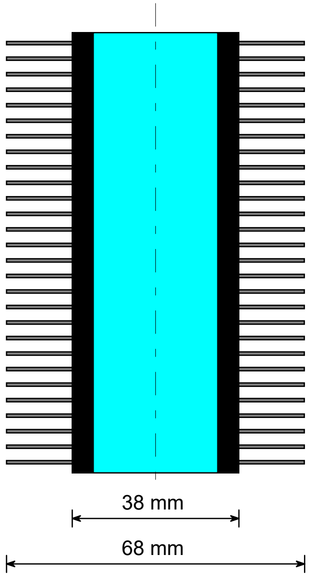
0 150 mm

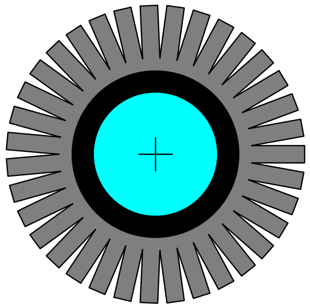
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPB1 (OTB)
Date: 06/11/20	
Drawing No:	

HPE3 (OTB) Hardware Design







Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	17.68
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	96990 m^2
Maximum gas velocity	10.91 m/s
Gas pressure drop	5.877 millibar
Water side velocity	1.96 m/s
Water side pressure drop	5.68 bar
Heat transfer from gas	73325 kW
Heat transfer to water	72960 kW

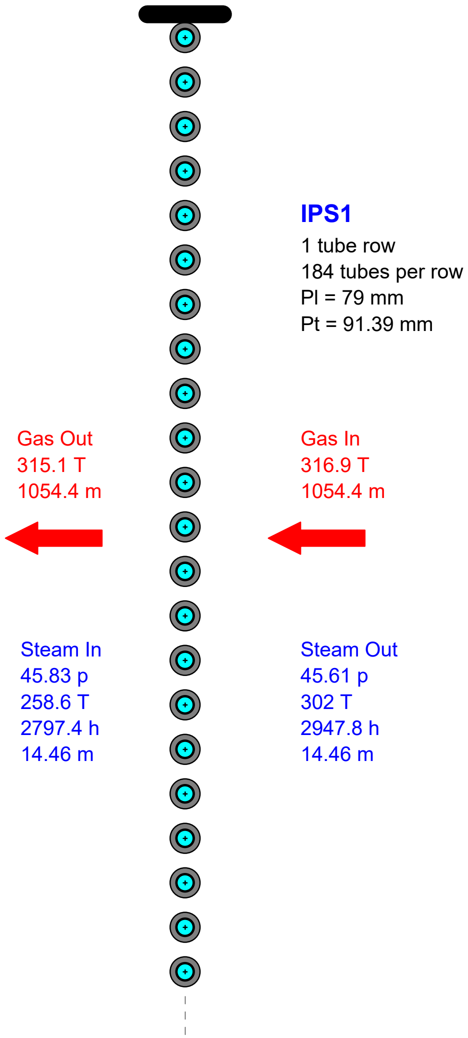
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

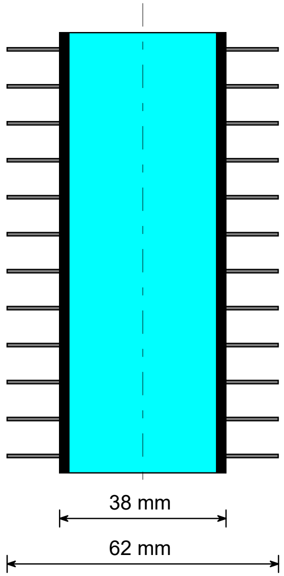
0 150 mm

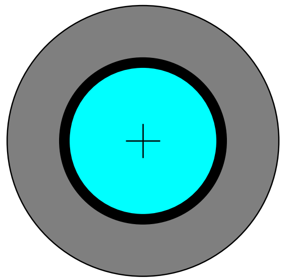
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE3 (OTB)
Date: 06/11/20	
Drawing No:	

IPS1 Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	7.626 mm
Fin thickness	0.8 mm
Number of fins per meter	118.7
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.39 mm
# of tube rows (longitudinal)	1
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2154.4 m^2
Maximum gas velocity	9.397 m/s
Gas pressure drop	0.1551 millibar
Steam side velocity	4.146 m/s
Steam side pressure drop	0.2208 bar
Heat transfer from gas	2184.3 kW
Heat transfer to steam	2173.4 kW

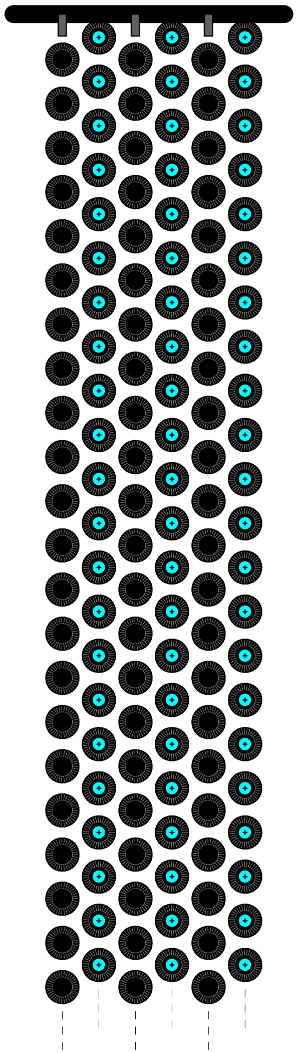
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPS1
Date: 06/11/20	
Drawing No:	

HPE2 Hardware Design



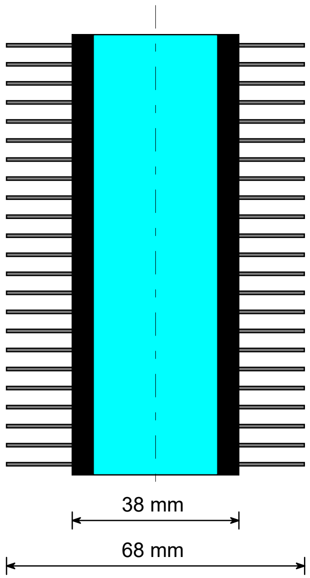
HPE2
6 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

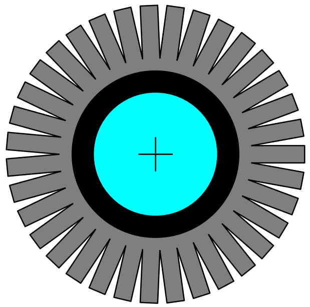
Gas Out
289.8 T
1054.4 m

Gas In
315.1 T
1054.4 m

Water In
202.9 p
258.7 T
1127.9 h
152.3 m

Water Out
200.8 p
297.7 T
1322 h
152.3 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	3.555 mm
Fin thickness	0.8 mm
Number of fins per meter	229.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	27374 m^2
Maximum gas velocity	9.851 m/s
Gas pressure drop	1.529 millibar
Water side velocity	1.683 m/s
Water side pressure drop	2.175 bar
Heat transfer from gas	29720 kW
Heat transfer to water	29572 kW

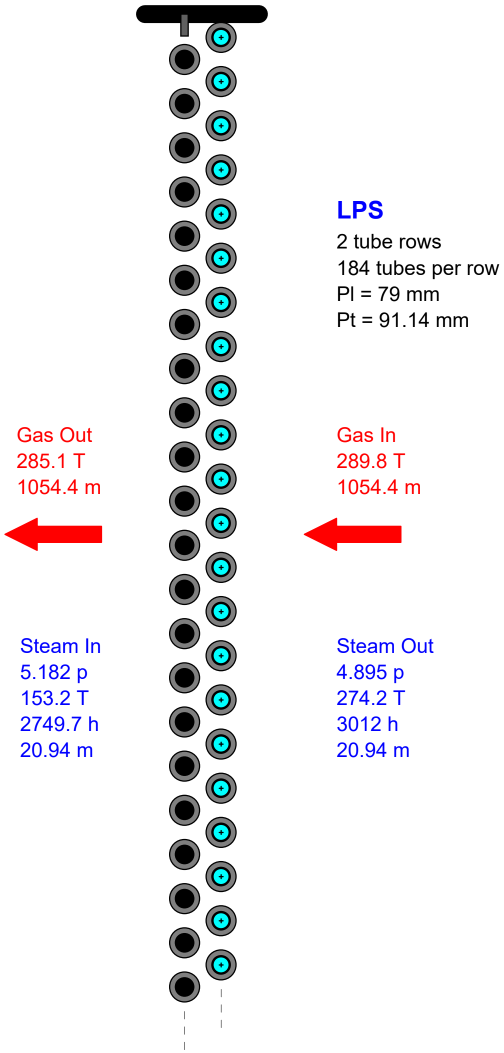
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

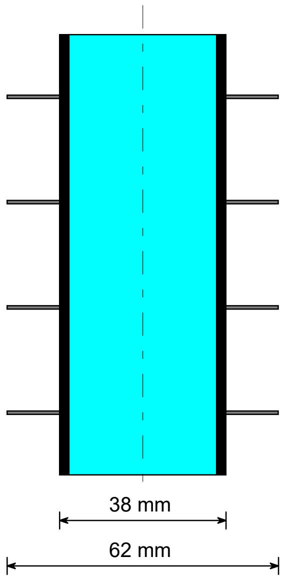
0 150 mm

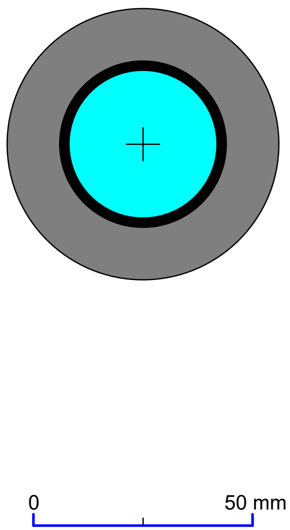
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE2
Date: 06/11/20	
Drawing No:	

LPS Hardware Design



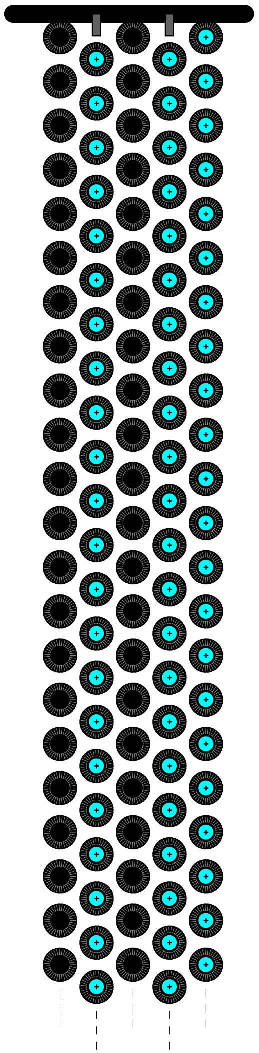




Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	23.26 mm
Fin thickness	0.8 mm
Number of fins per meter	41.56
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2091.2 m^2
Maximum gas velocity	8.731 m/s
Gas pressure drop	0.1942 millibar
Steam side velocity	55.27 m/s
Steam side pressure drop	0.2864 bar
Heat transfer from gas	5513 kW
Heat transfer to steam	5485 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPS
Date: 06/11/20	
Drawing No:	



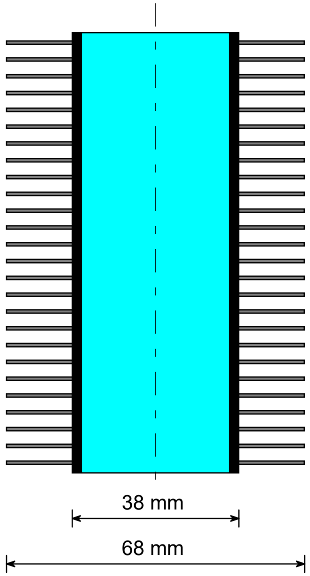
IPB
5 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

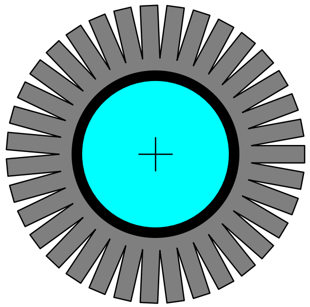
Gas Out
267.8 T
1054.4 m

Gas In
285.1 T
1054.4 m

Water In
45.83 p
258.3 T
1126.3 h
12.03 m

Steam Out
45.83 p
258.6 T
2797.4 h
12.03 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.045 mm
Fin thickness	0.8 mm
Number of fins per meter	260
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	5
# of rows per pass	1.251
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	25540 m^2
Maximum gas velocity	9.552 m/s
Gas pressure drop	1.337 millibar
Water side velocity	1.336 m/s
Water side pressure drop	0 bar
Heat transfer from gas	20210 kW
Heat transfer to steam/water	20110 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

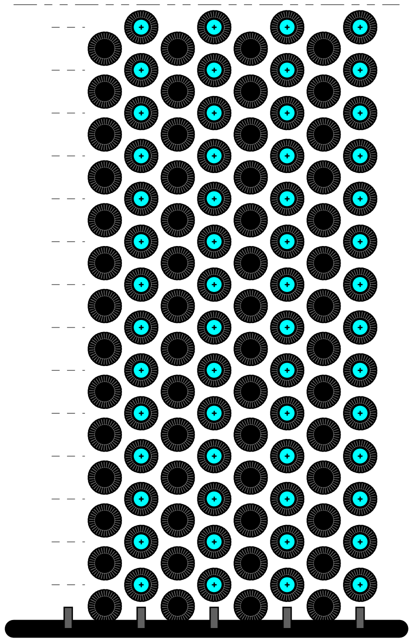
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPB
Date: 06/11/20	
Drawing No:	

IPE2 Hardware Design

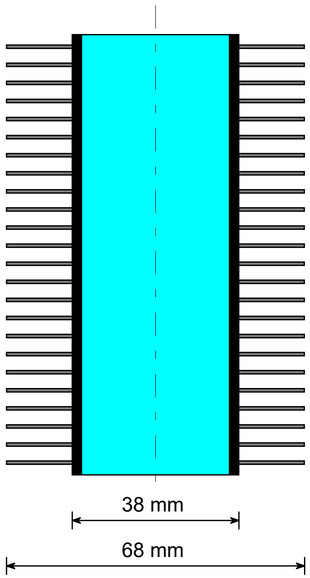
Parallel HX

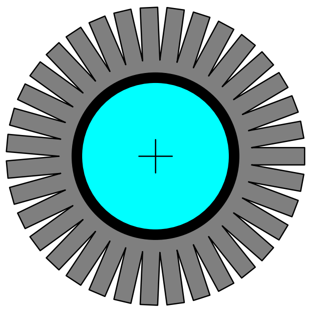


IPE2 (Parallel)
14 tube rows
14 tubes per row
Pl = 79 mm
Pt = 88.19 mm

Gas Out	Gas In
204.1 T	267.8 T
80.88 m	80.88 m

Water In	Water Out
47.26 p	45.83 p
155.6 T	258.3 T
658.9 h	1126.3 h
12.15 m	12.15 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.339 mm
Fin thickness	0.8 mm
Number of fins per meter	241.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	88.19 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	14
Tube length	20.4 m
Gas path transverse width	1.279 m
Gas path frontal area	26.09 m^2
HX total outside surface area	5089 m^2
Maximum gas velocity	9.418 m/s
Gas pressure drop	3.685 millibar
Water side velocity	1.128 m/s
Water side pressure drop	1.429 bar
Heat transfer from gas	5708 kW
Heat transfer to water	5680 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

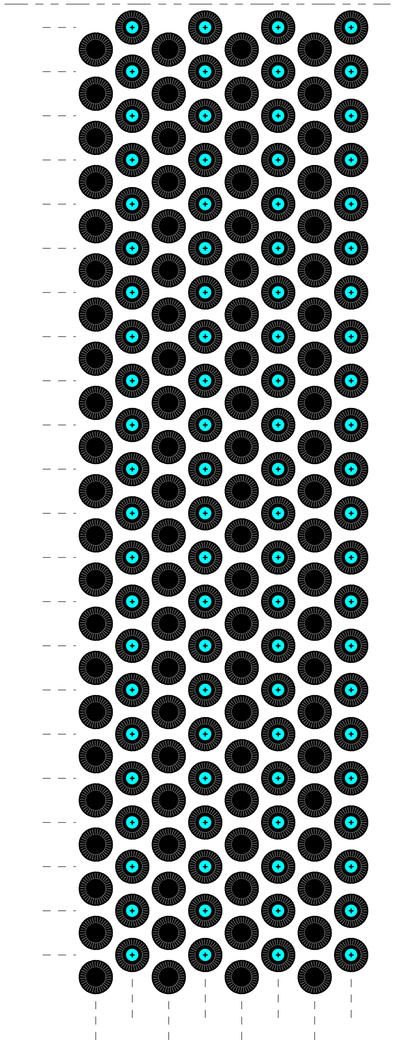
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPE2 (Parallel)
Date: 06/11/20	
Drawing No:	

HPE0 Hardware Design

Parallel HX



HPE0 (Parallel)

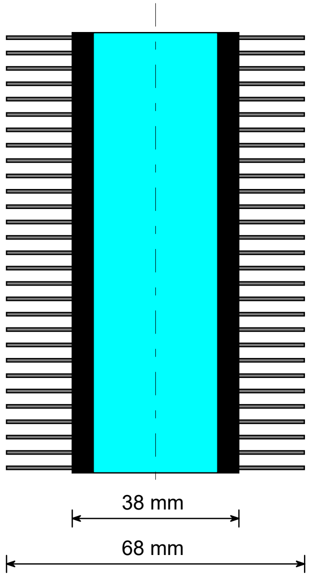
14 tube rows
170 tubes per row
Pl = 79 mm
Pt = 91.12 mm

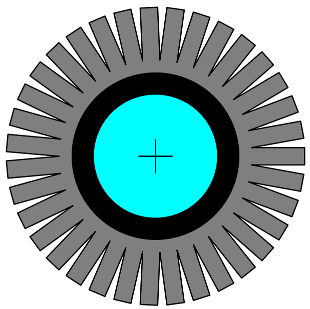
Gas Out
204.1 T
973.5 m

Gas In
267.8 T
973.5 m

Water In
208.4 p
159.1 T
683.6 h
152.3 m

Water Out
202.9 p
258.7 T
1127.9 h
152.3 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.699 mm
Fin thickness	0.8 mm
Number of fins per meter	285.8
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.12 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	170
Tube length	20.4 m
Gas path transverse width	15.54 m
Gas path frontal area	316.9 m^2
HX total outside surface area	72030 m^2
Maximum gas velocity	8.964 m/s
Gas pressure drop	3.685 millibar
Water side velocity	1.623 m/s
Water side pressure drop	5.443 bar
Heat transfer from gas	67999 kW
Heat transfer to water	67661 kW

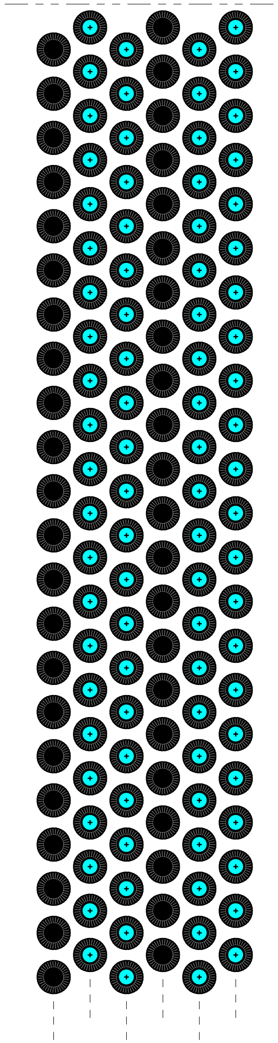
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE0 (Parallel)
Date: 06/11/20	
Drawing No:	

Parallel HX



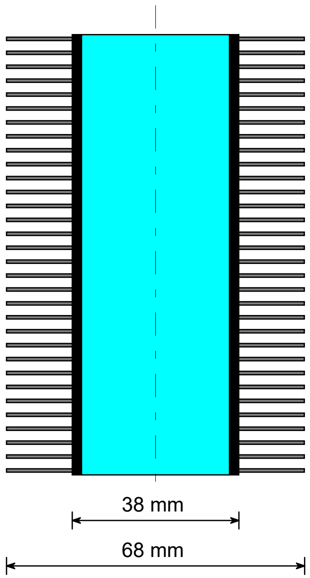
LPB
6 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

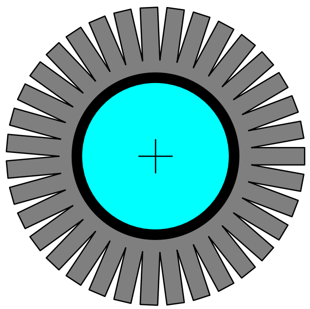
Gas Out
165.4 T
1054.4 m

Gas In
204.1 T
1054.4 m

Water In
5.182 p
153.8 T
648.6 h
20.94 m

Steam Out
5.182 p
153.2 T
2749.7 h
20.94 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	2.359 mm
Fin thickness	0.8 mm
Number of fins per meter	316.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1.501
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	36720 m^2
Maximum gas velocity	8.196 m/s
Gas pressure drop	1.519 millibar
Water side velocity	1.666 m/s
Water side pressure drop	0 bar
Heat transfer from gas	44223 kW
Heat transfer to steam/water	44003 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

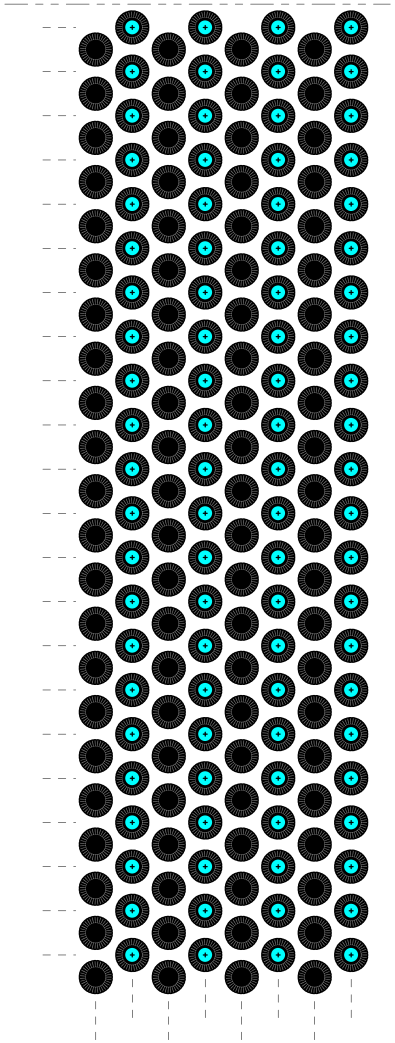
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPB
Date: 06/11/20	
Drawing No:	

LTE Hardware Design

Parallel HX



LTE

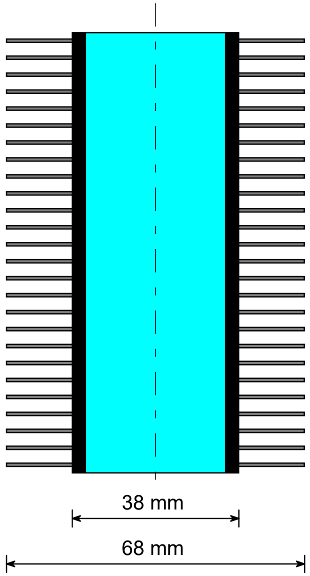
10 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

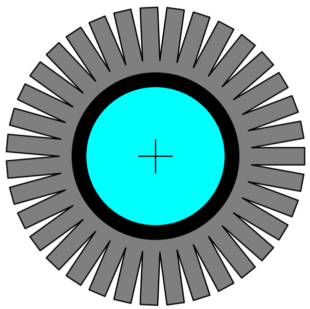
Gas Out
132.5 T
1054.4 m

Gas In
165.4 T
1054.4 m

Water In
5.461 p
108.1 T
454.4 h
192 m

Water Out
5.264 p
153.8 T
648.6 h
192 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	3.048 mm
Fin height	15 mm
Fin spacing	3.077 mm
Fin thickness	0.8 mm
Number of fins per meter	257.9
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	10
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	50703 m^2
Maximum gas velocity	7.329 m/s
Gas pressure drop	1.919 millibar
Water side velocity	1.397 m/s
Water side pressure drop	0.1977 bar
Heat transfer from gas	37478 kW
Heat transfer to water	37292 kW

Flow out of drawing
Flow into drawing

p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

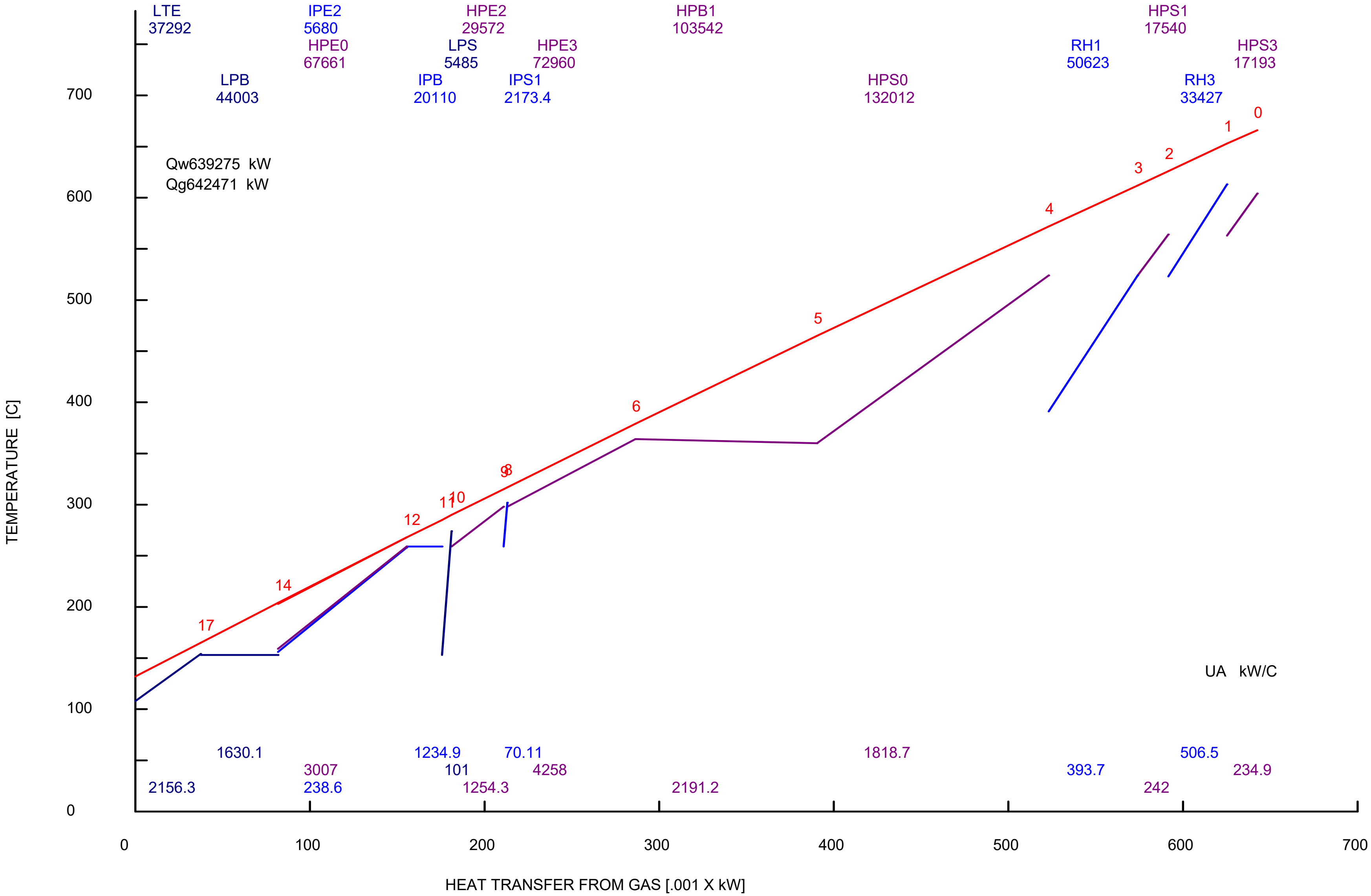
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LTE
Date: 06/11/20	
Drawing No:	

GT MASTER 29.0 AECOM

Net Power 722753 kW
LHV Net Heat Rate 6933 kJ/kWh
LHV Net Efficiency 51.93 %

HRSG Temperature Profile



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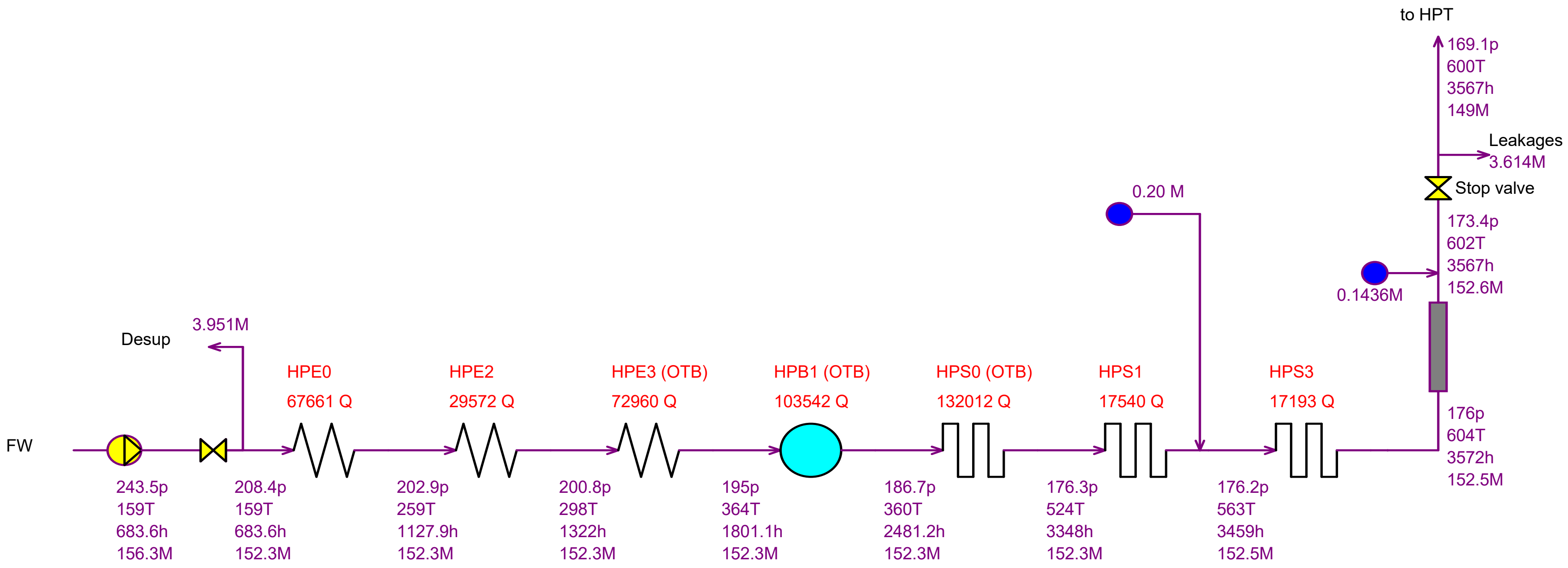
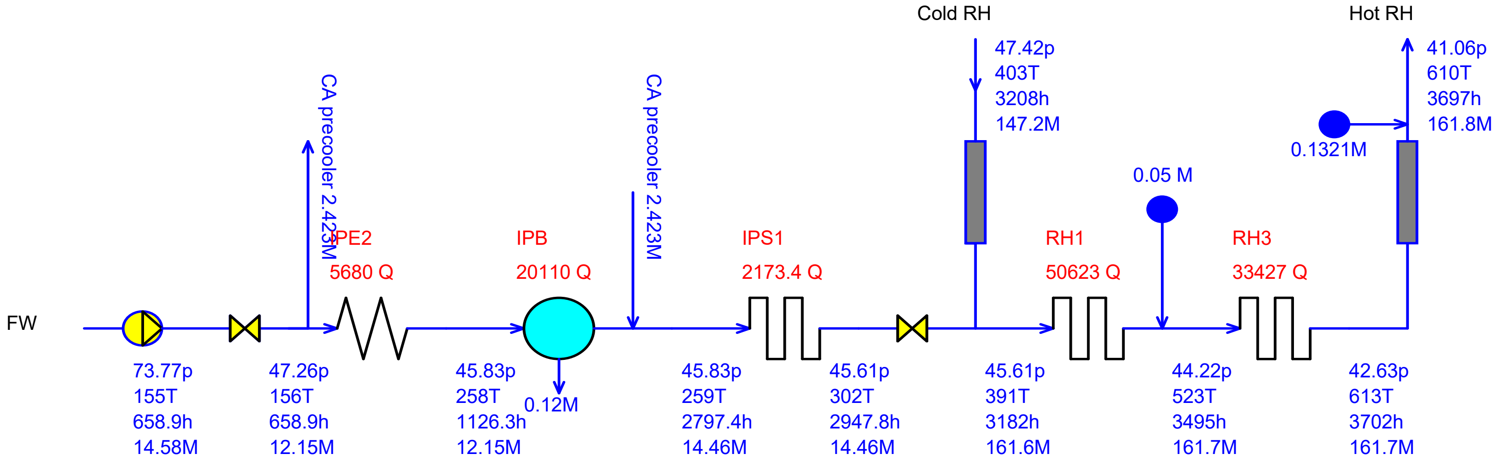
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

HP Water Path



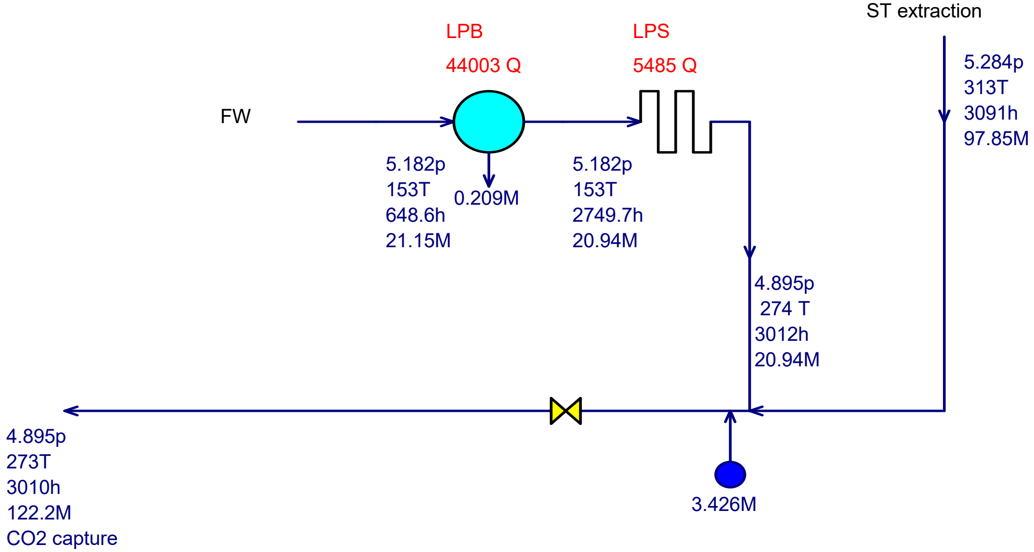
IP & Reheat Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

1220 06-11-2020 20:06:49 file= Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

LP Water Path

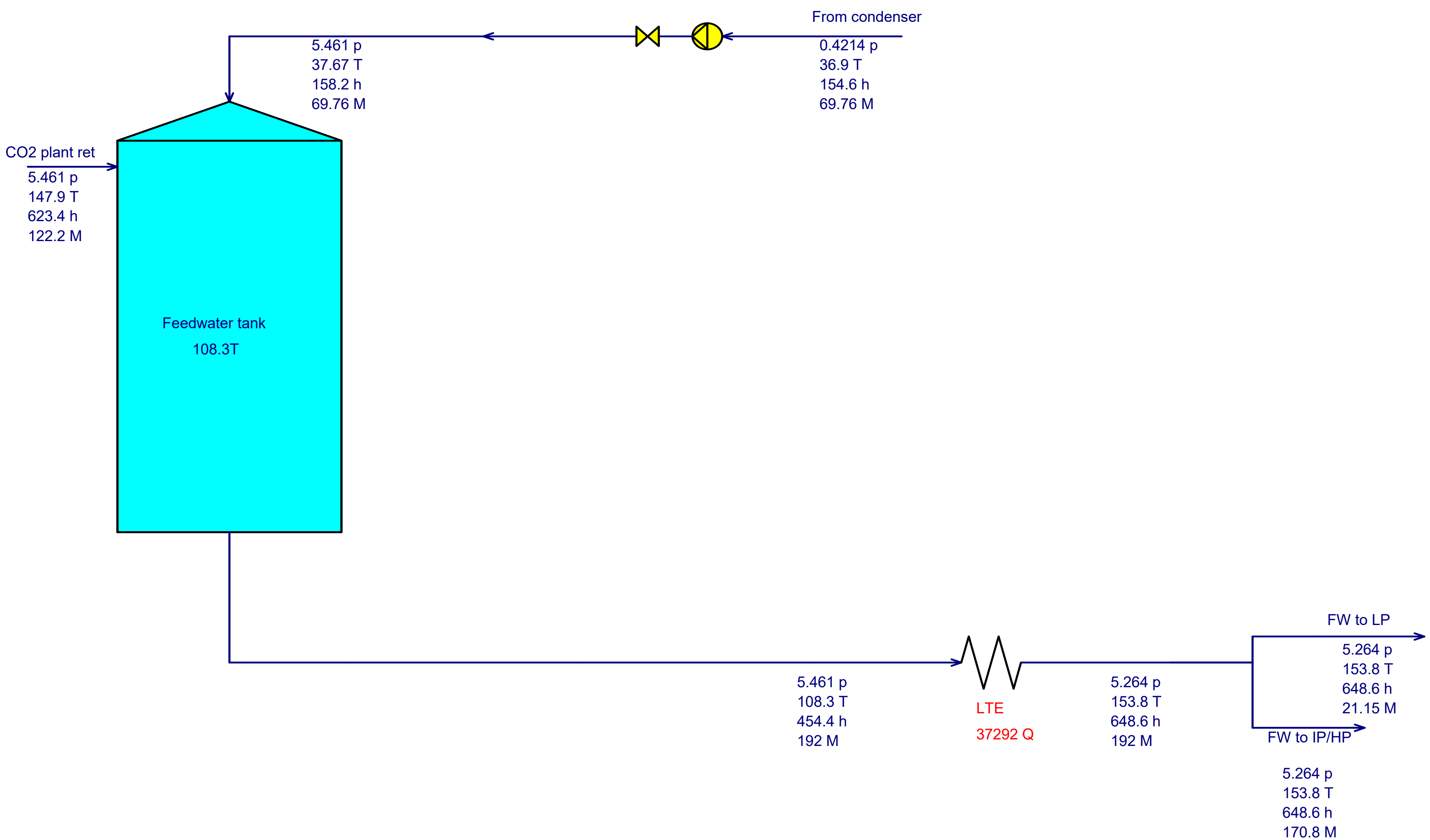


p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Feedwater Path

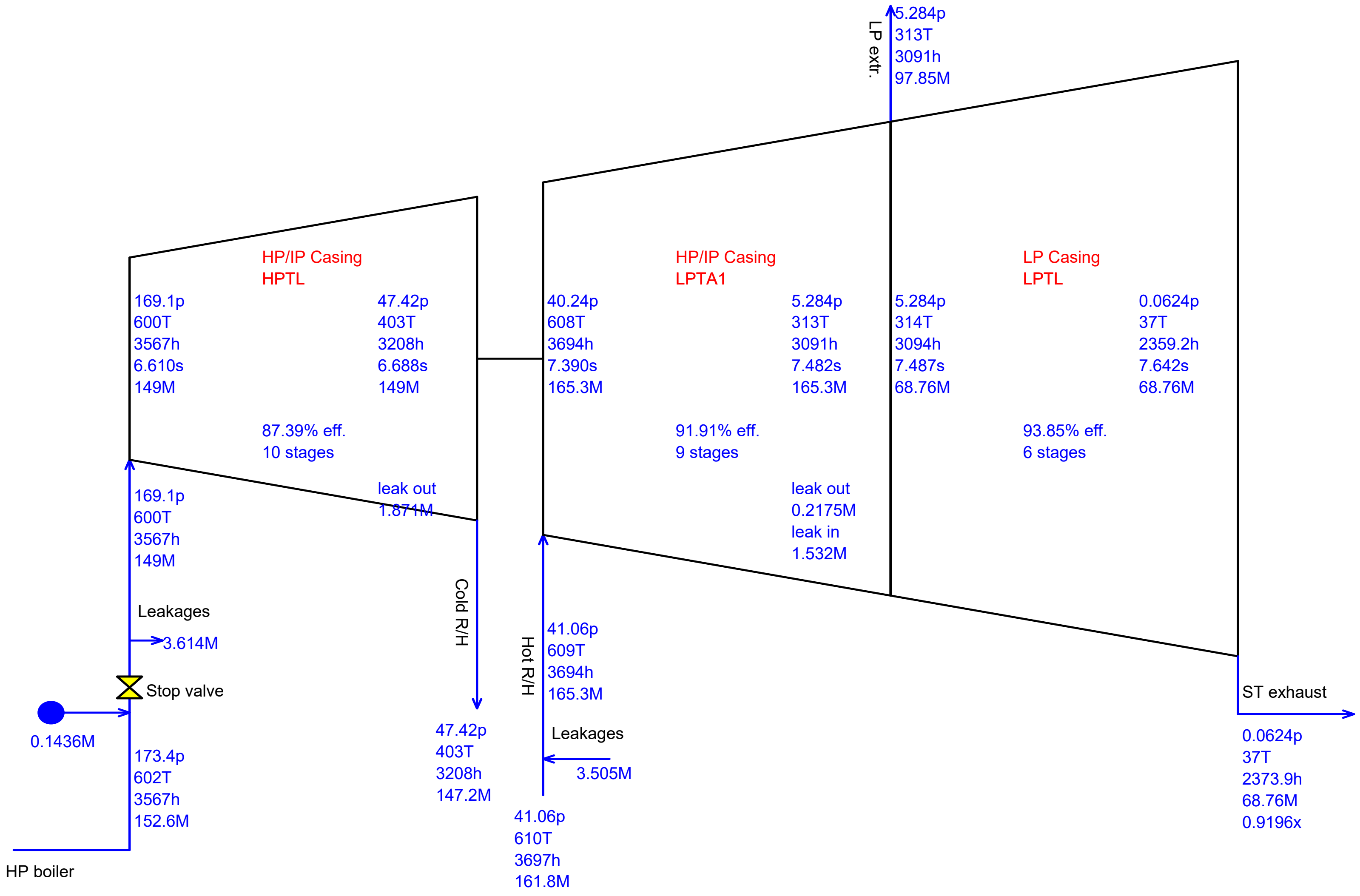


p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

1220 06-11-2020 20:06:49 file= Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

ST Expansion Power 202636 kW
ST Generator Output 199608 kW

Steam Turbine Group Data

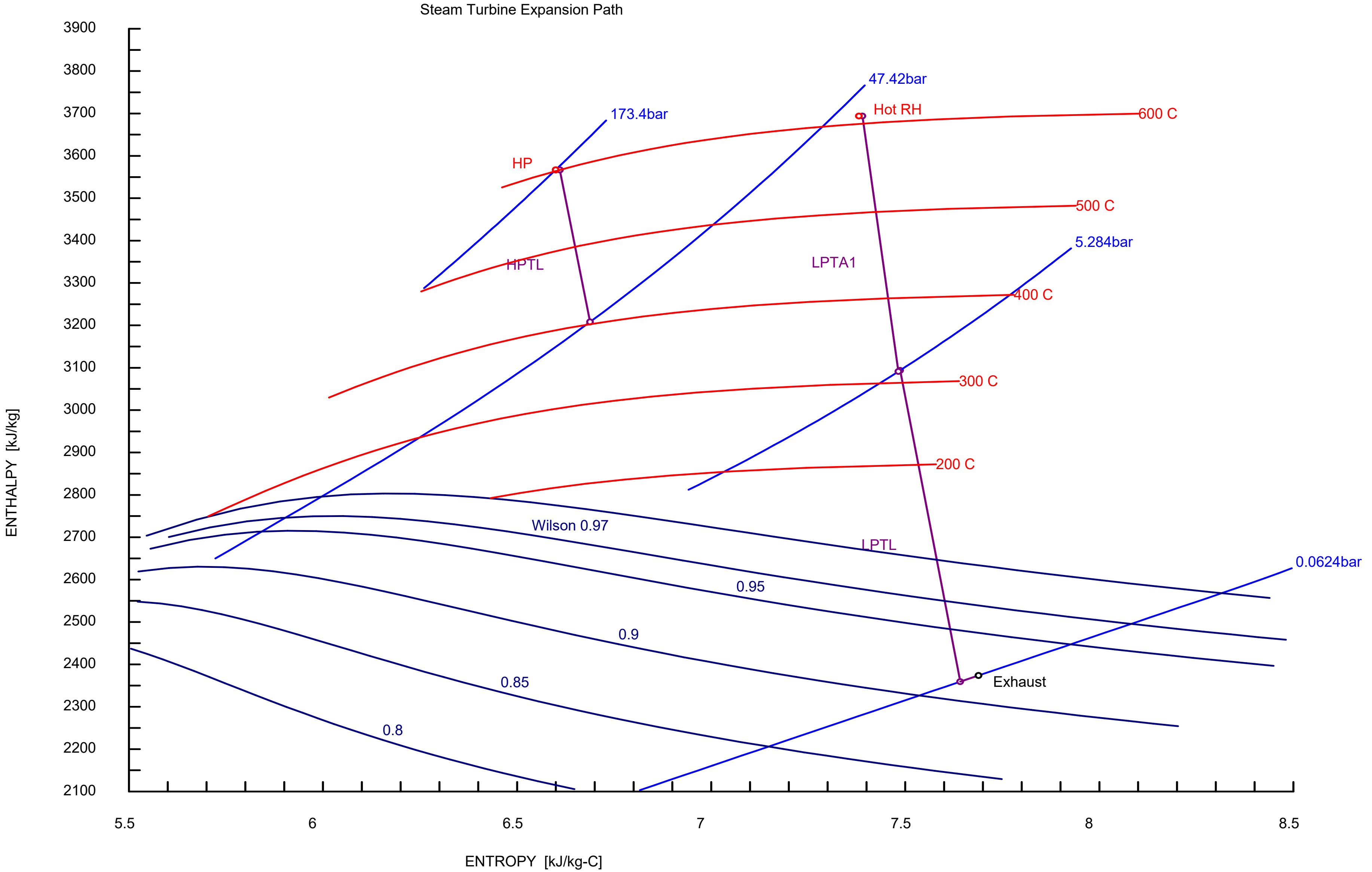


ST Model Adjustments: Disabled
p[bar], T[C], h[kJ/kg], s[kJ/kg-C], M[kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 20:06:49 file=

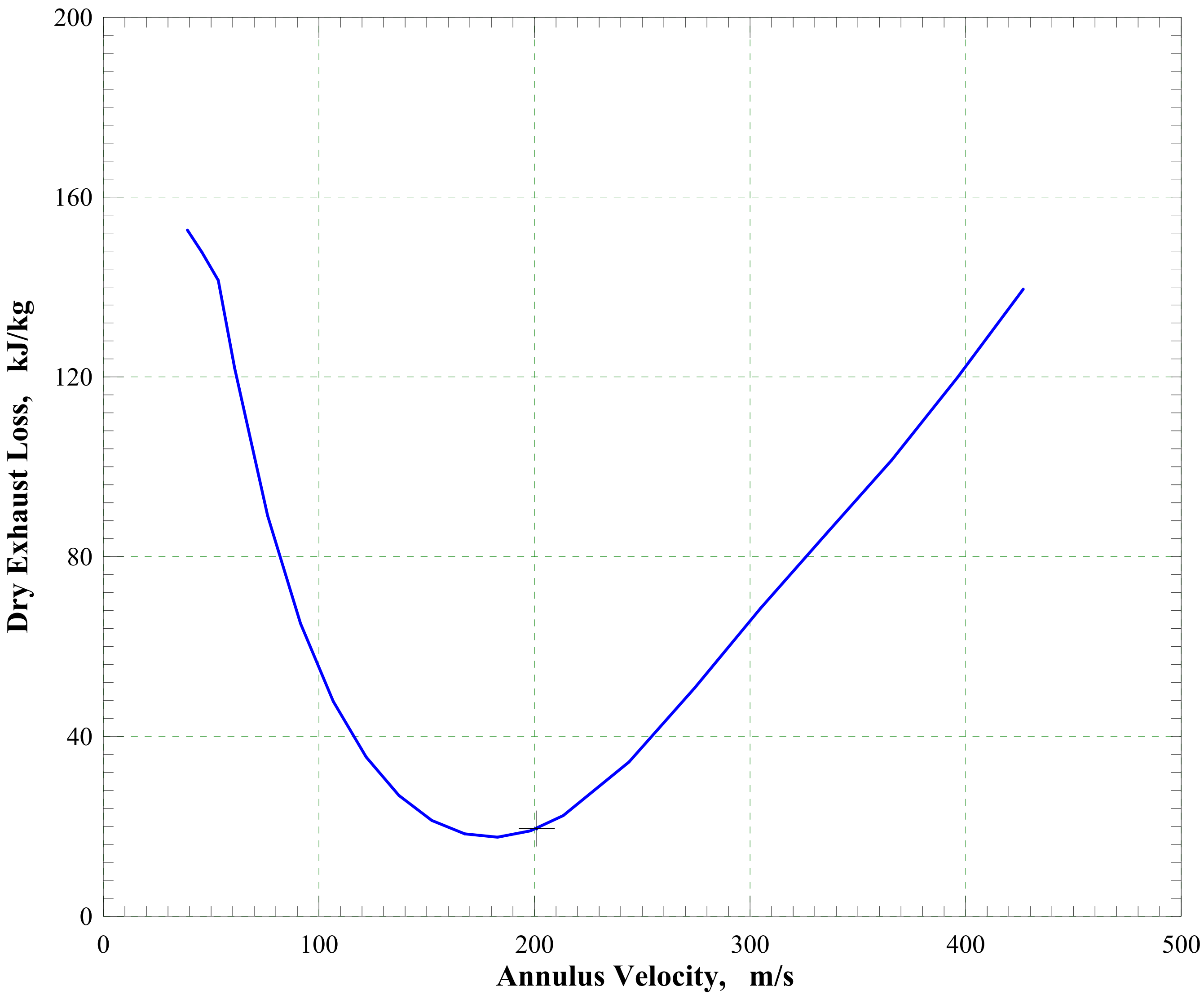
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

GT MASTER 29.0 AECOM

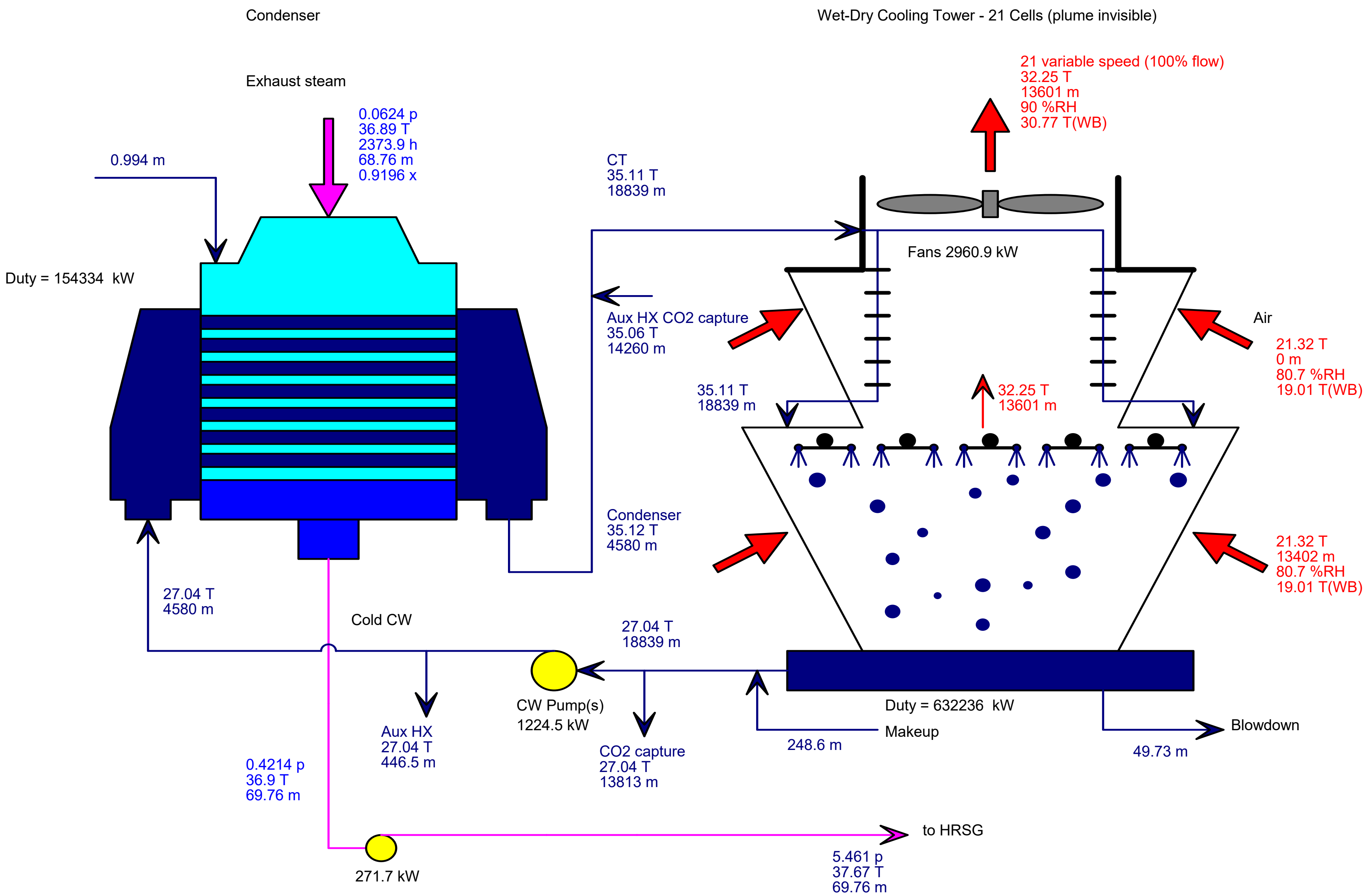
ST Expansion Power 202636 kW
ST Generator Output 199608 kW



Steam Turbine Exhaust Loss



Cooling System



p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

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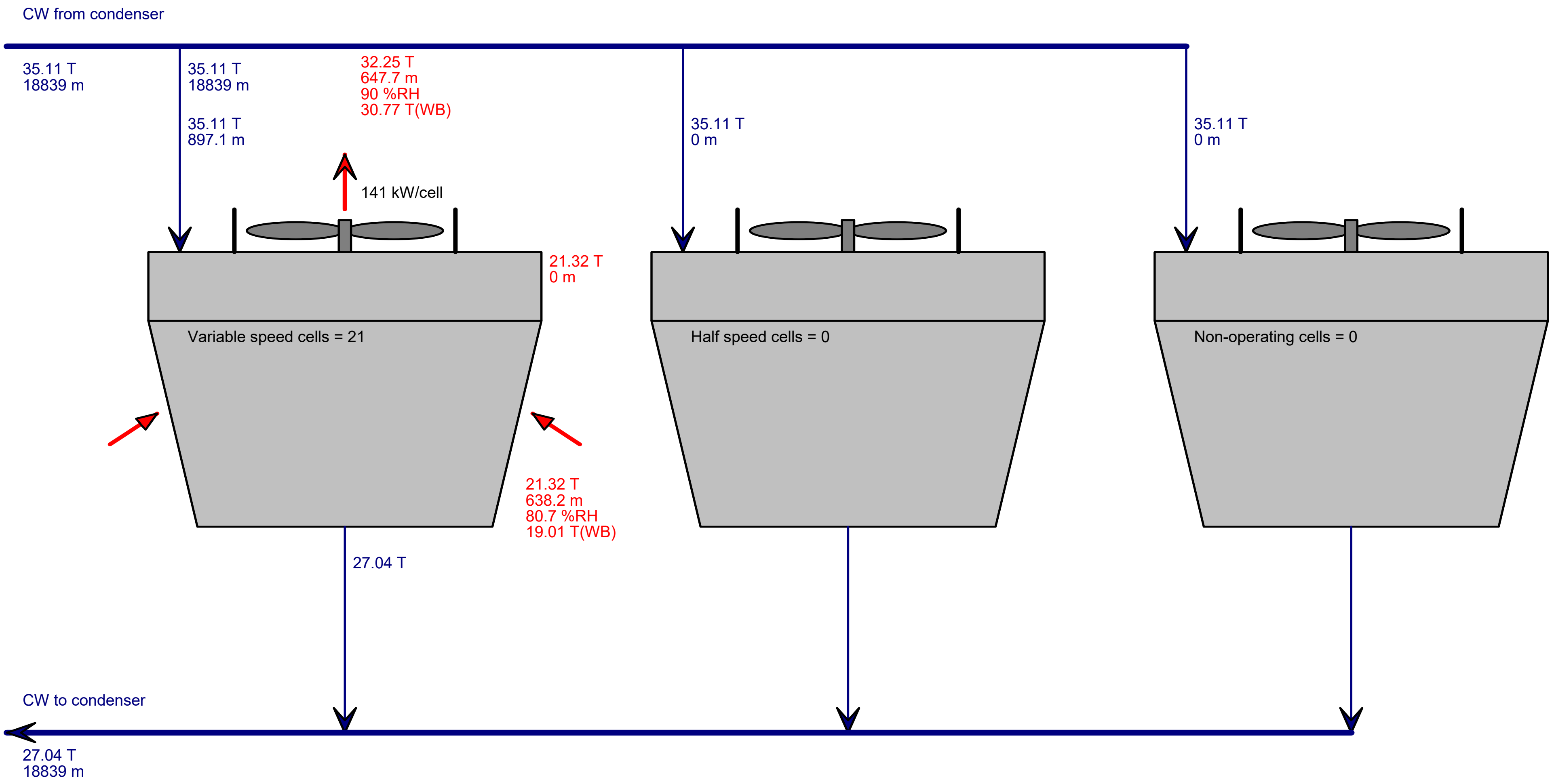
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Cooling Tower Cells - 21 existing cells

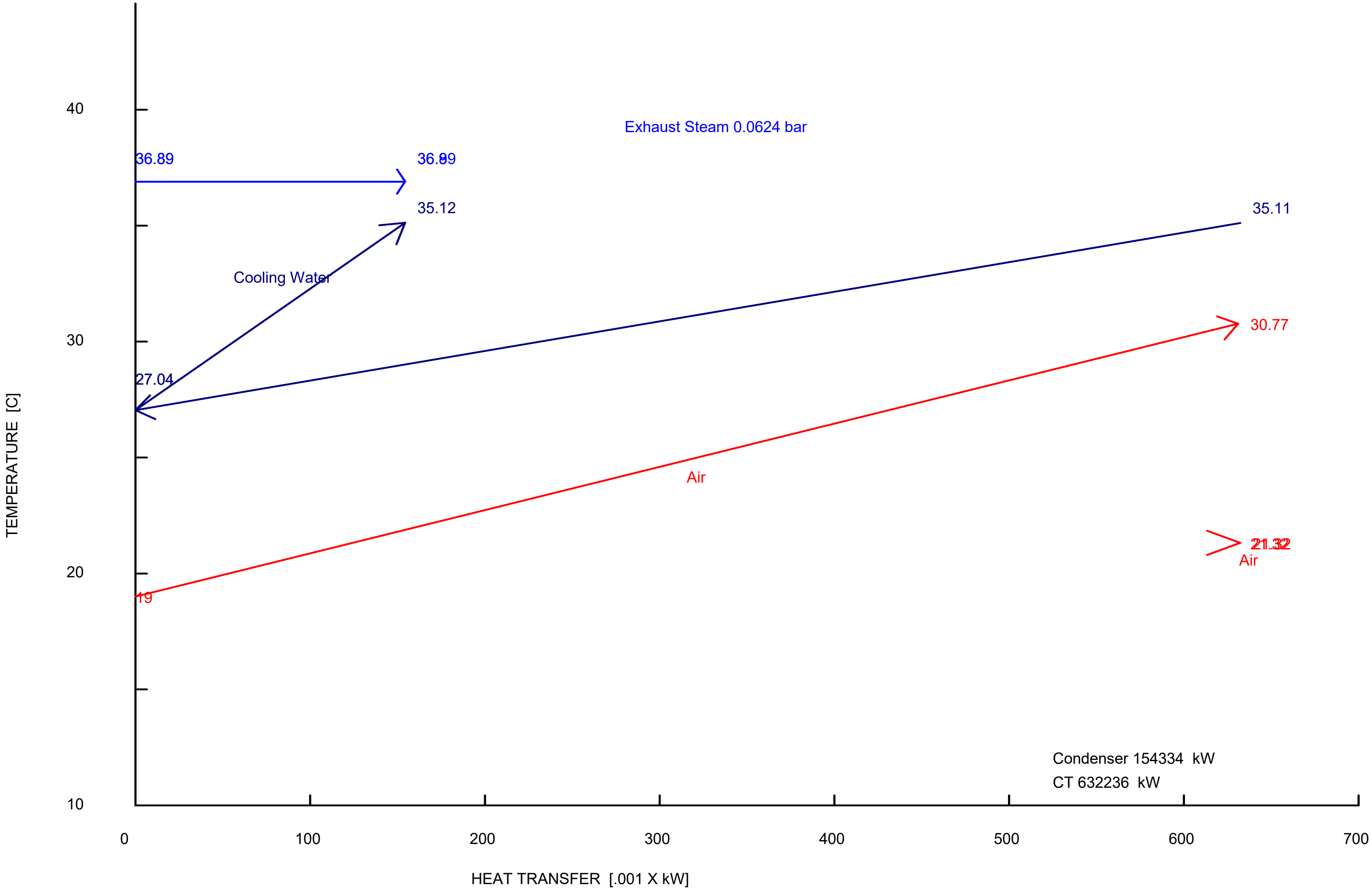


p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Water Cooled Condenser and Wet-Dry Cooling Tower T-Q Diagram



AIR STATES:

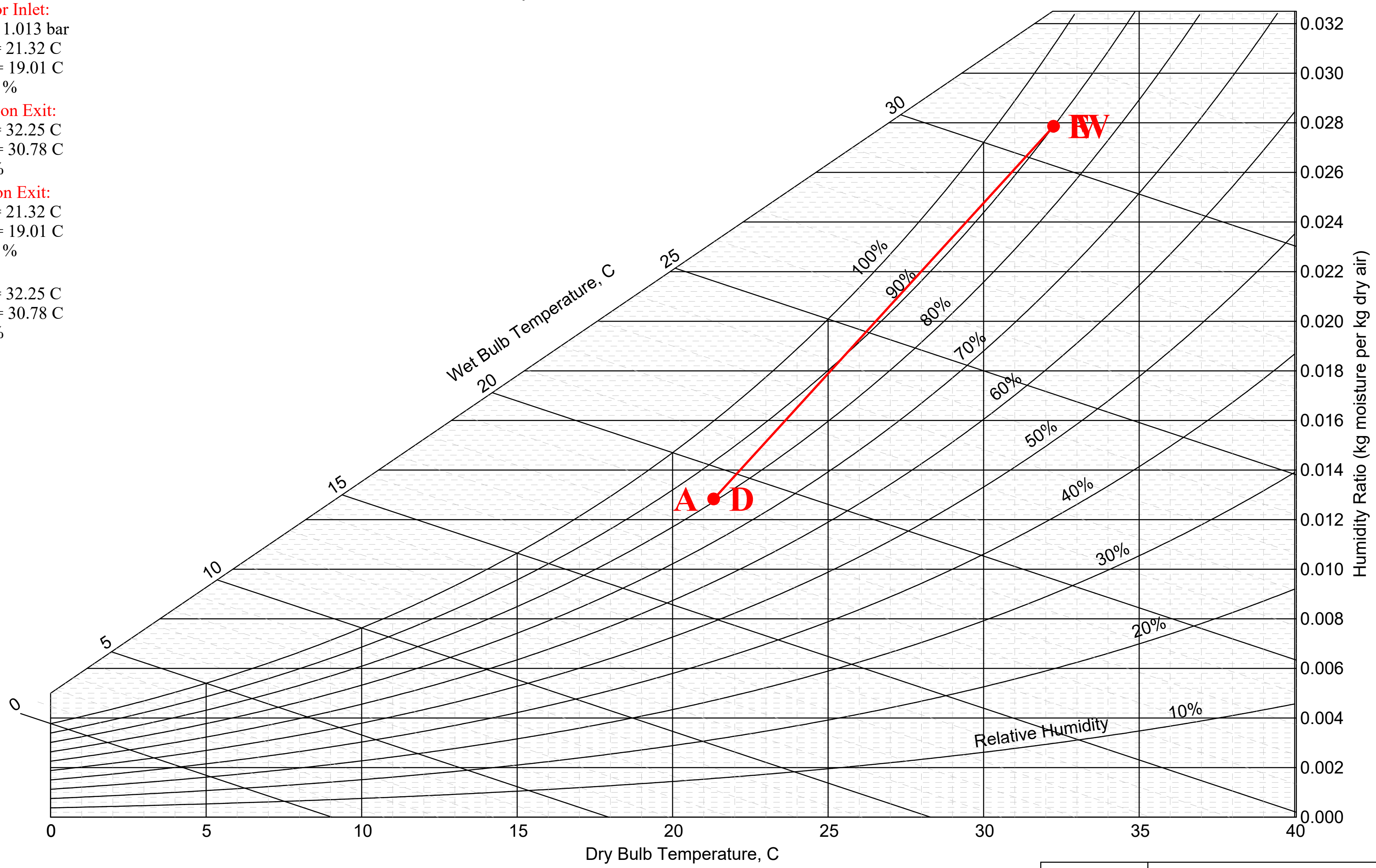
A) Ambient or Inlet:
- Pressure = 1.013 bar
- Dry bulb = 21.32 C
- Wet bulb = 19.01 C
- RH = 80.7 %

W) Wet Section Exit:
- Dry bulb = 32.25 C
- Wet bulb = 30.78 C
- RH = 90 %

D) Dry Section Exit:
- Dry bulb = 21.32 C
- Wet bulb = 19.01 C
- RH = 80.7 %

E) Air Exit:
- Dry bulb = 32.25 C
- Wet bulb = 30.78 C
- RH = 90 %

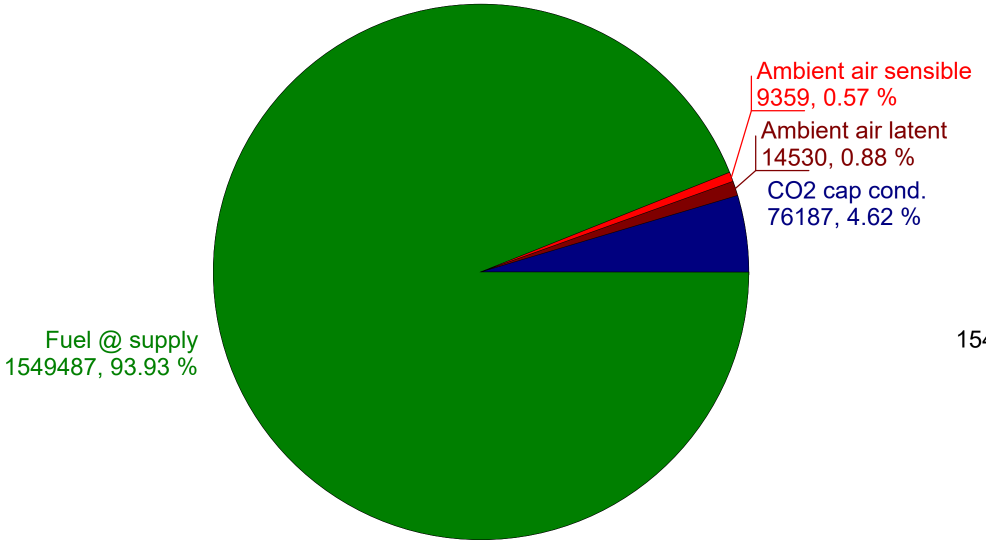
Psychrometric Chart



Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Cooling Tower
Date: 06/11/20	
Drawing No:	

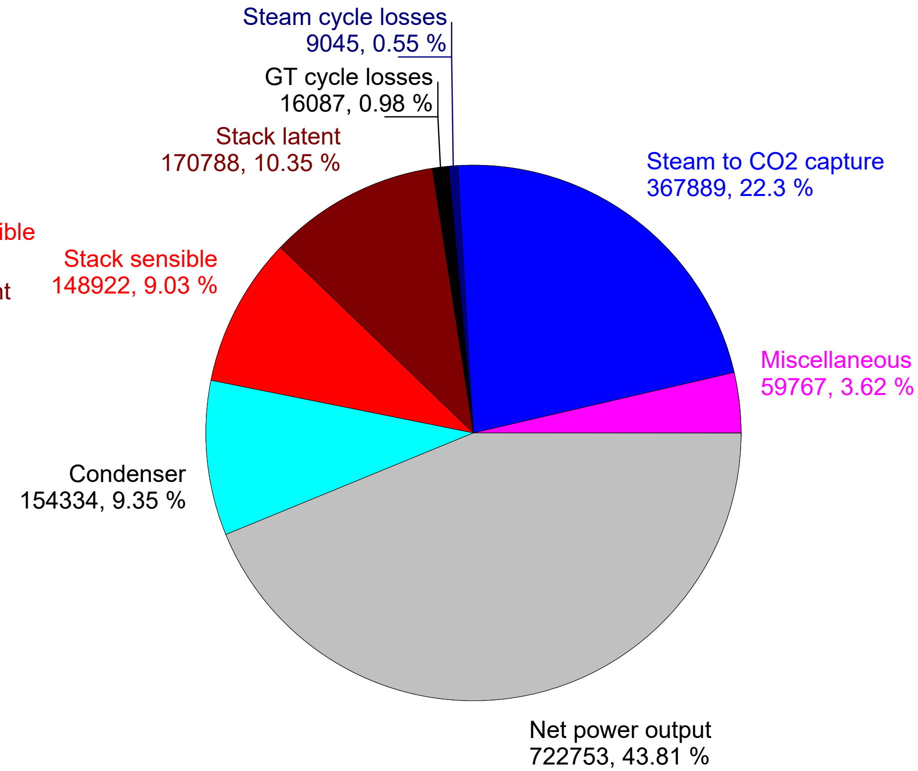
Plant Energy In [kW]

Plant energy in = 1649584 kW
Plant fuel chemical LHV input = 1391862 kW, HHV = 1544429 kW
Plant net LHV elec. eff. = 51.93 % (100% * 722753 / 1391862), Net HHV elec. eff. = 46.8 %



Plant Energy Out [kW]

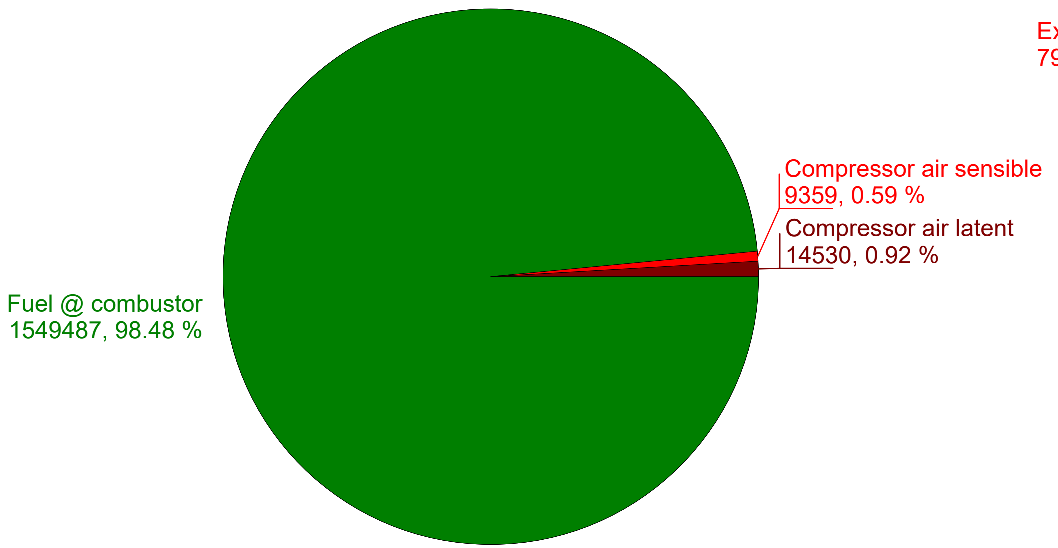
Plant energy out = 1649855 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

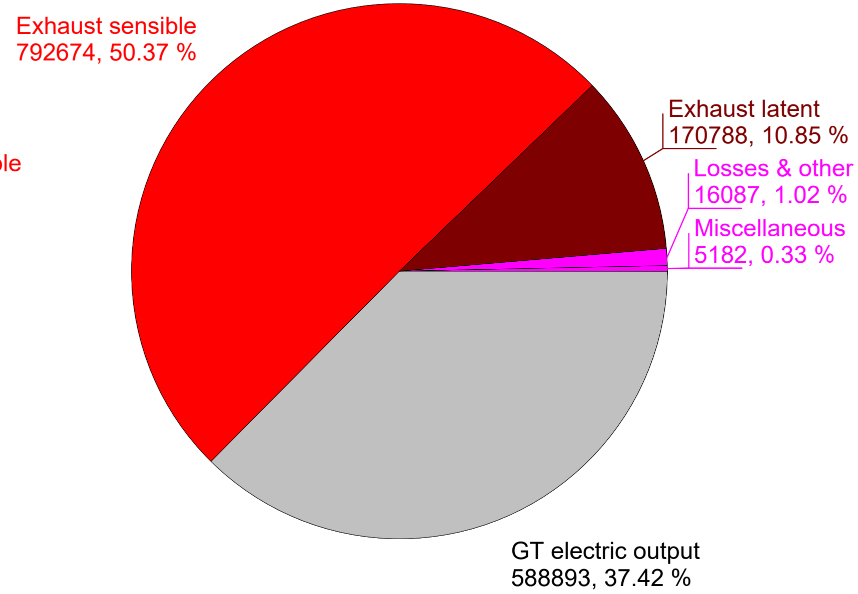
GT Cycle Energy In [kW]

GT cycle energy in = 1573376 kW
GT fuel chemical LHV input = 1391862 kW, HHV = 1544429 kW



GT Cycle Energy Out [kW]

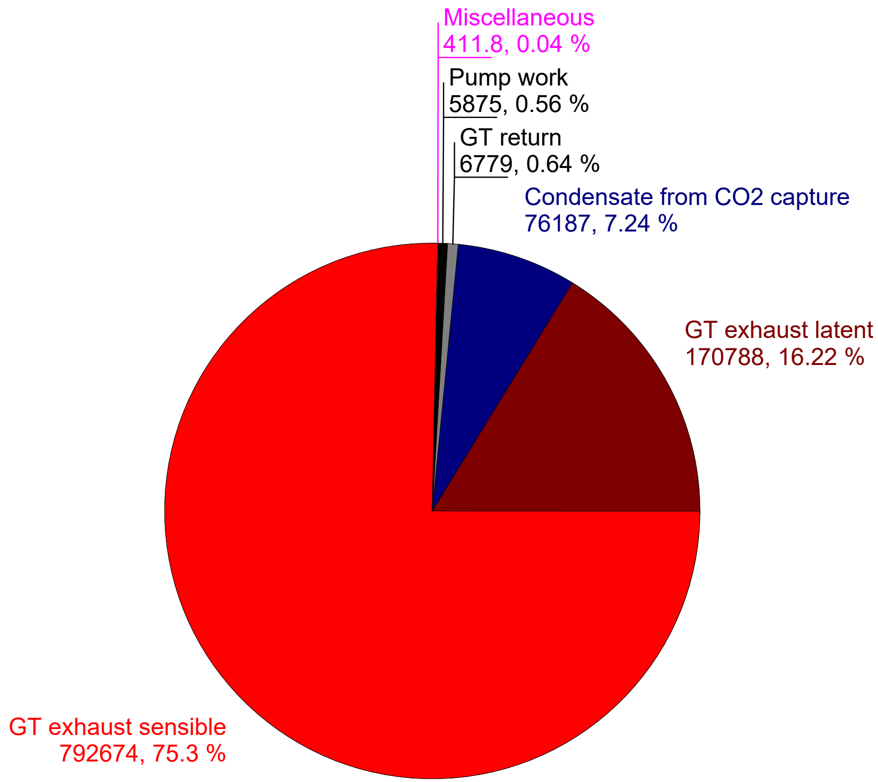
GT cycle energy out = 1573624 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

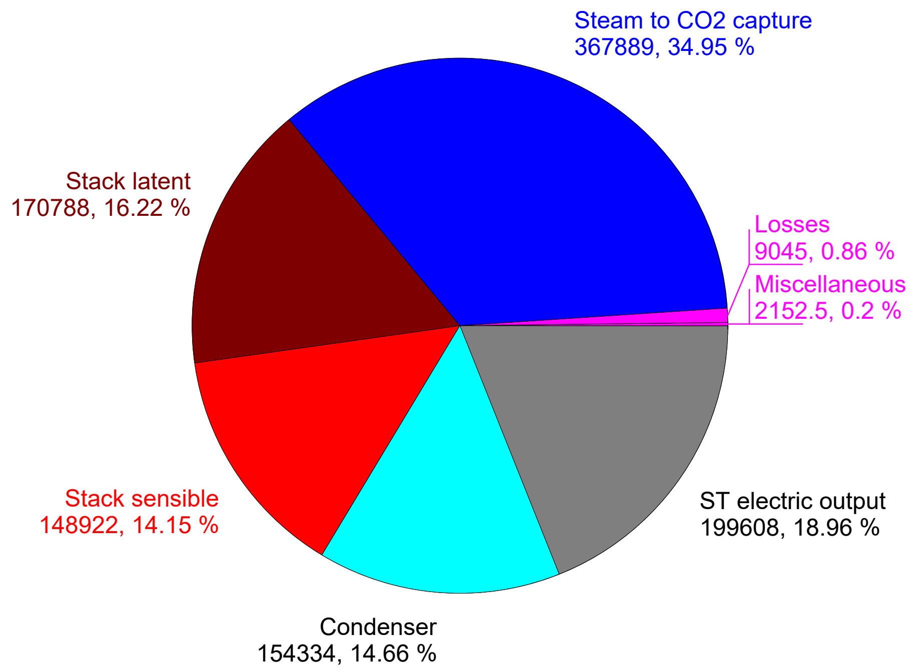
Steam Cycle Energy In [kW]

Steam cycle energy in = 1052716 kW



Steam Cycle Energy Out [kW]

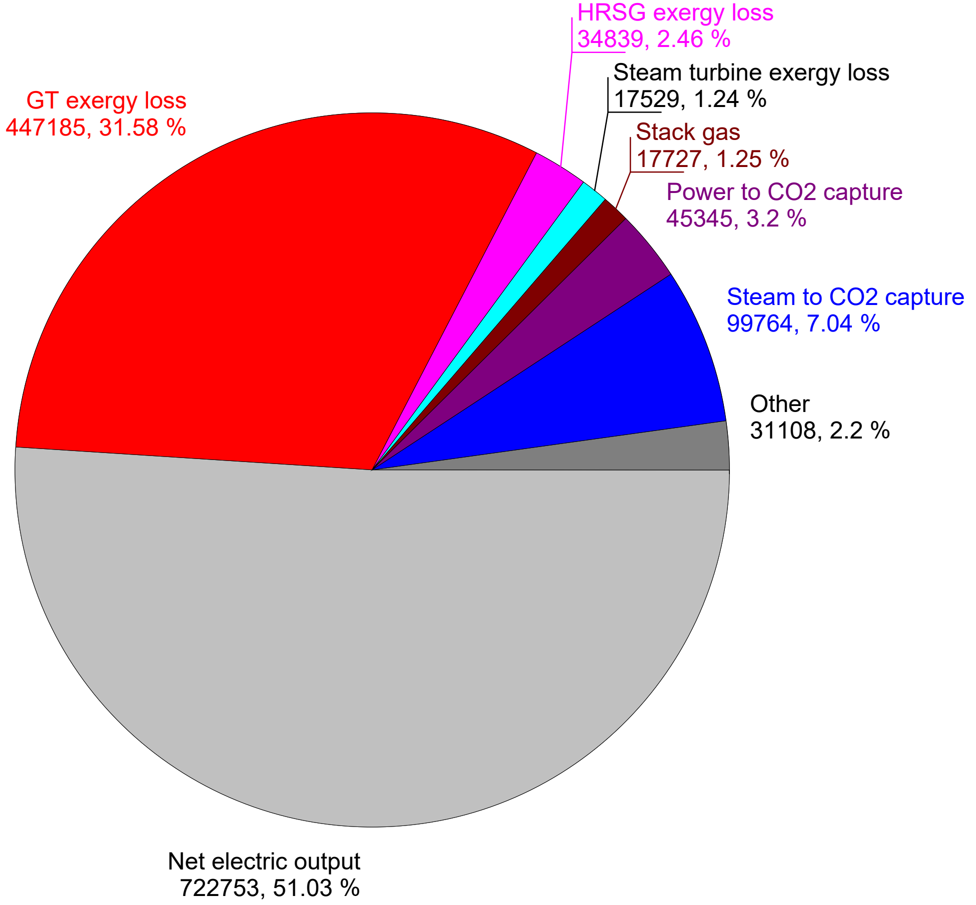
Steam cycle energy out = 1052738 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Plant Exergy Analysis [kW]

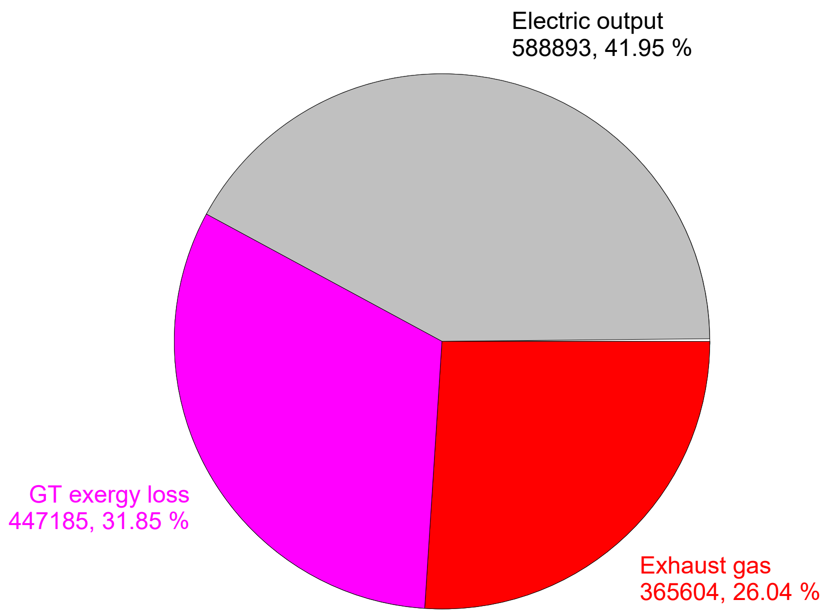
Plant exergy input = 1416250 kW
Fuel exergy input = 1405251 kW
Plant fuel chemical LHV input = 1391862 kW, HHV = 1544429 kW



Reference: 1.013 bar, 25 C, water as vapor.

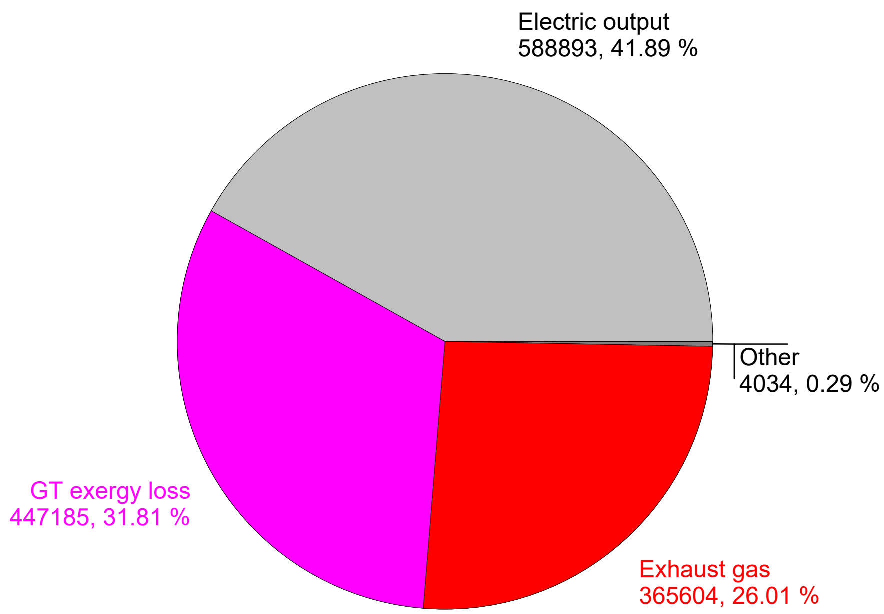
GT Exergy Analysis [kW]

GT exergy in = 1403882 kW



GT & Peripheral Exergy Analysis [kW]

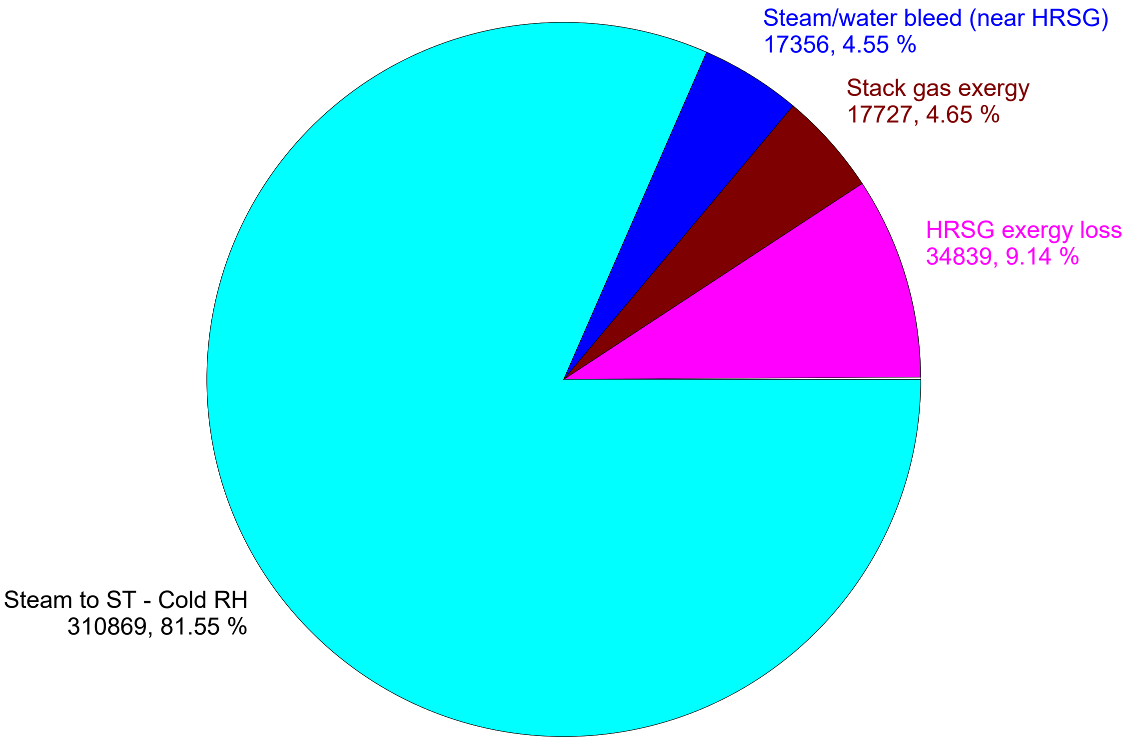
GT & peripheral exergy in = 1405715 kW



Reference: 1.013 bar, 25 C, water as vapor.

HRSG Exergy Analysis [kW]

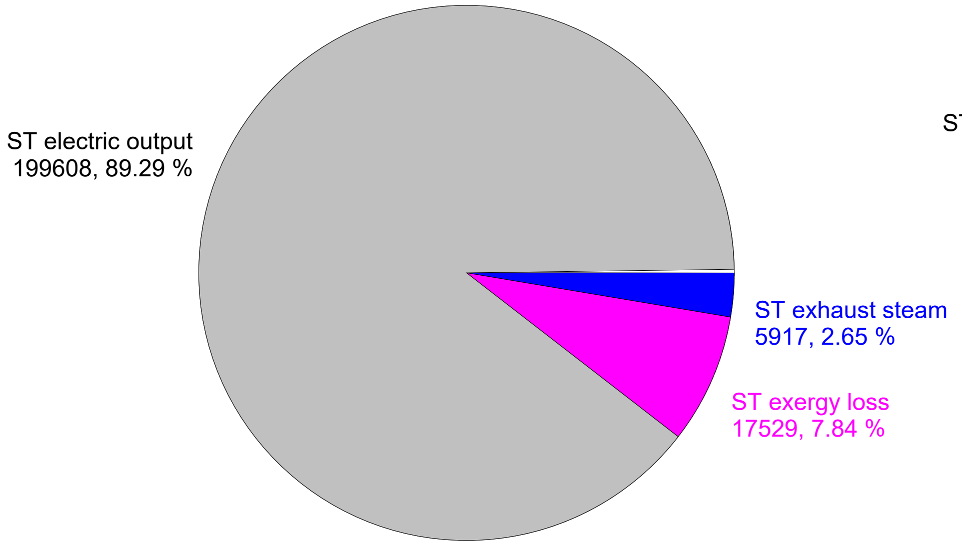
HRSG exergy in = 381199 kW



Reference: 1.013 bar, 25 C, water as vapor.

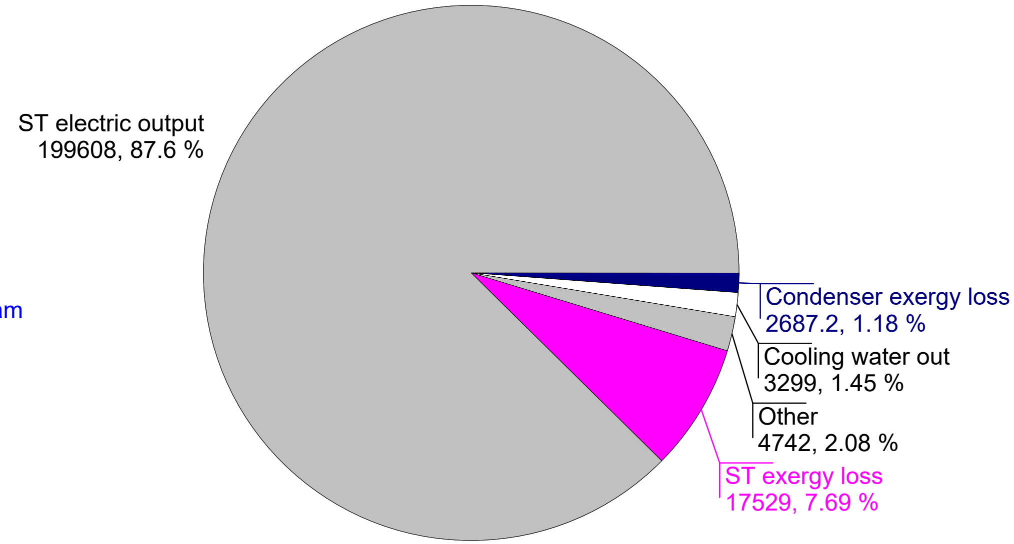
ST Exergy Analysis [kW]

ST exergy in = 223547 kW



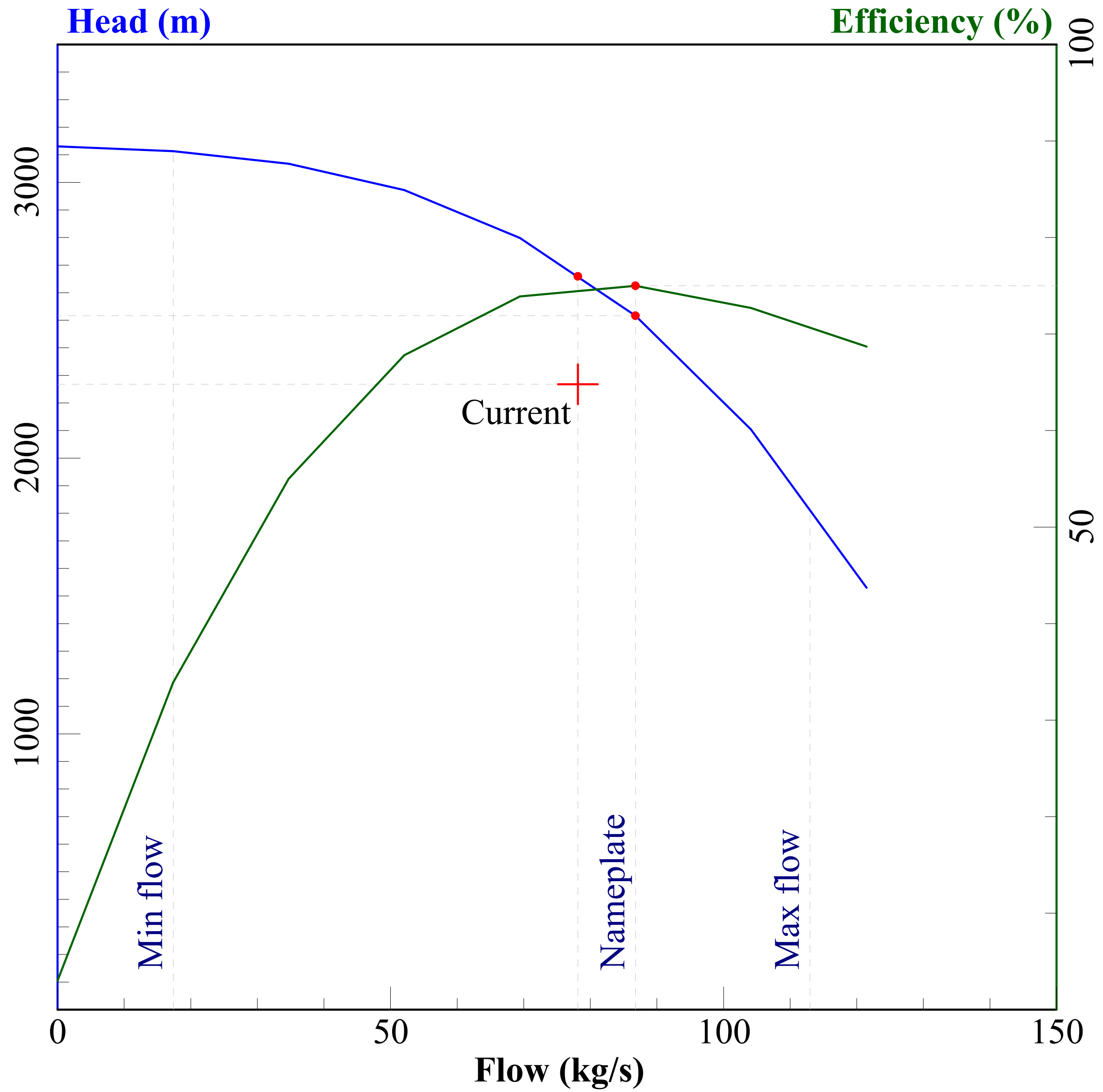
ST & Condenser Exergy Analysis [kW]

ST & condenser exergy in = 227865 kW



Reference: 1.013 bar, 25 C, water as vapor.

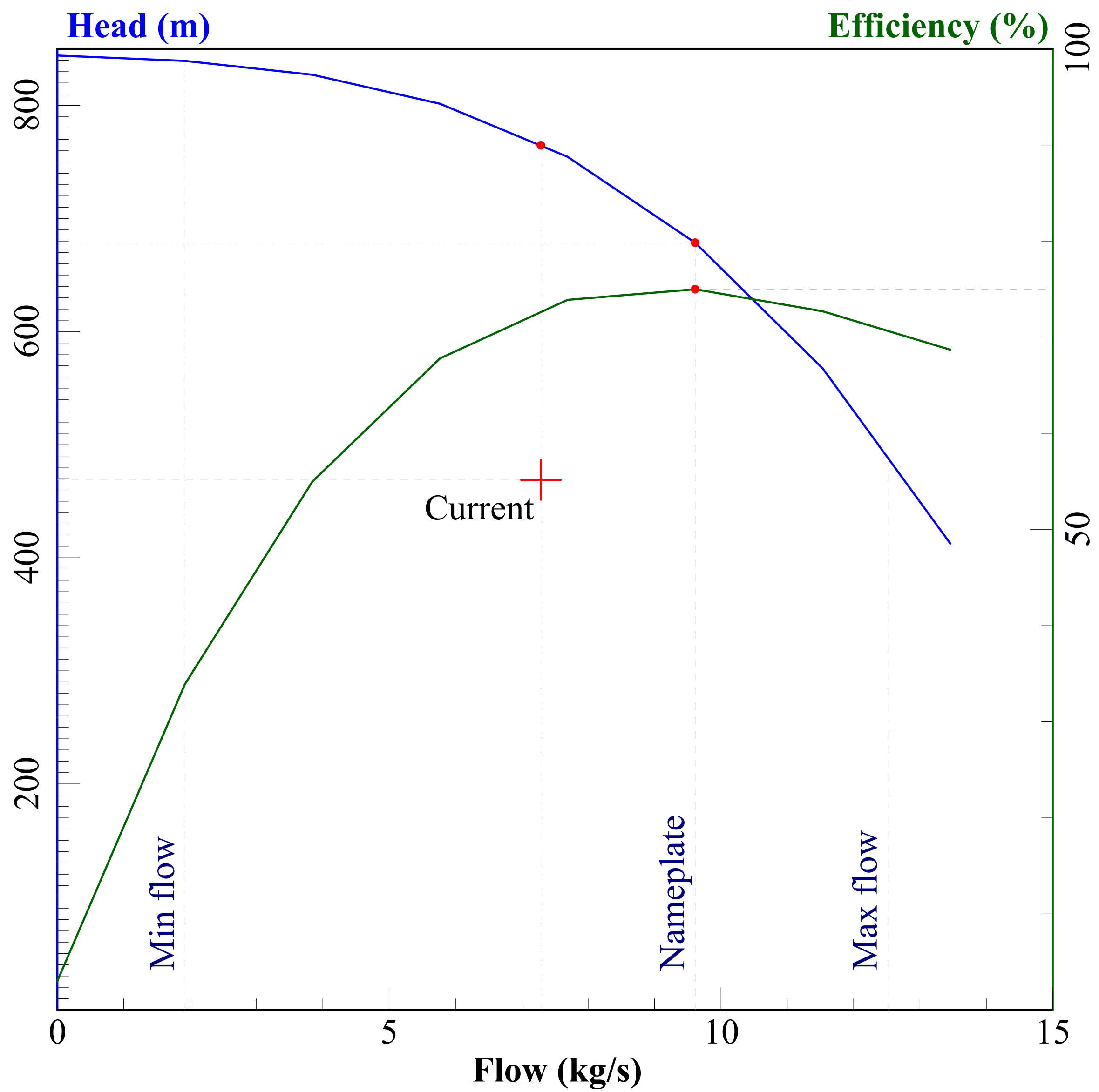
HP Feedwater Pump (P1)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	86.77 kg/s
Nameplate head	2516.5 m
Nameplate flow (nominal)	5678 lpm
Nameplate head (nominal)	2560.3 m
Nameplate RPM	3000
Current pump flow	78.13 kg/s
Current head	2659.1 m
Current head after valve	2267.6 m
Current RPM	3000
Minimum continuous flow	17.38 kg/s
Maximum continuous flow	113 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HP Feedwater Pump (P1)
Date: 06/11/20	
Drawing No:	

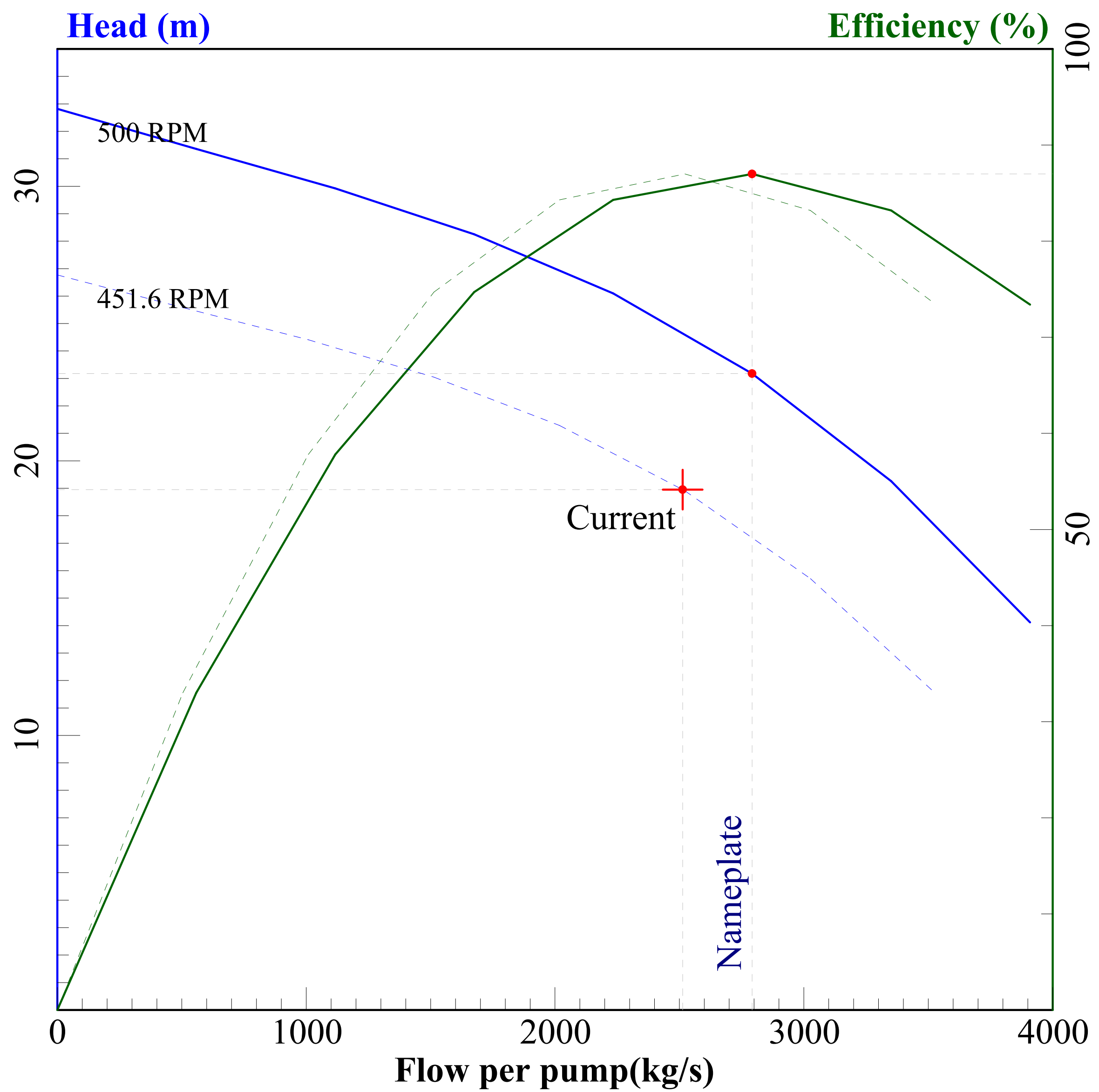
IP Feedwater Pump (P2)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	9.612 kg/s
Nameplate head	678.6 m
Nameplate flow (nominal)	662.4 lpm
Nameplate head (nominal)	701 m
Nameplate RPM	3000
Current pump flow	7.288 kg/s
Current head	764.7 m
Current head after valve	468.8 m
Current RPM	3000
Minimum continuous flow	1.926 kg/s
Maximum continuous flow	12.52 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IP Feedwater Pump (P2)
Date: 06/11/20	
Drawing No:	

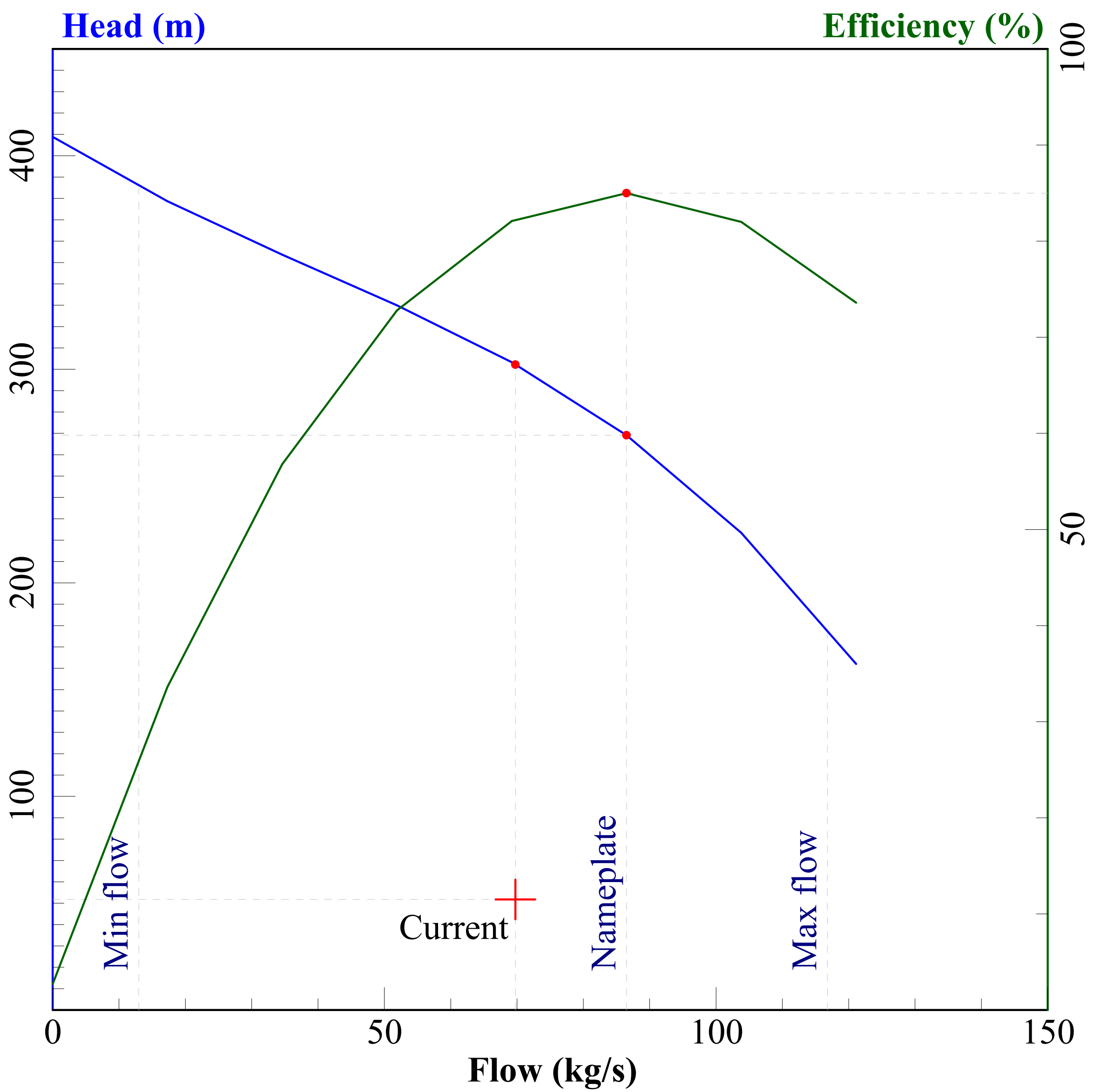
Condenser C.W. Pump (P4)



No. per Condenser	2
No. operating per Condenser	2
Nameplate flow	2792.3 kg/s
Nameplate head	23.18 m
Nameplate flow (nominal)	170344 lpm
Nameplate head (nominal)	24.38 m
Nameplate RPM	500
Current pump flow	2513 kg/s
Current head	18.95 m
Current head after valve	18.95 m
Current RPM	451.6

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condenser C.W. Pump (P4)
Date: 06/11/20	
Drawing No:	

Condensate Forwarding Pump (P6)



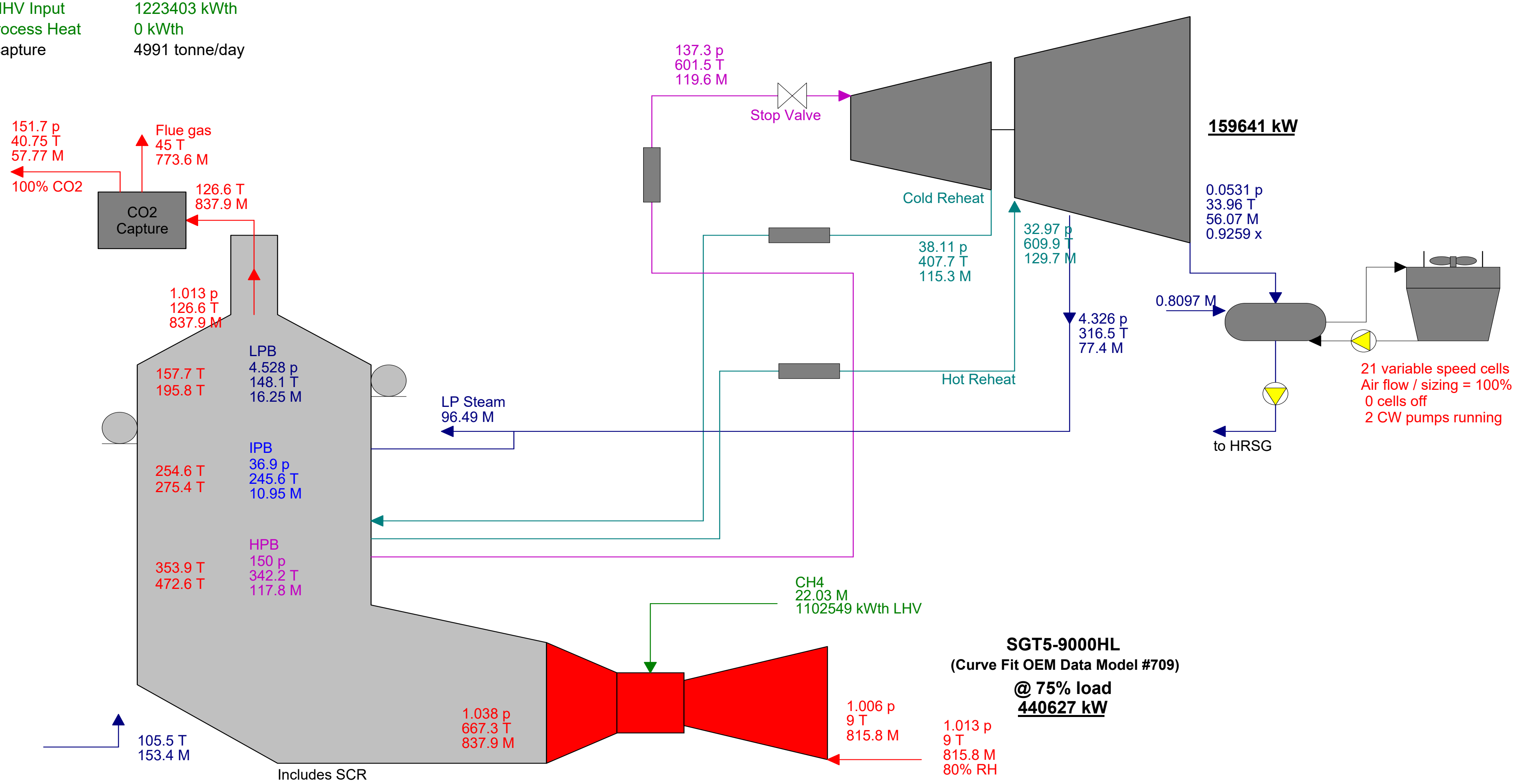
No. per Condenser	2
No. operating per Condenser	1
Nameplate flow	86.51 kg/s
Nameplate head	269.2 m
Nameplate flow (nominal)	5300 lpm
Nameplate head (nominal)	274.3 m
Nameplate RPM	1500
Current pump flow	69.76 kg/s
Current head	302.2 m
Current head after valve	51.74 m
Current RPM	1500
Minimum continuous flow	12.98 kg/s
Maximum continuous flow	116.8 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condensate Forwarding Pump (P6)
Date: 06/11/20	
Drawing No:	

GT MASTER 29.0 AECOM

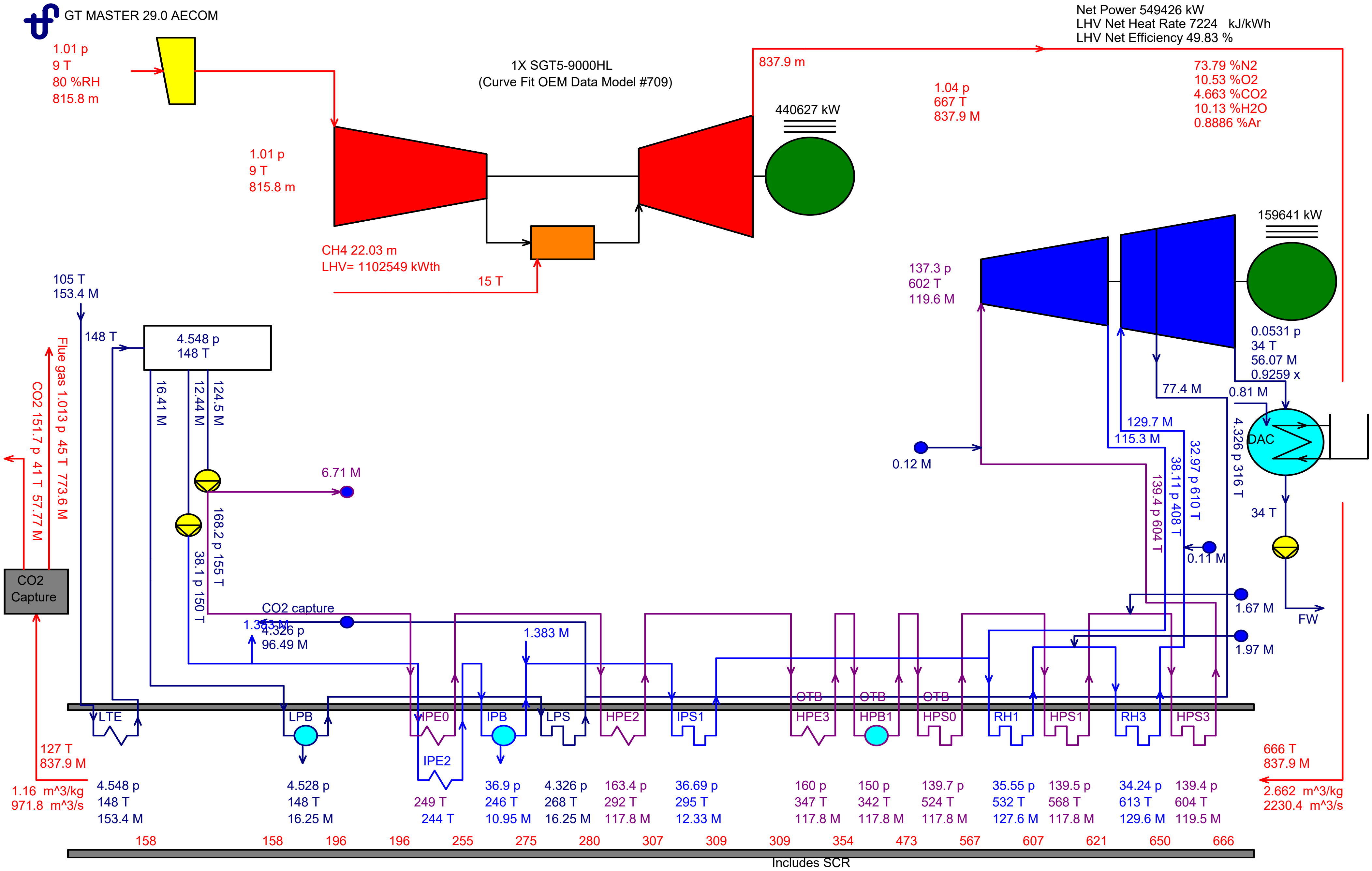
Gross Power	600268 kW
Net Power	549426 kW
Aux. & Losses	50842 kW
LHV Gross Heat Rate	6612 kJ/kWh
LHV Net Heat Rate	7224 kJ/kWh
LHV Gross Electric Eff.	54.44 %
LHV Net Electric Eff.	49.83 %
Fuel LHV Input	1102549 kWth
Fuel HHV Input	1223403 kWth
Net Process Heat	0 kWth
CO2 capture	4991 tonne/day

Ambient
1.013 P
9 T
80% RH
7.353 Twb



p [bar] T [C] M [kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 20:06:49 file=

GT MASTER 29.0 AECOM
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM



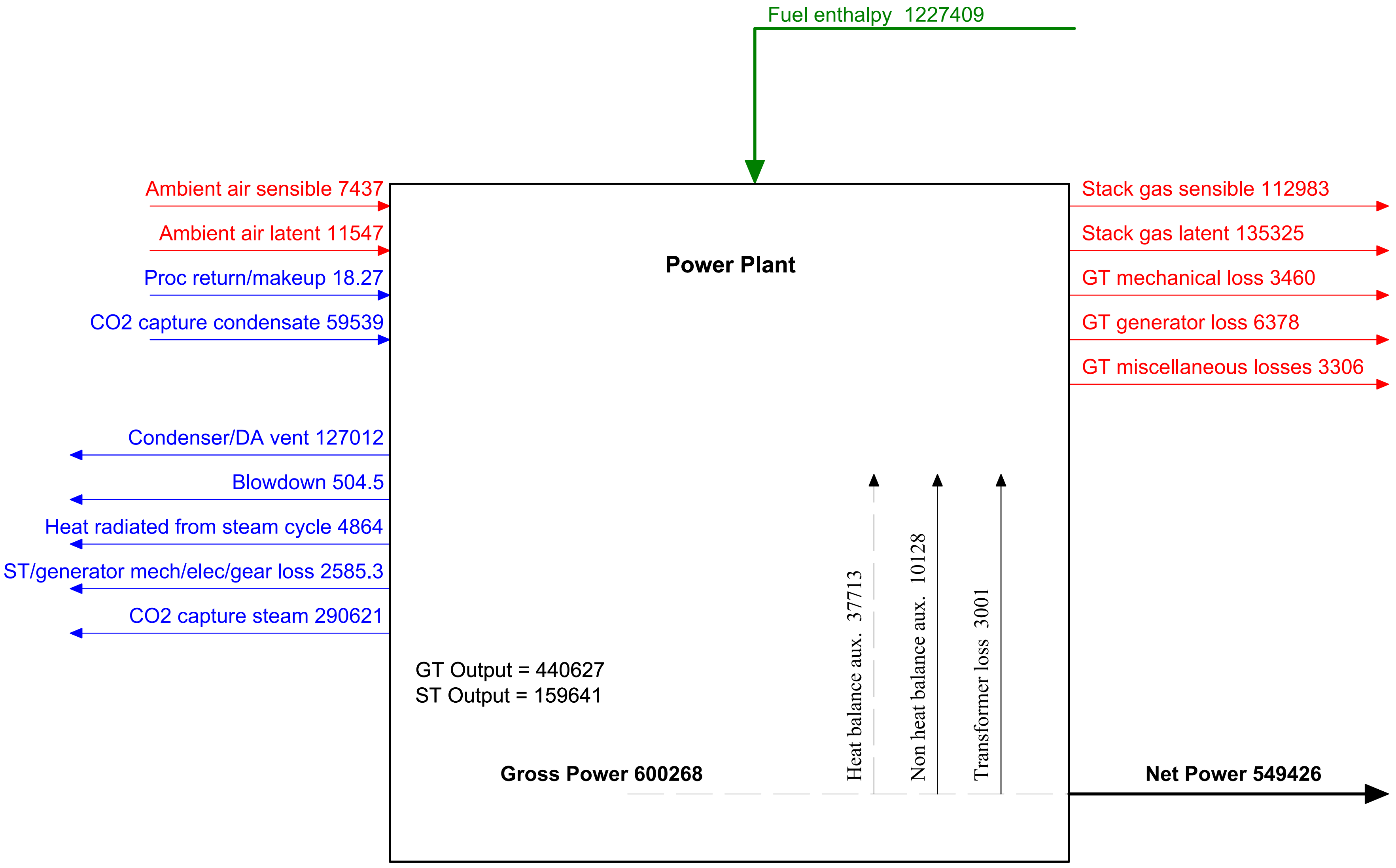
p[bar], T[C], M[kg/s], Steam Properties: IAPWS-IF97

1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Fuel chemical LHV input = 1102549 kW
Fuel chemical HHV input = 1223403 kW

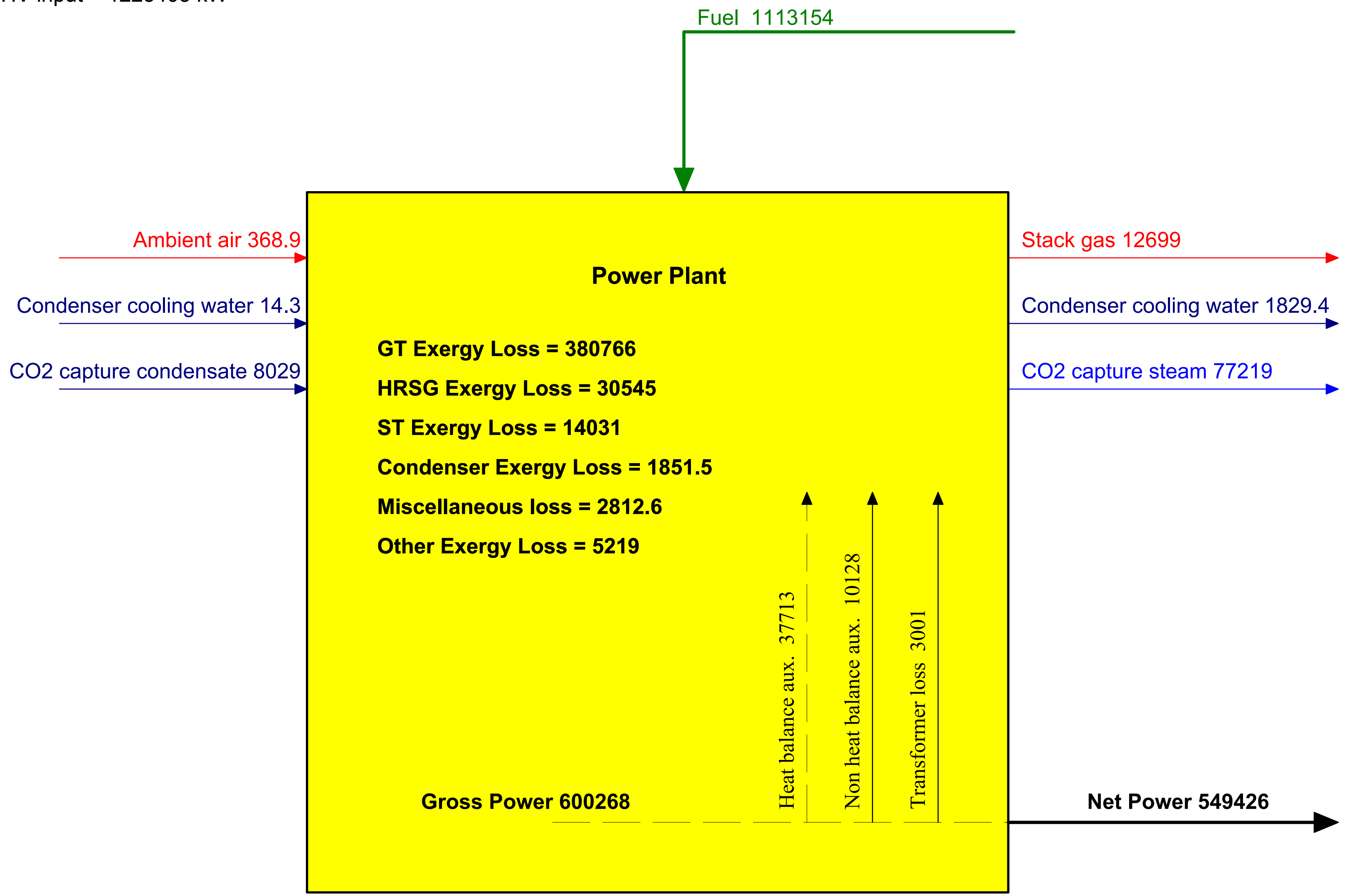
Power Plant Energy Flow Schematic [kW]



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Fuel exergy input = 1113154 kW
Fuel chemical LHV input = 1102549 kW
Fuel chemical HHV input = 1223403 kW

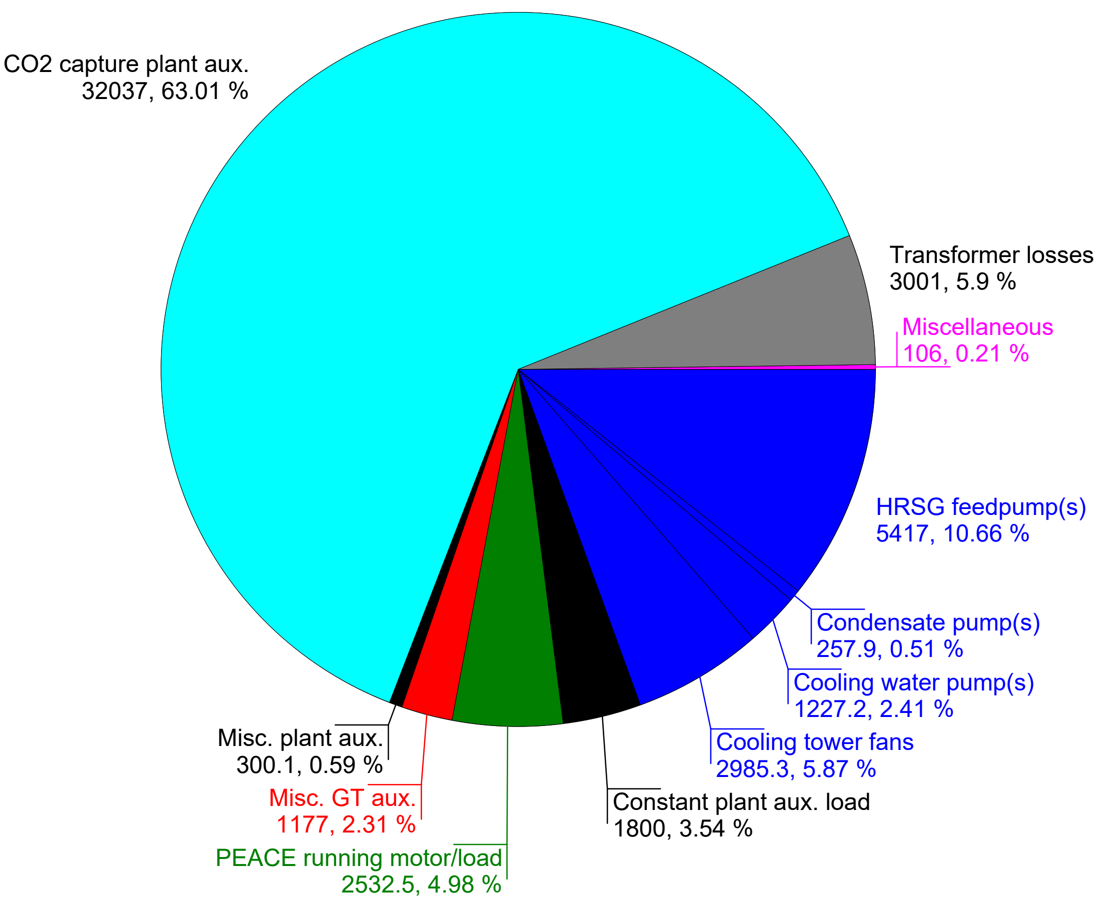
Power Plant Exergy Flow Schematic [kW]



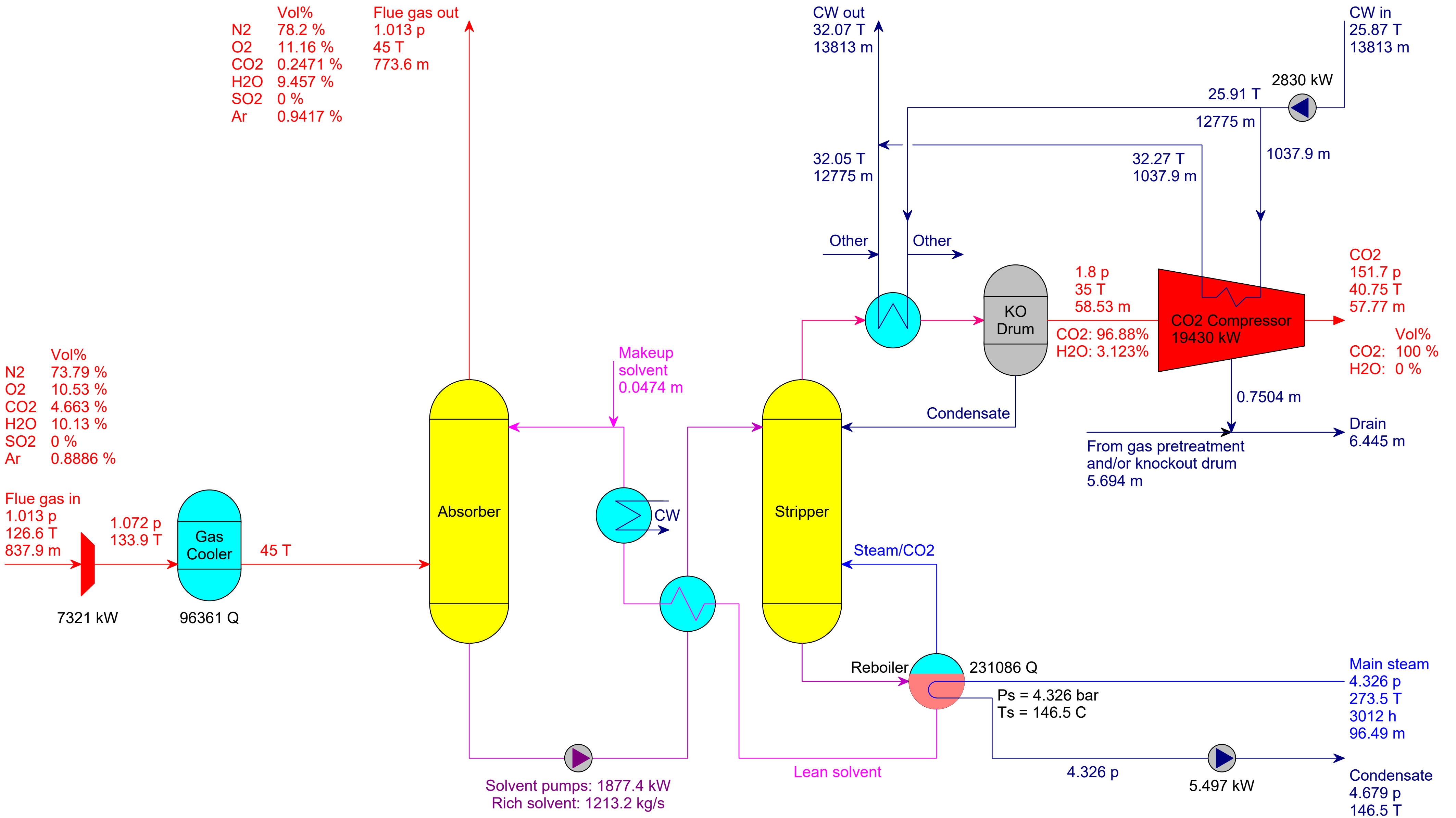
Reference: 1.013 bar, 25 C, water as vapor.

Auxiliaries & Losses [kW]

Total auxiliaries & transformer losses = 50842 kW



CO2 Capture Plant Flow Diagram

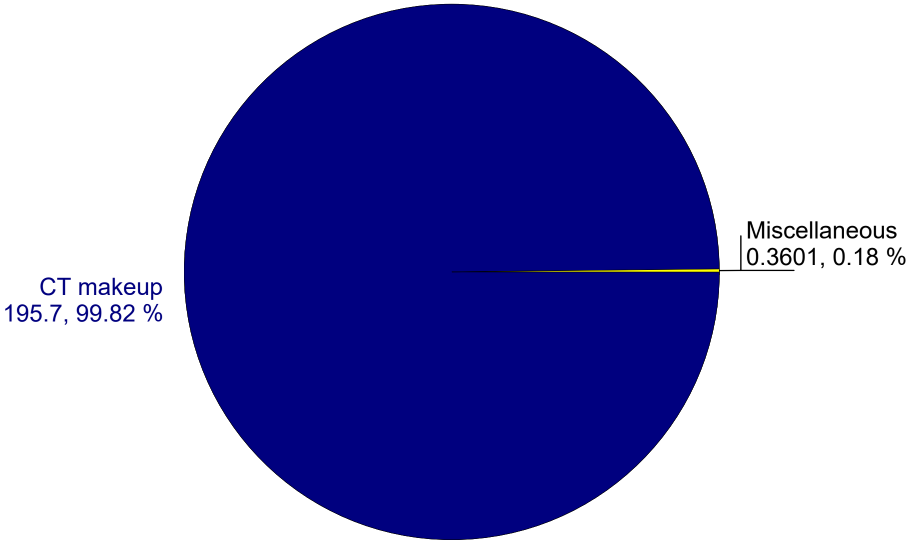


Process: Amine-based
CO2 capture: 57.77 kg/s, 4991 tonne/day
CO2 capture efficiency: 95 %
Heat input: 231086 kW, 231.1 MW, 4000 kJ/kg CO2
Total electrical power consumption: 32037 kW
Solvent consumption: 4.093 tonne/day

p[bar] T[C] h[kJ/kg] m[kg/s] Q[kW]

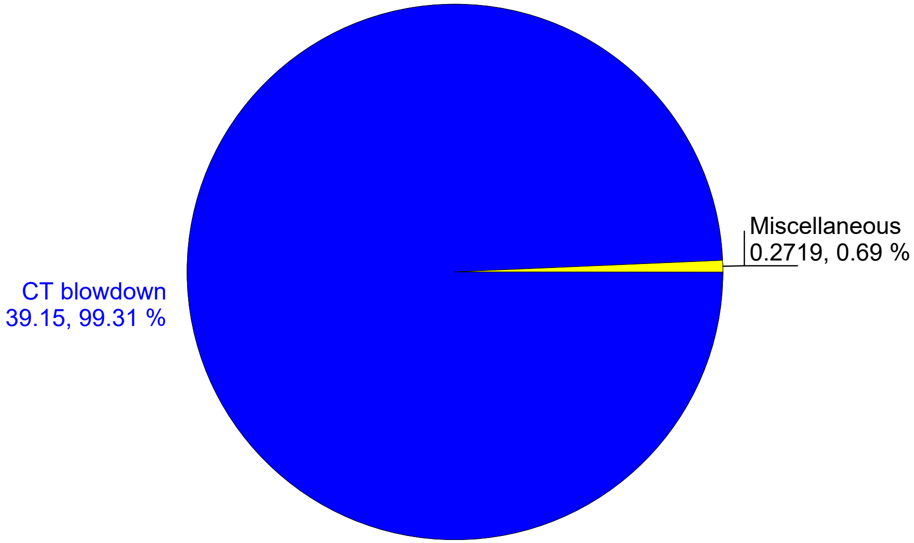
Plant Water Consumption [kg/s]

Plant water consumption = 196.1 kg/s

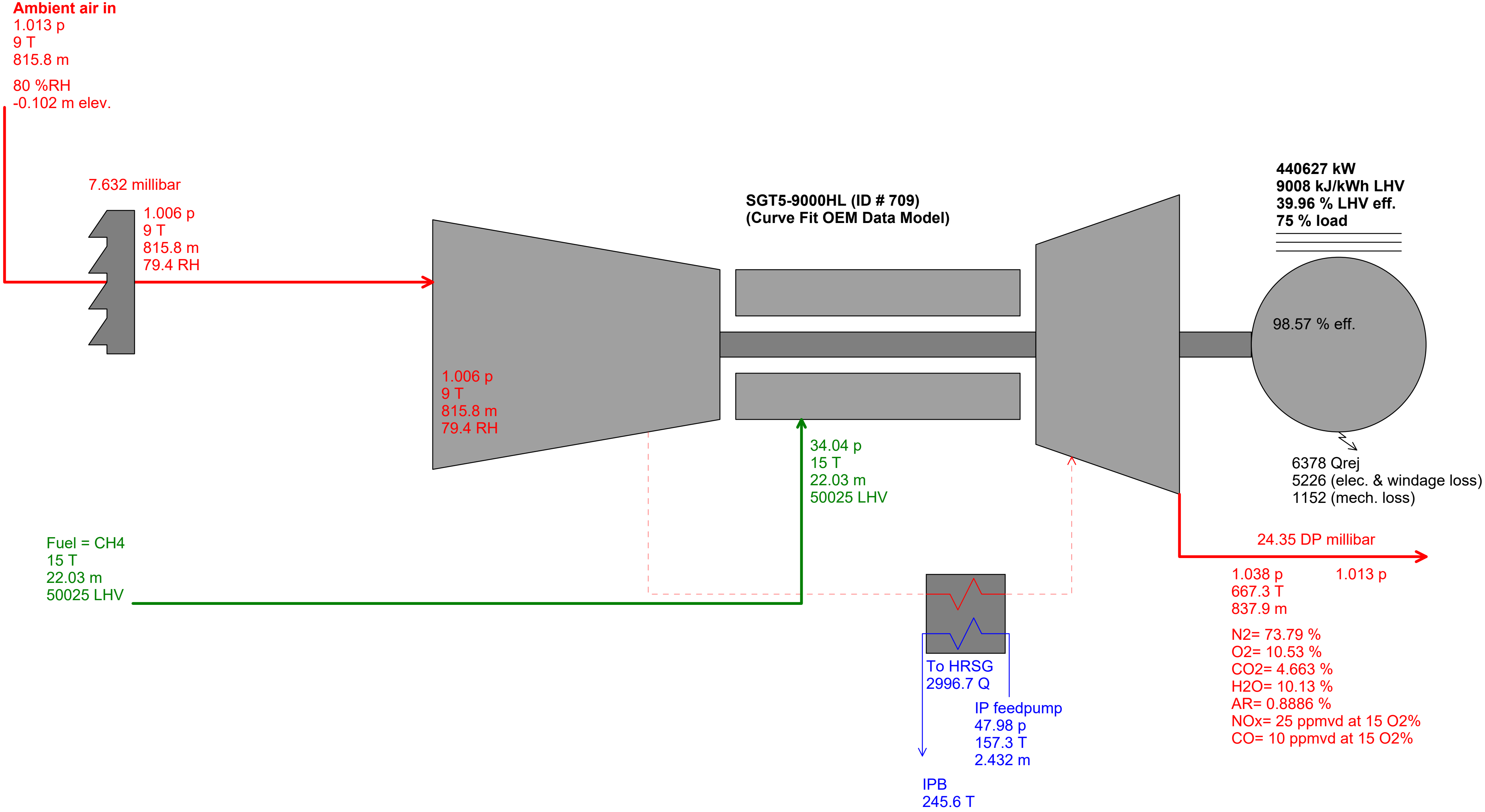


Plant Water Discharge [kg/s]

Plant water discharge = 39.42 kg/s

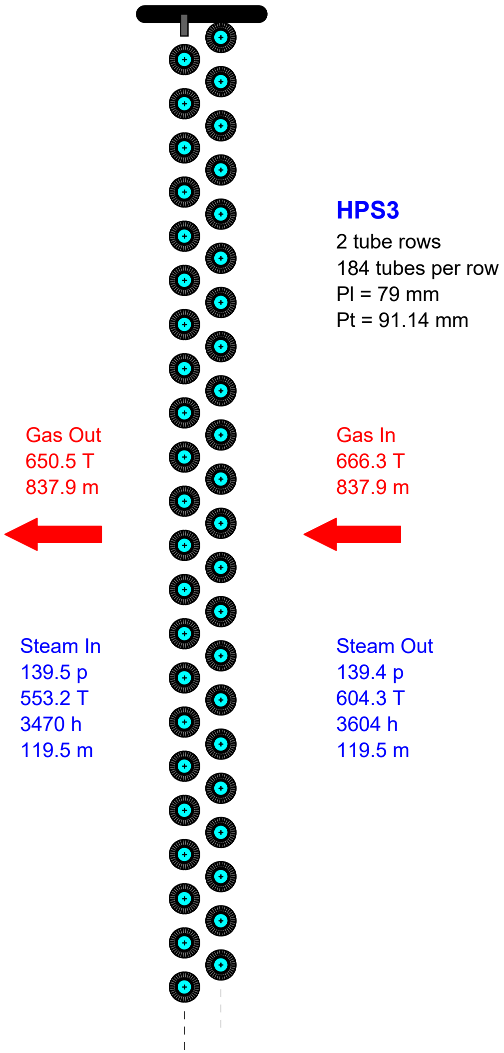


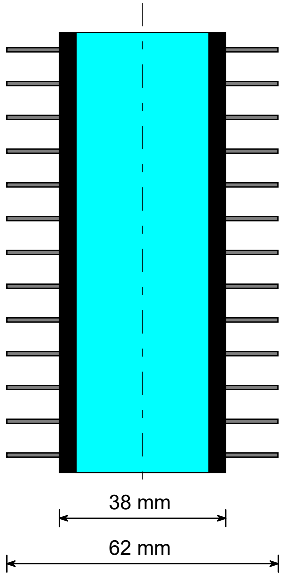
GT generator power = 440627 kW
GT Heat Rate @ gen term = 9008 kJ/kWh
GT efficiency @ gen term = 36.02% HHV = 39.96% LHV
GT @ 75 % rating



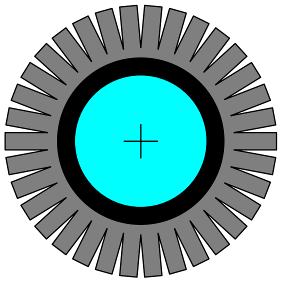
p[bar], T[C], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

HPS3 Hardware Design





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP304
Tube material	TP347HFG
Tube outer diameter	38 mm
Tube wall thickness	3.81 mm
Fin height	12 mm
Fin spacing	6.723 mm
Fin thickness	1 mm
Number of fins per meter	129.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4645 m^2
Maximum gas velocity	12.06 m/s
Gas pressure drop	0.3941 millibar
Steam side velocity	11.68 m/s
Steam side pressure drop	0.1419 bar
Heat transfer from gas	16024 kW
Heat transfer to steam	15944 kW



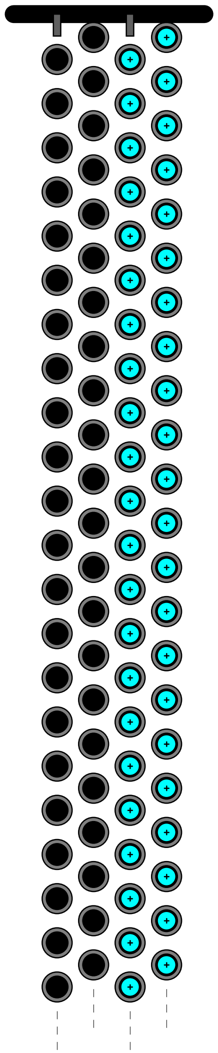
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS3
Date: 06/11/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

RH3 Hardware Design



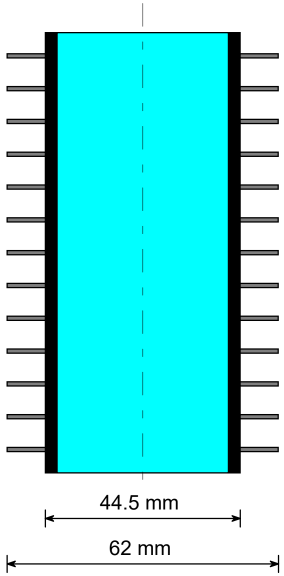
RH3
4 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

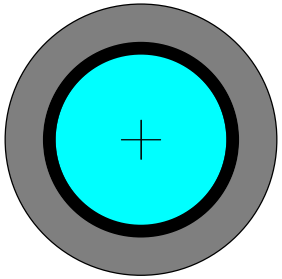
Gas Out
621 T
837.9 m

Gas In
650.5 T
837.9 m

Steam In
35.55 p
512.4 T
3479 h
129.6 m

Steam Out
34.24 p
612.5 T
3708 h
129.6 m





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	TP347HFG
Tube outer diameter	44.5 mm
Tube wall thickness	2.667 mm
Fin height	8.75 mm
Fin spacing	6.507 mm
Fin thickness	1 mm
Number of fins per meter	133.2
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	8064 m^2
Maximum gas velocity	13.29 m/s
Gas pressure drop	0.7829 millibar
Steam side velocity	31.67 m/s
Steam side pressure drop	1.313 bar
Heat transfer from gas	29829 kW
Heat transfer to steam	29681 kW

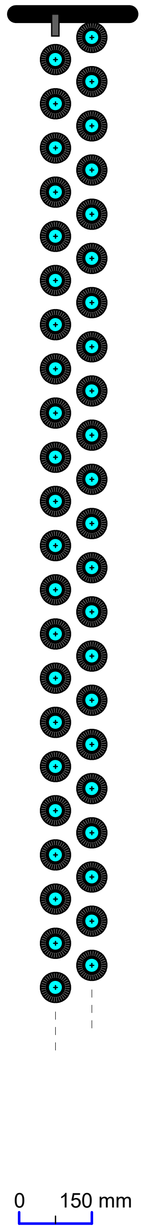
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0   150 mm

0   50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH3
Date: 06/11/20	
Drawing No:	

HPS1 Hardware Design



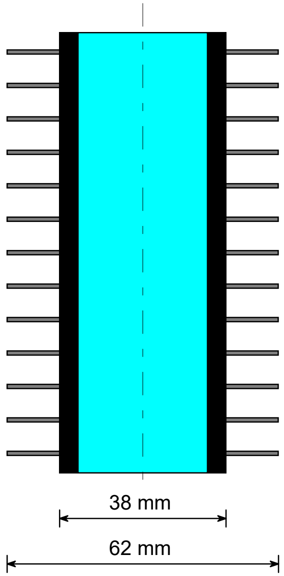
HPS1
2 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

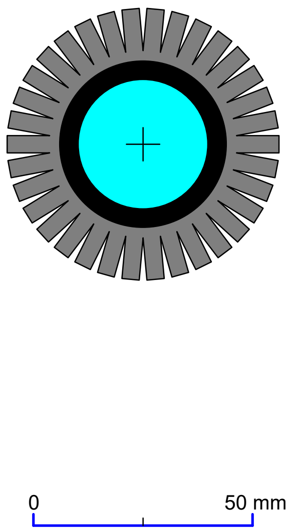
Gas Out
607.1 T
837.9 m

Gas In
621 T
837.9 m

Steam In
139.7 p
524.3 T
3392 h
117.8 m

Steam Out
139.5 p
568.3 T
3510 h
117.8 m





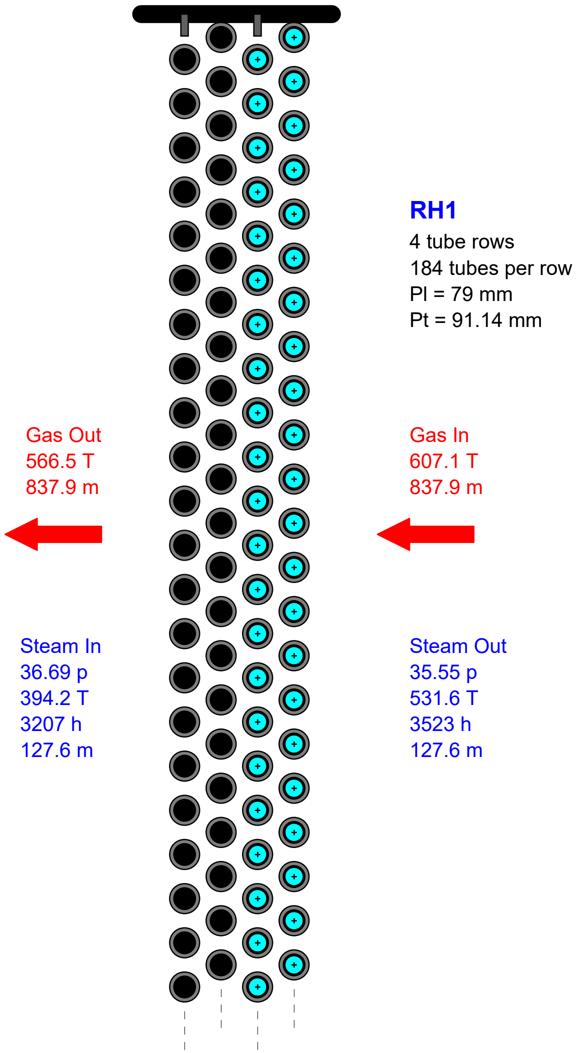
Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T91
Tube outer diameter	38 mm
Tube wall thickness	4.191 mm
Fin height	12 mm
Fin spacing	6.65 mm
Fin thickness	1 mm
Number of fins per meter	130.7
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4680 m^2
Maximum gas velocity	11.49 m/s
Gas pressure drop	0.374 millibar
Steam side velocity	11.47 m/s
Steam side pressure drop	0.1463 bar
Heat transfer from gas	13964 kW
Heat transfer to steam	13895 kW

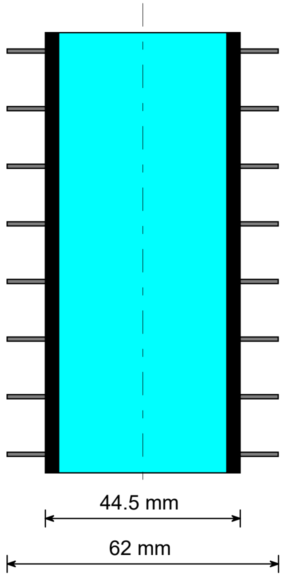
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS1
Date: 06/11/20	
Drawing No:	

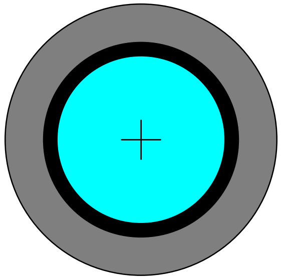
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

1 2 3 4 5 6 7 8

RH1 Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T22
Tube outer diameter	44.5 mm
Tube wall thickness	3.048 mm
Fin height	8.75 mm
Fin spacing	12.19 mm
Fin thickness	1 mm
Number of fins per meter	75.8
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	5493 m^2
Maximum gas velocity	12.29 m/s
Gas pressure drop	0.5658 millibar
Steam side velocity	27.19 m/s
Steam side pressure drop	1.145 bar
Heat transfer from gas	40517 kW
Heat transfer to steam	40316 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

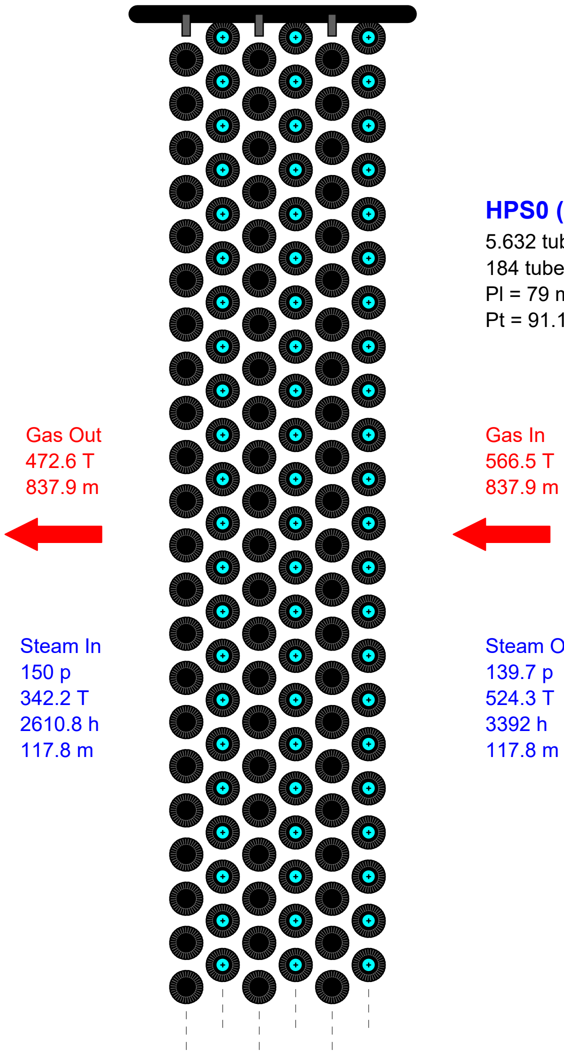
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH1
Date: 06/11/20	
Drawing No:	

1 2 3 4 5 6 7 8

HPS0 (OTB) Hardware Design



HPS0 (OTB)

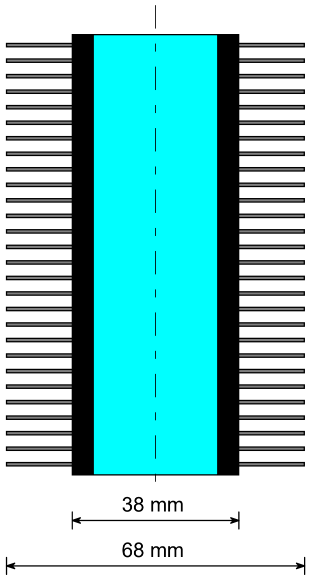
5.632 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

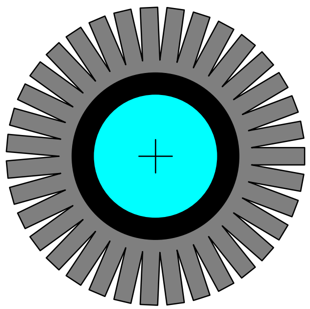
Gas Out
472.6 T
837.9 m

Gas In
566.5 T
837.9 m

Steam In
150 p
342.2 T
2610.8 h
117.8 m

Steam Out
139.7 p
524.3 T
3392 h
117.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	5.632
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	30902 m^2
Maximum gas velocity	11.07 m/s
Gas pressure drop	1.668 millibar
Steam side velocity	18.54 m/s
Steam side pressure drop	10.34 bar
Heat transfer from gas	92487 kW
Heat transfer to steam	92026 kW

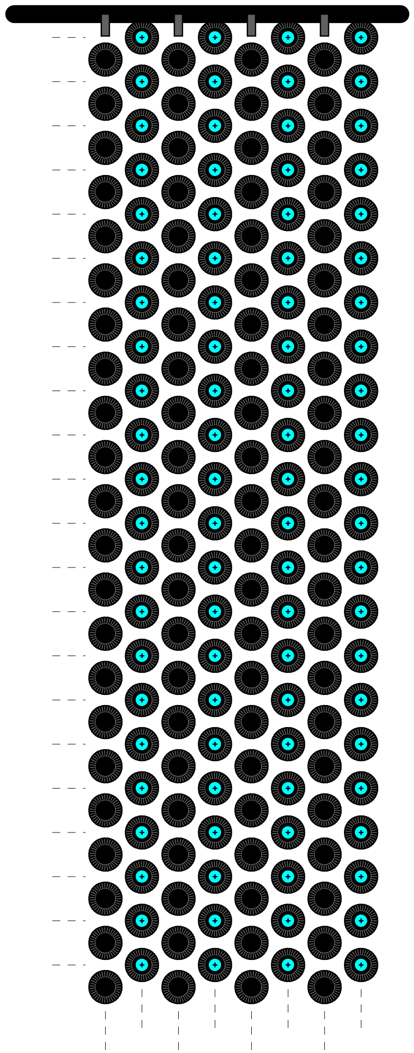
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS0 (OTB)
Date: 06/11/20	
Drawing No:	

HPB1 (OTB) Hardware Design



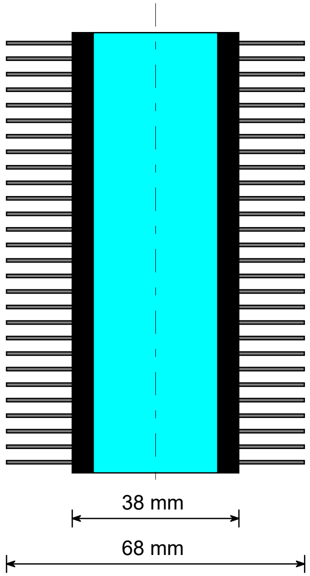
Gas Out
353.9 T
837.9 m

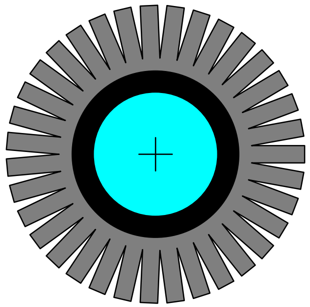
Water In
160 p
347.3 T
1649.6 h
117.8 m

HPB1 (OTB)
11 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
472.6 T
837.9 m

Steam Out
150 p
342.2 T
2610.8 h
117.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	11
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	59972 m^2
Maximum gas velocity	9.584 m/s
Gas pressure drop	2.732 millibar
Water side velocity	1.694 m/s
Water side pressure drop	9.965 bar
Heat transfer from gas	113810 kW
Heat transfer to steam/water	113244 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

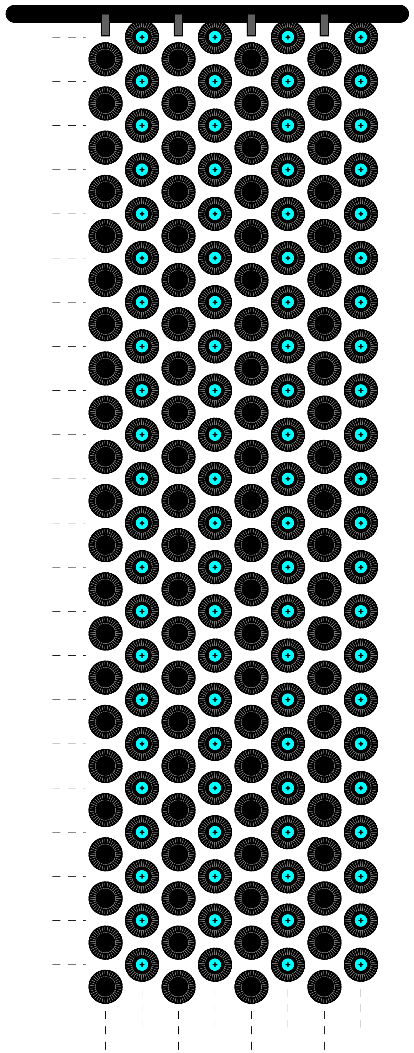
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPB1 (OTB)
Date: 06/11/20	
Drawing No:	

HPE3 (OTB) Hardware Design

Gas Out
309 T
837.9 m

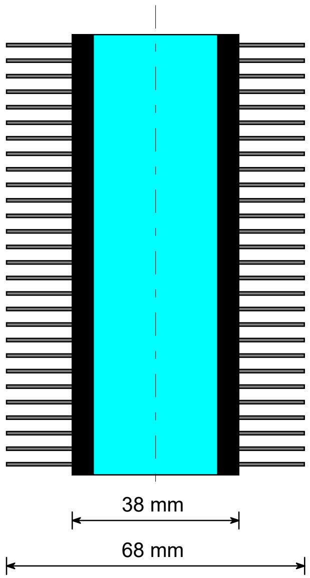
Water In
163.4 p
291.8 T
1292.9 h
117.8 m

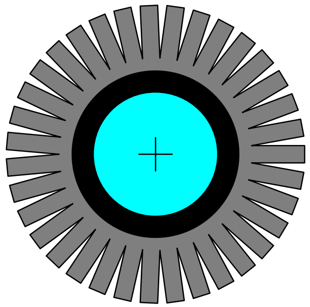


HPE3 (OTB)
17.44 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
353.9 T
837.9 m

Water Out
160 p
347.3 T
1649.6 h
117.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	17.44
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	95690 m^2
Maximum gas velocity	8.442 m/s
Gas pressure drop	3.814 millibar
Water side velocity	1.474 m/s
Water side pressure drop	3.448 bar
Heat transfer from gas	42233 kW
Heat transfer to water	42023 kW

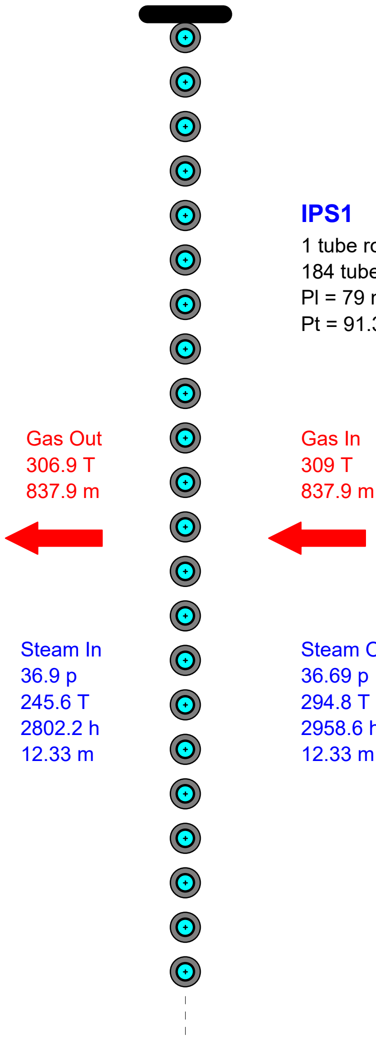
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

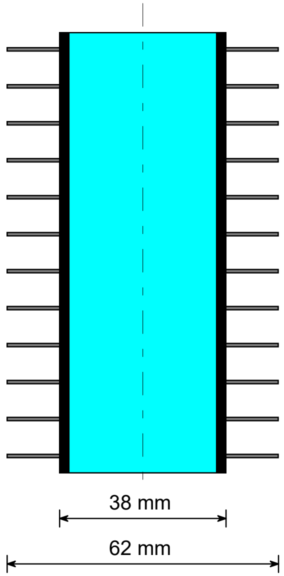
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE3 (OTB)
Date: 06/11/20	
Drawing No:	

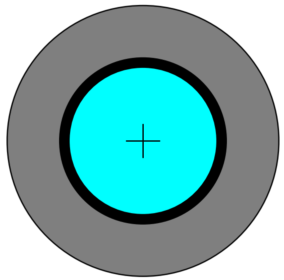
IPS1 Hardware Design



IPS1

1 tube row
184 tubes per row
Pl = 79 mm
Pt = 91.39 mm





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	7.626 mm
Fin thickness	0.8 mm
Number of fins per meter	118.7
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.39 mm
# of tube rows (longitudinal)	1
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2154.4 m^2
Maximum gas velocity	7.365 m/s
Gas pressure drop	0.1033 millibar
Steam side velocity	4.436 m/s
Steam side pressure drop	0.2062 bar
Heat transfer from gas	1938.4 kW
Heat transfer to steam	1928.7 kW

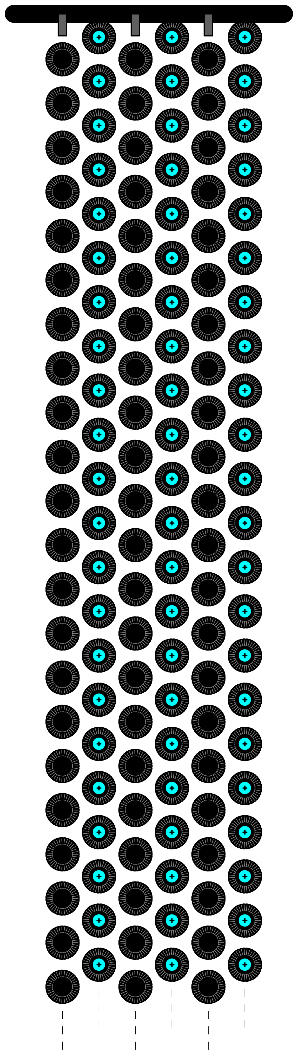
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPS1
Date: 06/11/20	
Drawing No:	

HPE2 Hardware Design



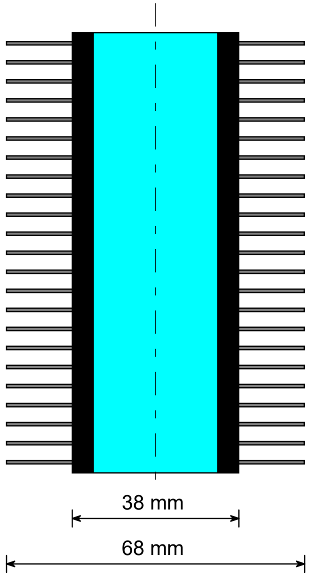
HPE2
6 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

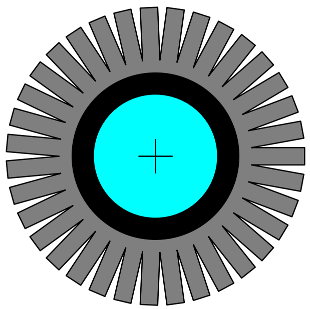
Gas Out
279.9 T
837.9 m

Gas In
306.9 T
837.9 m

Water In
164.8 p
248.8 T
1080.4 h
117.8 m

Water Out
163.4 p
291.8 T
1292.9 h
117.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	3.555 mm
Fin thickness	0.8 mm
Number of fins per meter	229.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	27374 m^2
Maximum gas velocity	7.705 m/s
Gas pressure drop	1.016 millibar
Water side velocity	1.288 m/s
Water side pressure drop	1.357 bar
Heat transfer from gas	25164 kW
Heat transfer to water	25039 kW

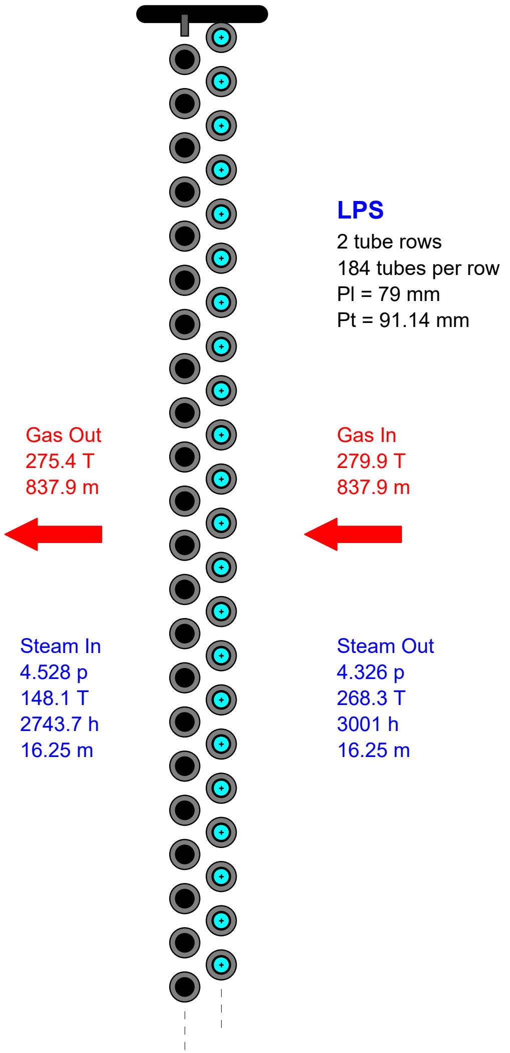
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

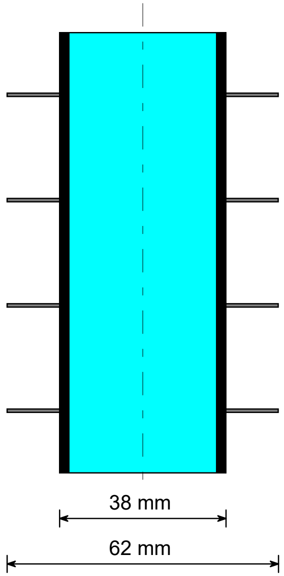
0 150 mm

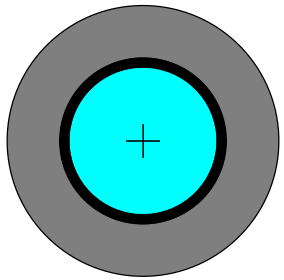
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE2
Date: 06/11/20	
Drawing No:	

LPS Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	23.26 mm
Fin thickness	0.8 mm
Number of fins per meter	41.56
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2091.2 m^2
Maximum gas velocity	6.816 m/s
Gas pressure drop	0.129 millibar
Steam side velocity	48.35 m/s
Steam side pressure drop	0.2028 bar
Heat transfer from gas	4203 kW
Heat transfer to steam	4182 kW

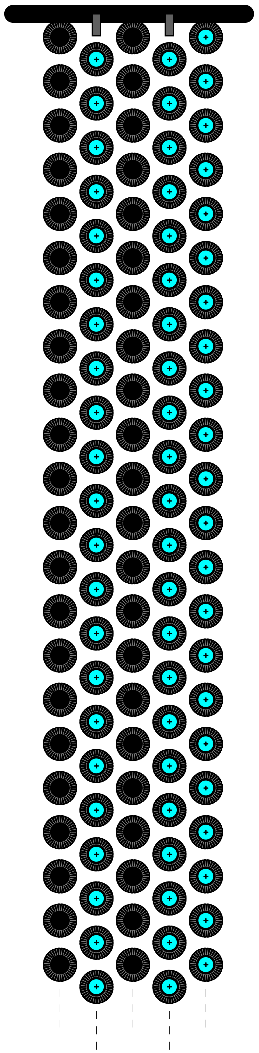
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPS
Date: 06/11/20	
Drawing No:	

IPB Hardware Design



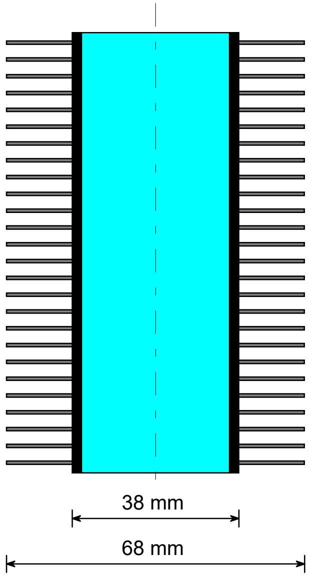
IPB
5 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

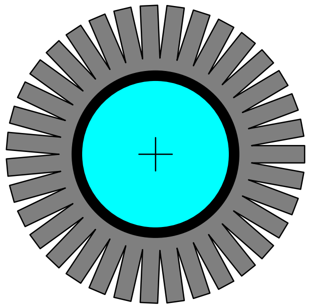
Gas Out
254.6 T
837.9 m

Gas In
275.4 T
837.9 m

Water In
36.9 p
243.9 T
1056.3 h
10.95 m

Steam Out
36.9 p
245.6 T
2802.2 h
10.95 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.045 mm
Fin thickness	0.8 mm
Number of fins per meter	260
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	5
# of rows per pass	1.251
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	25540 m^2
Maximum gas velocity	7.432 m/s
Gas pressure drop	0.8806 millibar
Water side velocity	1.186 m/s
Water side pressure drop	0 bar
Heat transfer from gas	19206 kW
Heat transfer to steam/water	19110 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

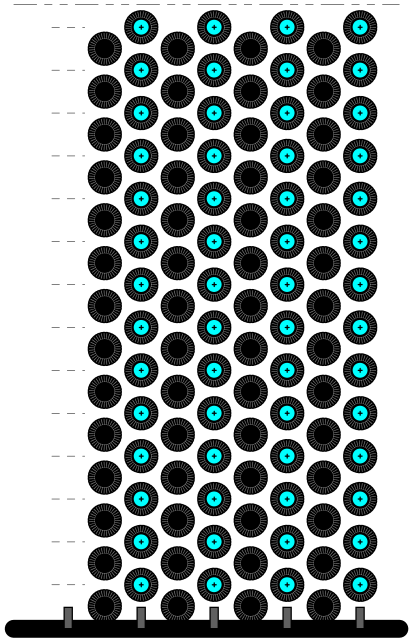
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPB
Date: 06/11/20	
Drawing No:	

IPE2 Hardware Design

Parallel HX



IPE2 (Parallel)

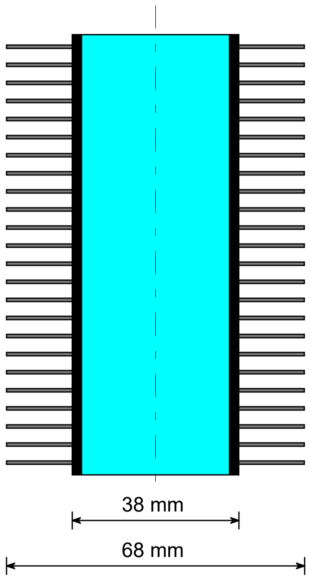
14 tube rows
14 tubes per row
Pl = 79 mm
Pt = 88.19 mm

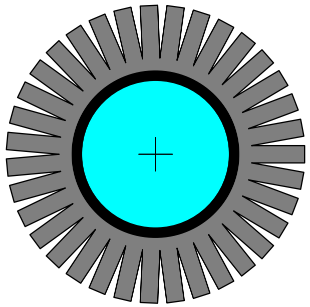
Gas Out
195.8 T
64.64 m

Gas In
254.6 T
64.64 m

Water In
38.1 p
150.4 T
635.9 h
11.05 m

Water Out
36.9 p
243.9 T
1056.3 h
11.05 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.339 mm
Fin thickness	0.8 mm
Number of fins per meter	241.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	88.19 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	14
Tube length	20.4 m
Gas path transverse width	1.279 m
Gas path frontal area	26.09 m^2
HX total outside surface area	5089 m^2
Maximum gas velocity	7.318 m/s
Gas pressure drop	2.433 millibar
Water side velocity	1.013 m/s
Water side pressure drop	1.2 bar
Heat transfer from gas	4671 kW
Heat transfer to water	4647 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

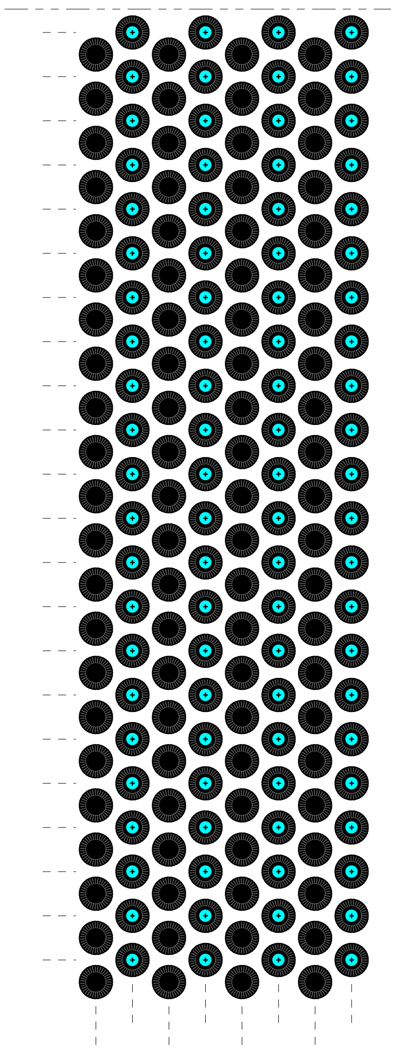
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPE2 (Parallel)
Date: 06/11/20	
Drawing No:	

HPE0 Hardware Design

Parallel HX



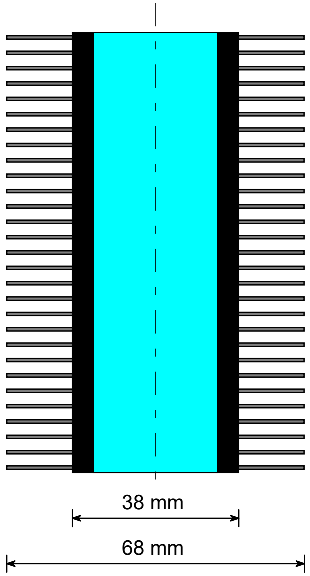
Gas Out
195.8 T
773.2 m

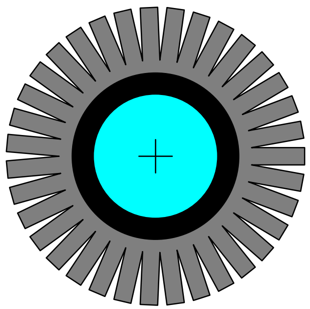
Water In
168.2 p
155.1 T
664.2 h
117.8 m

HPE0 (Parallel)
14 tube rows
170 tubes per row
Pl = 79 mm
Pt = 91.12 mm

Gas In
254.6 T
773.2 m

Water Out
164.8 p
248.8 T
1080.4 h
117.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.699 mm
Fin thickness	0.8 mm
Number of fins per meter	285.8
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.12 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	170
Tube length	20.4 m
Gas path transverse width	15.54 m
Gas path frontal area	316.9 m^2
HX total outside surface area	72030 m^2
Maximum gas velocity	6.973 m/s
Gas pressure drop	2.433 millibar
Water side velocity	1.248 m/s
Water side pressure drop	3.418 bar
Heat transfer from gas	49272 kW
Heat transfer to water	49027 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

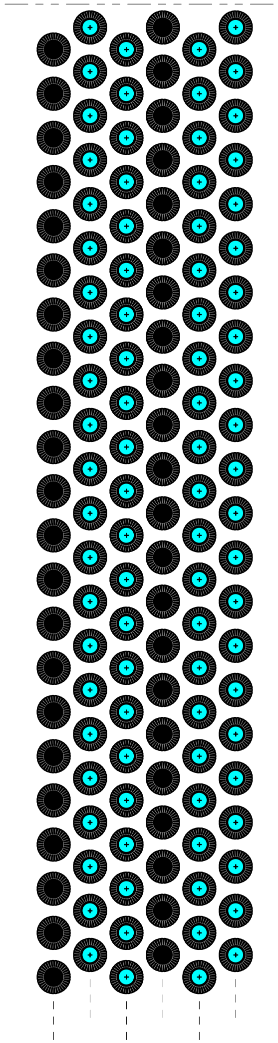
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE0 (Parallel)
Date: 06/11/20	
Drawing No:	

LPB Hardware Design

Parallel HX



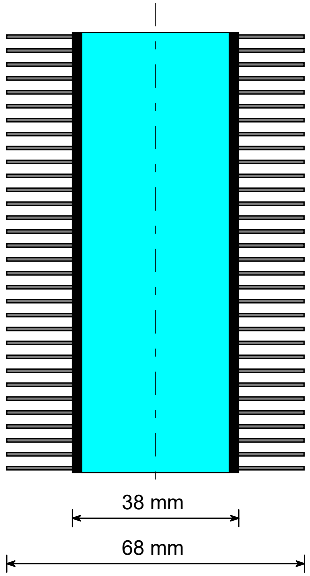
LPB
6 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

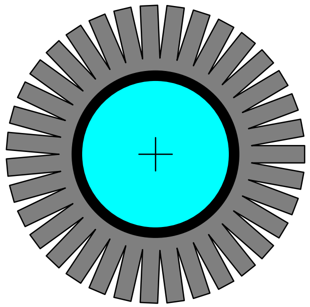
Gas Out
157.7 T
837.9 m

Gas In
195.8 T
837.9 m

Water In
4.528 p
148.3 T
624.9 h
16.25 m

Steam Out
4.528 p
148.1 T
2743.7 h
16.25 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	2.359 mm
Fin thickness	0.8 mm
Number of fins per meter	316.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1.501
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	36720 m^2
Maximum gas velocity	6.398 m/s
Gas pressure drop	1.006 millibar
Water side velocity	1.286 m/s
Water side pressure drop	0 bar
Heat transfer from gas	34597 kW
Heat transfer to steam/water	34425 kW

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPB
Date: 06/11/20	
Drawing No:	

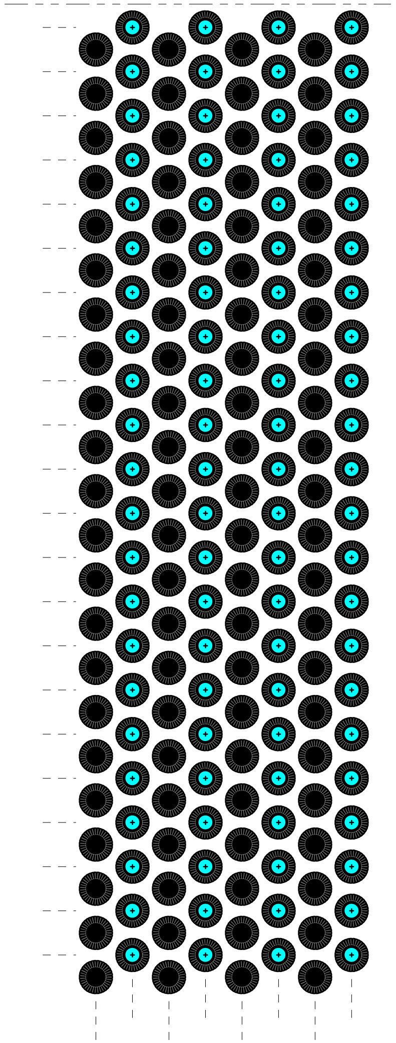
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

LTE Hardware Design

Parallel HX



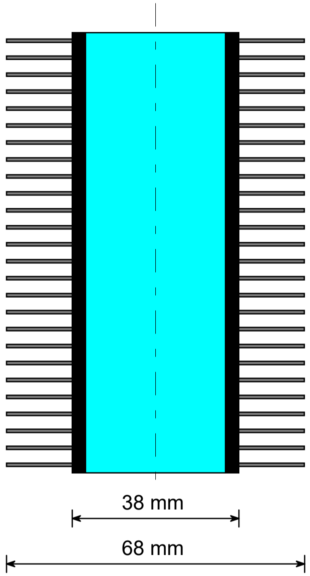
LTE
10 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

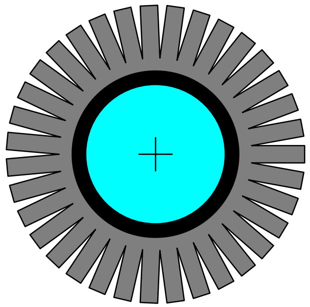
Gas Out
126.6 T
837.9 m

Gas In
157.7 T
837.9 m

Water In
4.68 p
105.4 T
442.6 h
153.4 m

Water Out
4.548 p
148.3 T
624.9 h
153.4 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	3.048 mm
Fin height	15 mm
Fin spacing	3.077 mm
Fin thickness	0.8 mm
Number of fins per meter	257.9
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	10
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	50703 m^2
Maximum gas velocity	5.729 m/s
Gas pressure drop	1.273 millibar
Water side velocity	1.112 m/s
Water side pressure drop	0.1321 bar
Heat transfer from gas	28107 kW
Heat transfer to water	27967 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

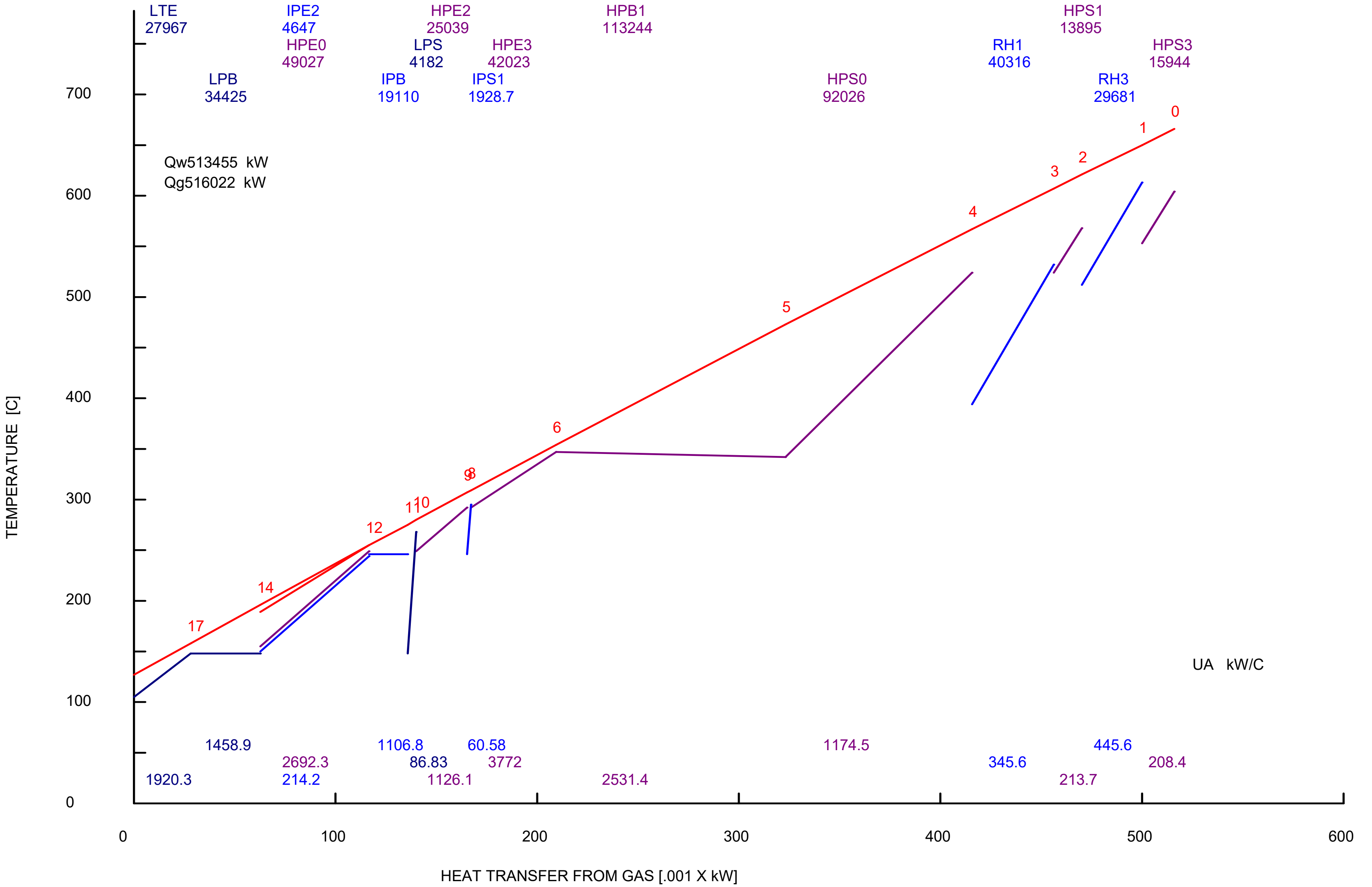
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LTE
Date: 06/11/20	
Drawing No:	

GT MASTER 29.0 AECOM

Net Power 549426 kW
LHV Net Heat Rate 7224 kJ/kWh
LHV Net Efficiency 49.83 %

HRSG Temperature Profile



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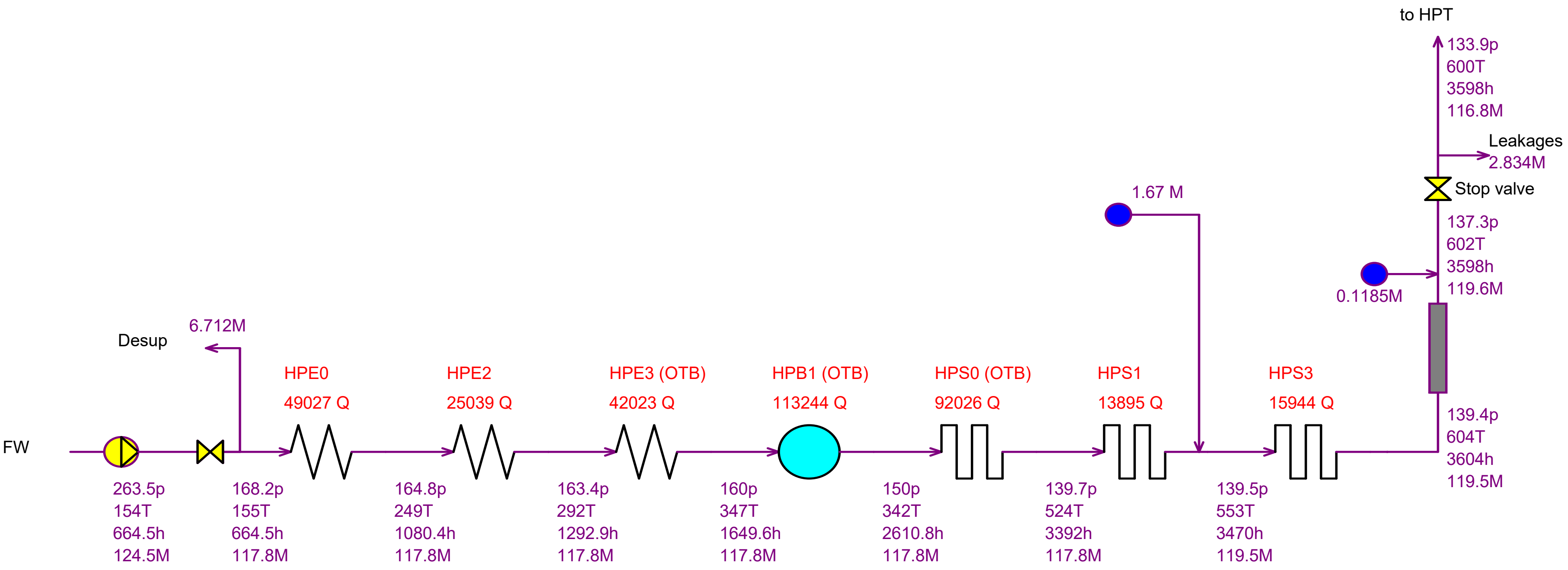
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

HP Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

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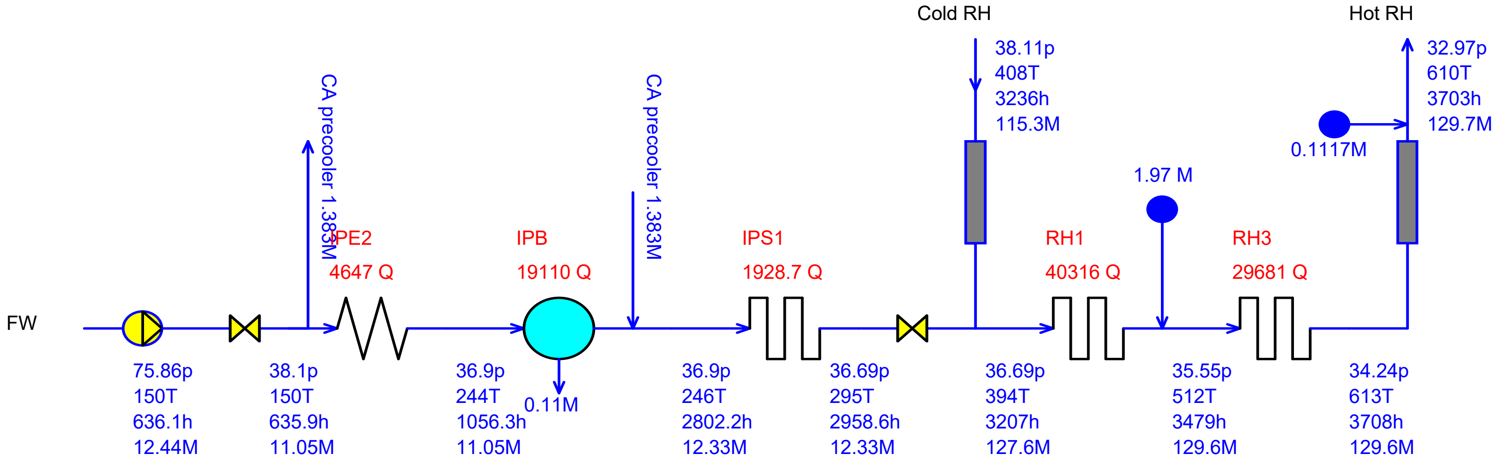
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

IP & Reheat Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

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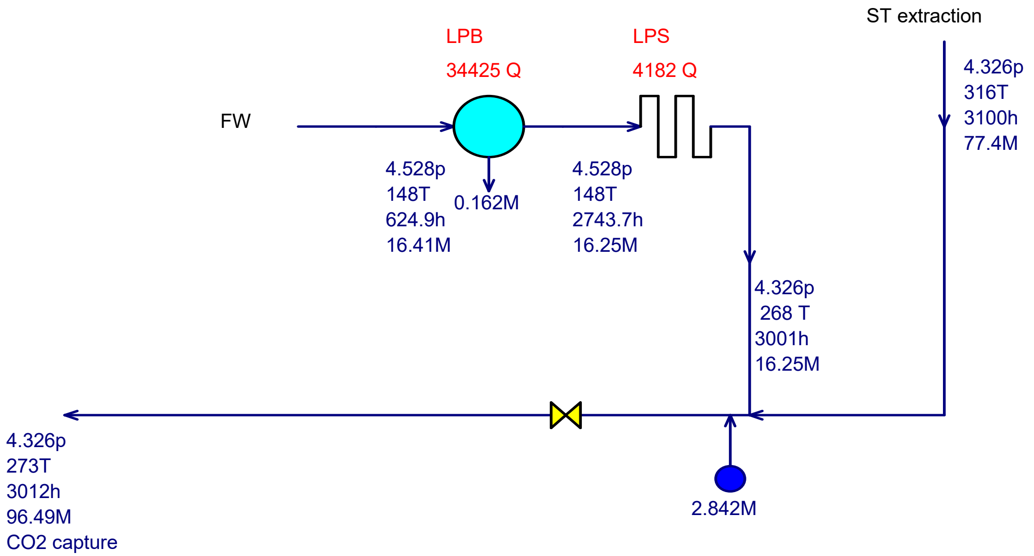
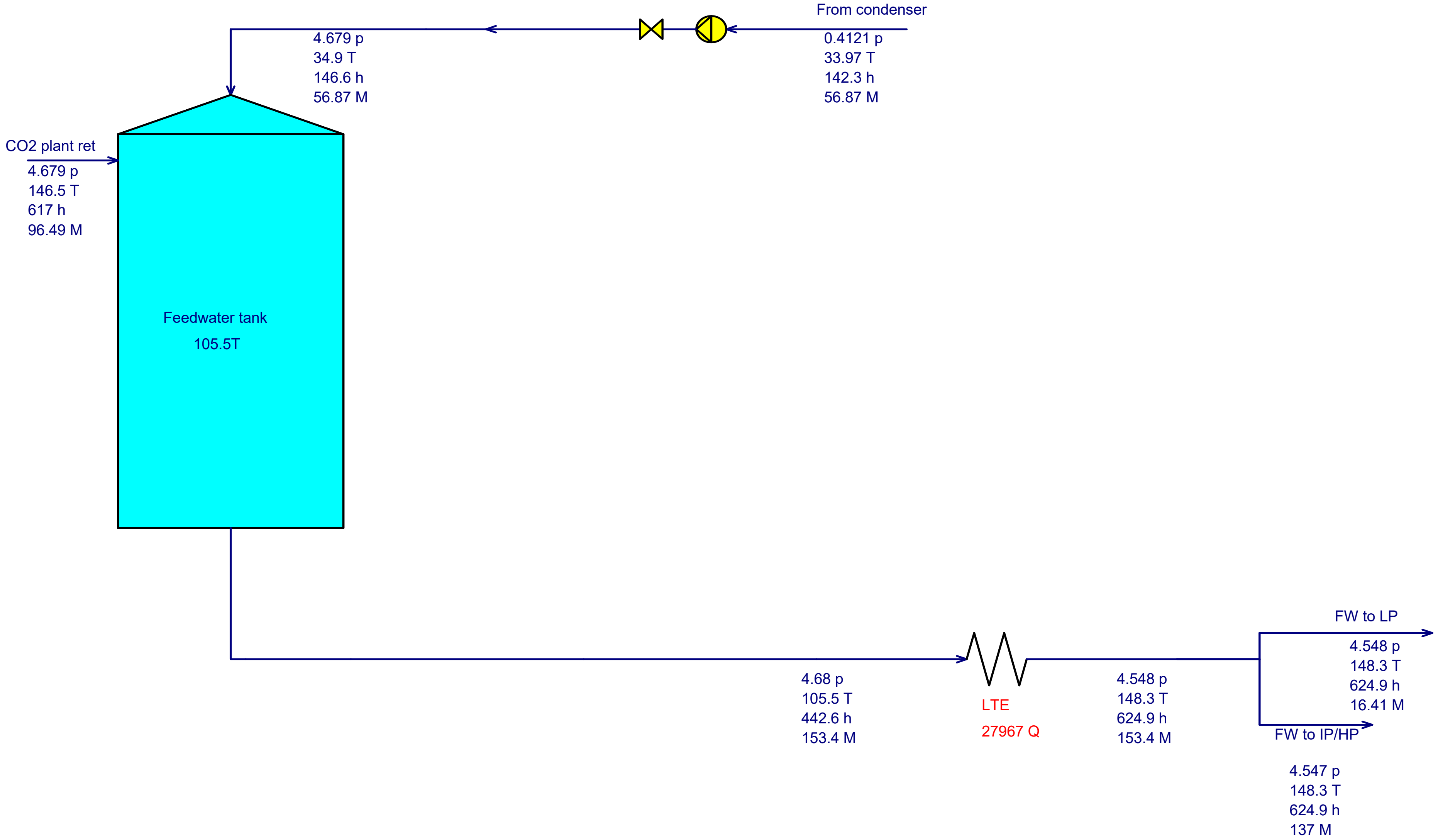
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

LP Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

Feedwater Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

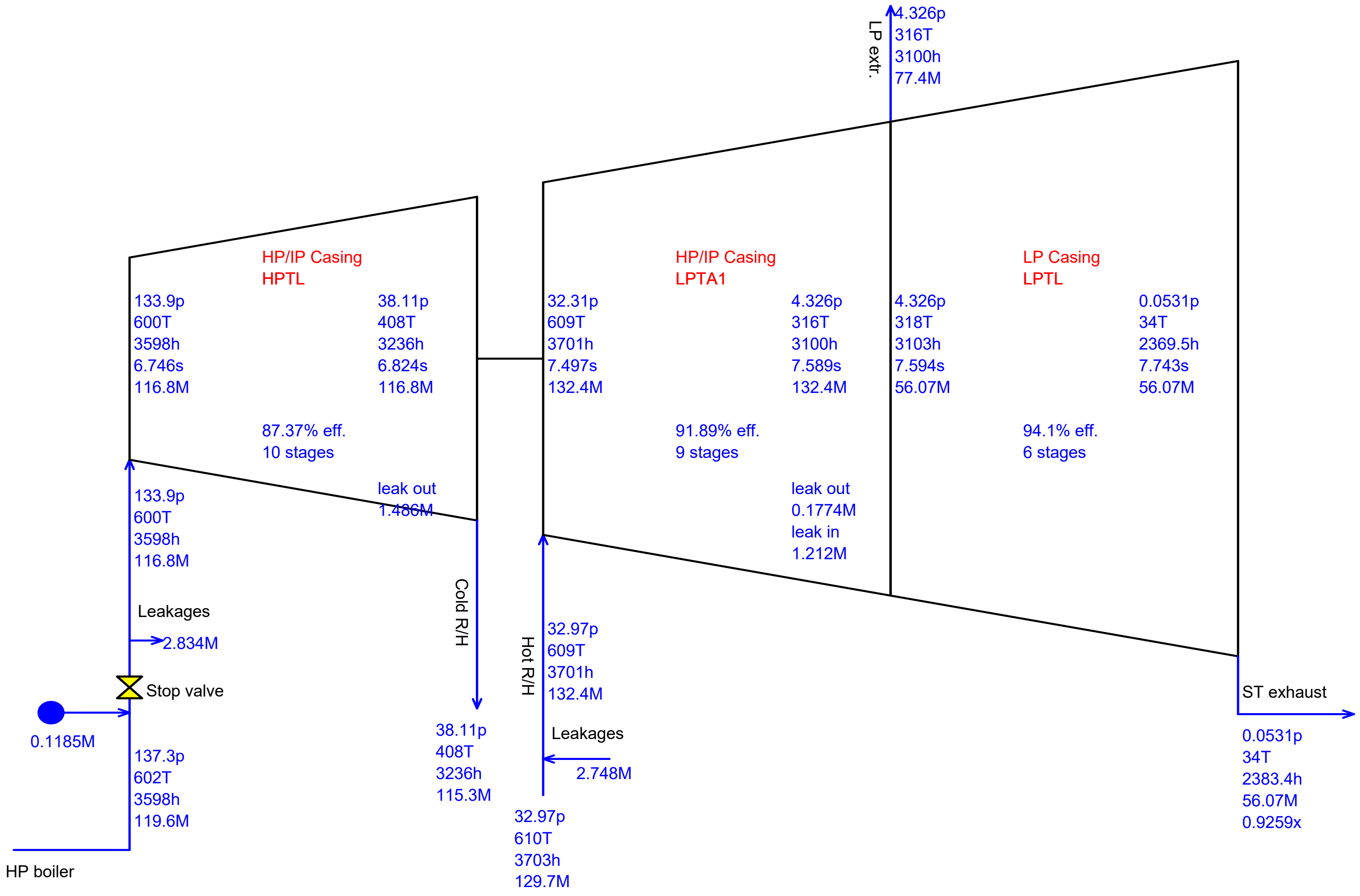
1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

GT MASTER 29.0 AECOM

ST Expansion Power 162227 kW
ST Generator Output 159641 kW

Steam Turbine Group Data



ST Model Adjustments: Disabled
p[bar], T[C], h[kJ/kg], s[kJ/kg-C], M[kg/s], Steam Properties: IAPWS-IF97
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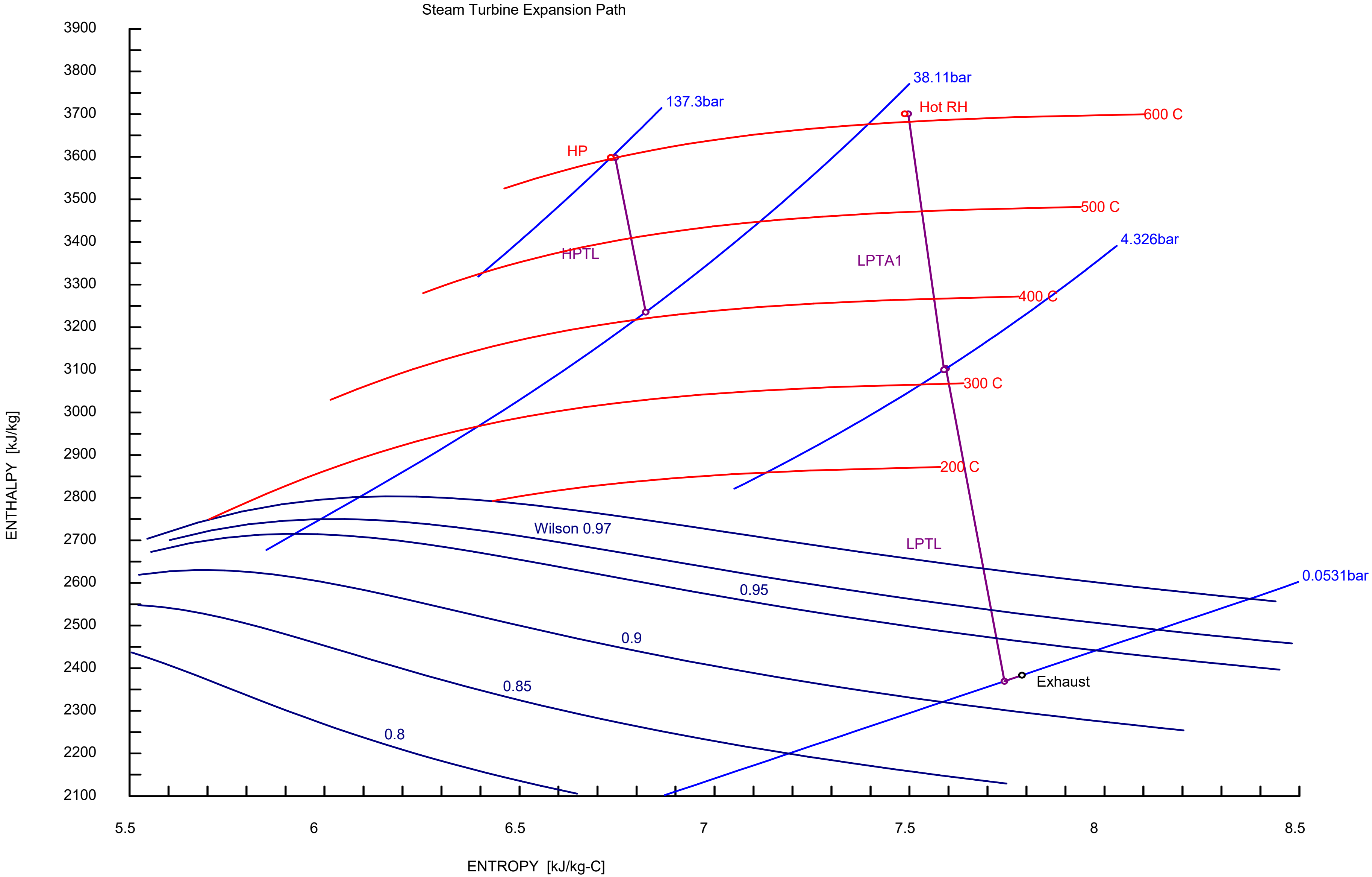
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

GT MASTER 29.0 AECOM

ST Expansion Power 162227 kW
ST Generator Output 159641 kW



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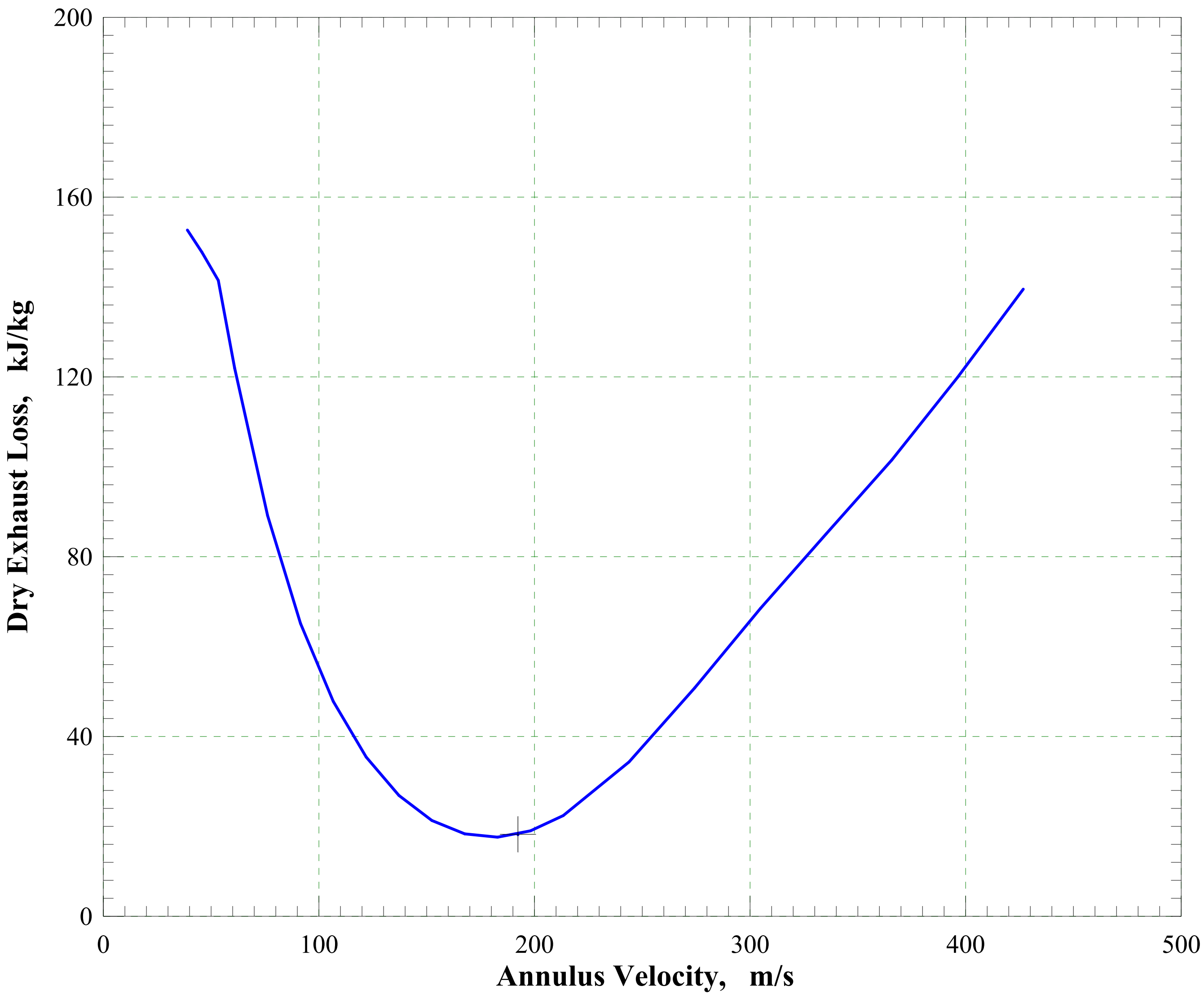
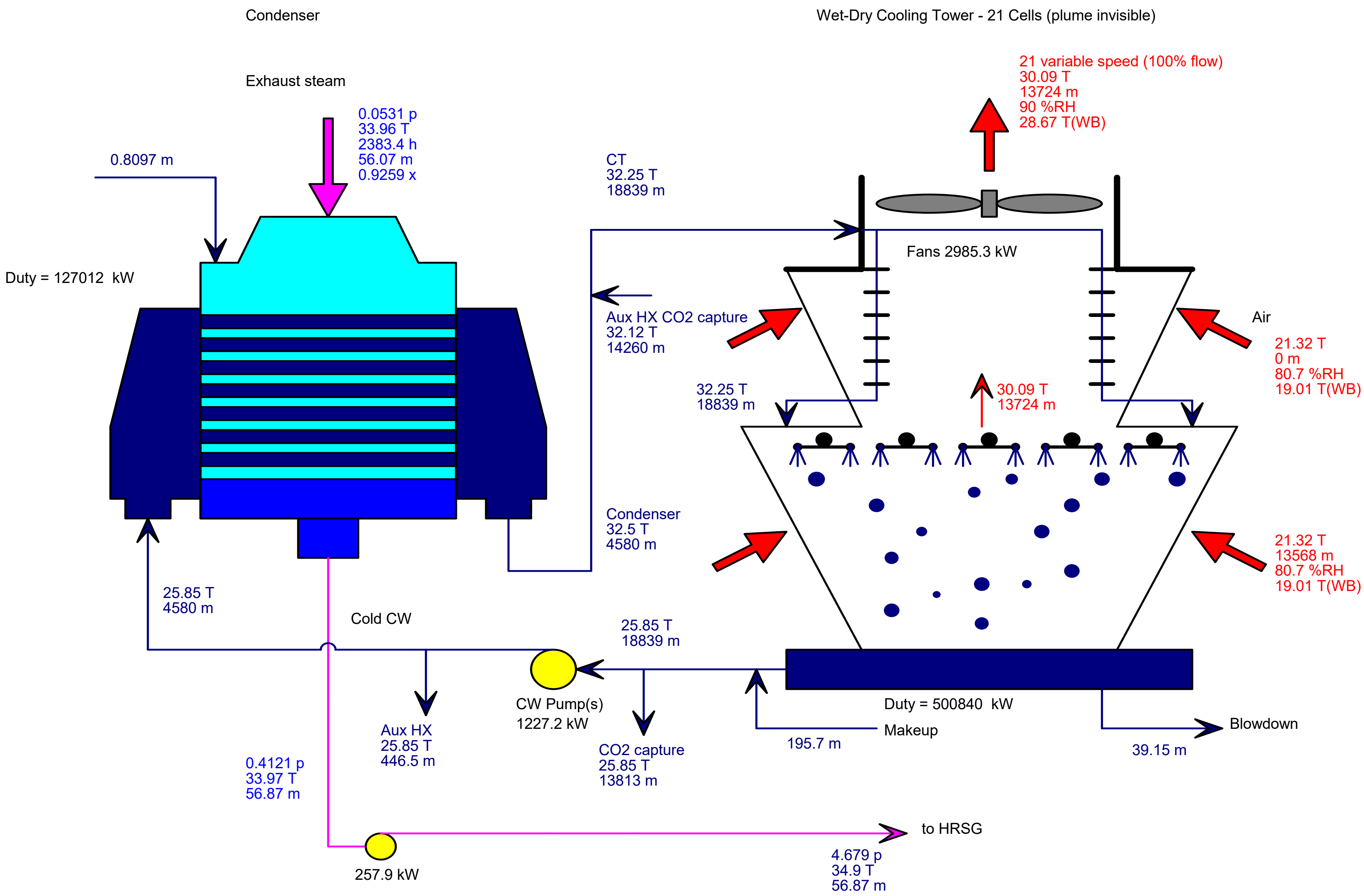
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Steam Turbine Exhaust Loss



Cooling System



p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

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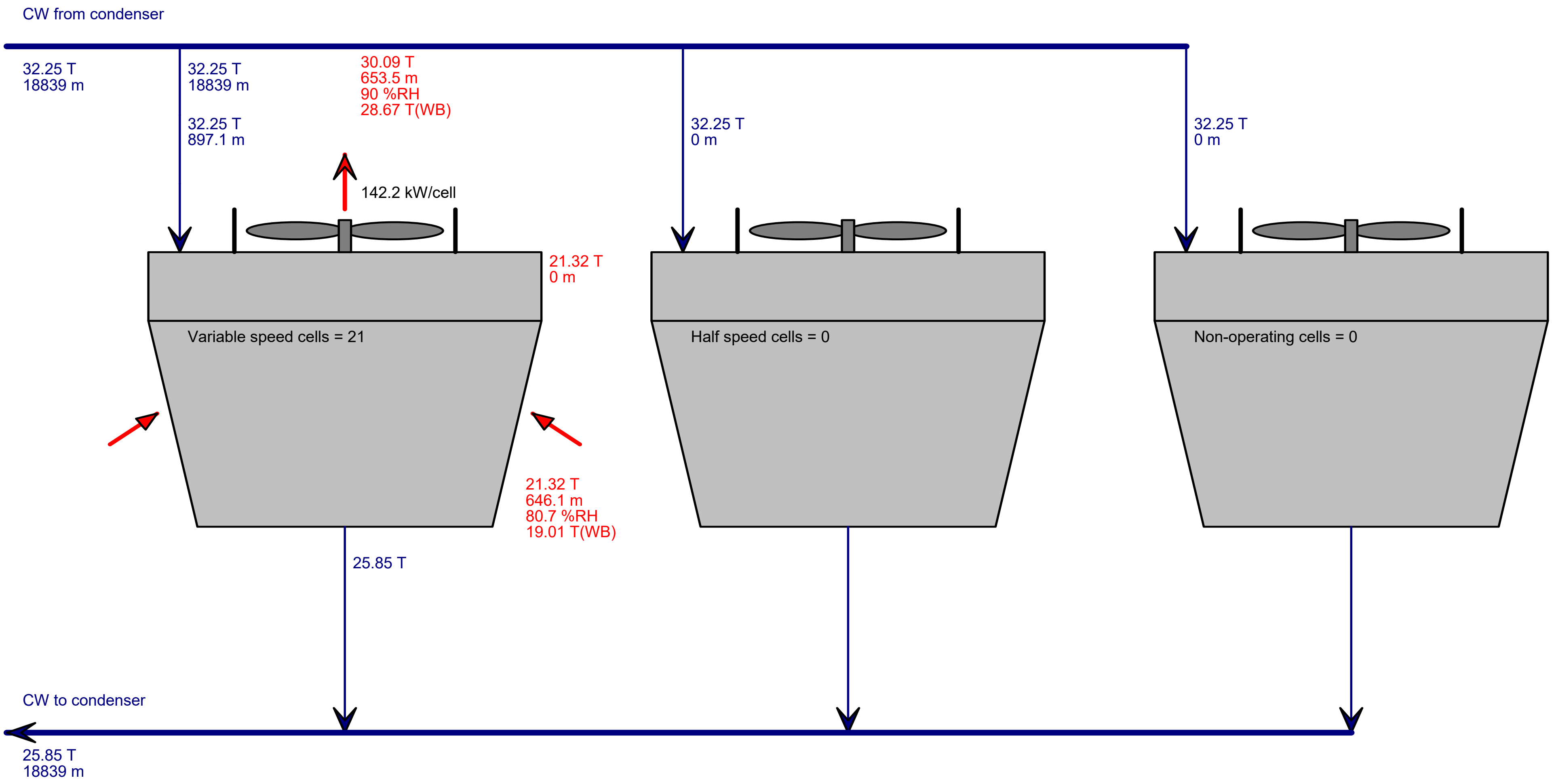
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Cooling Tower Cells - 21 existing cells



p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

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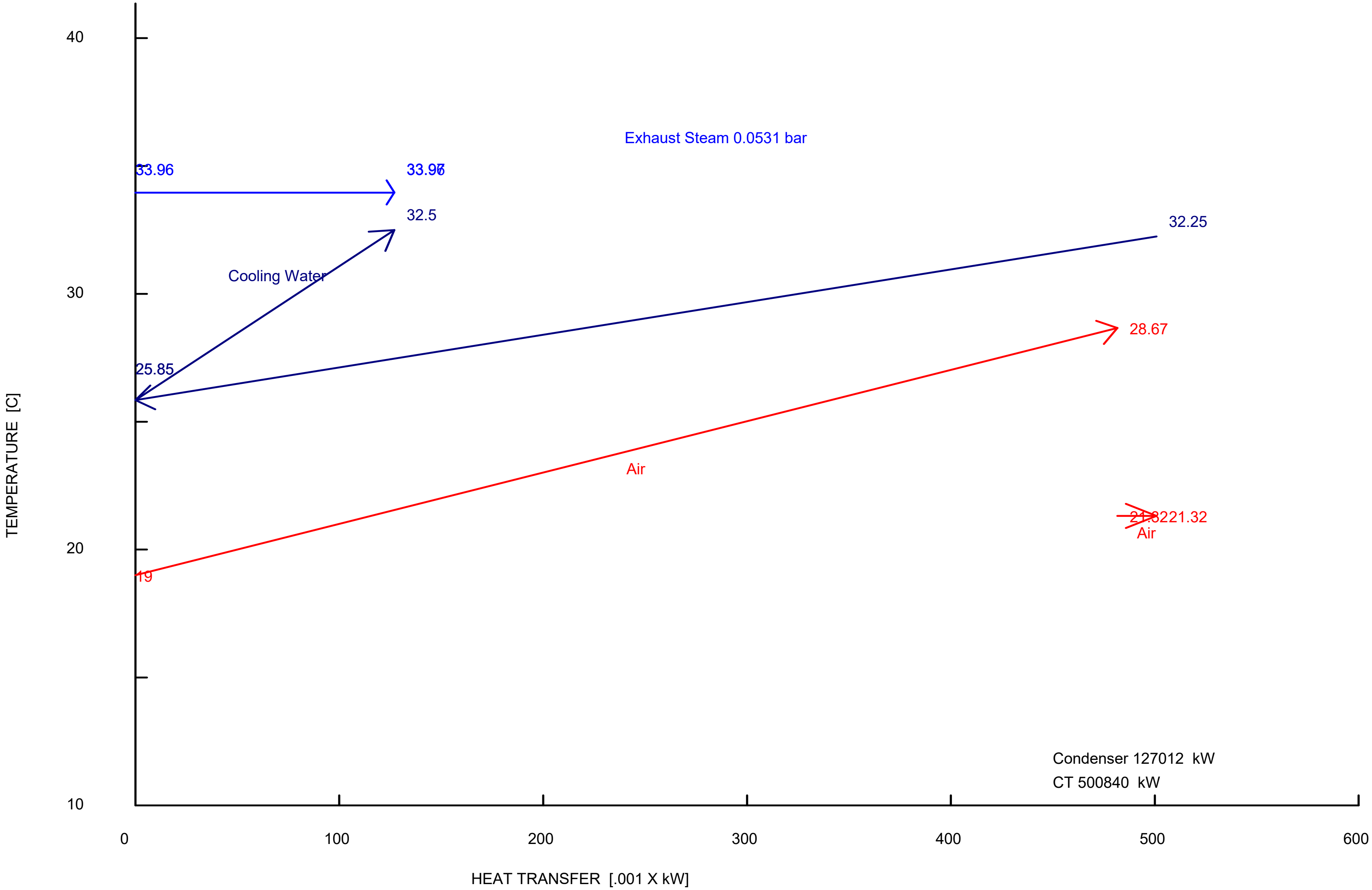
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Water Cooled Condenser and Wet-Dry Cooling Tower T-Q Diagram



AIR STATES:

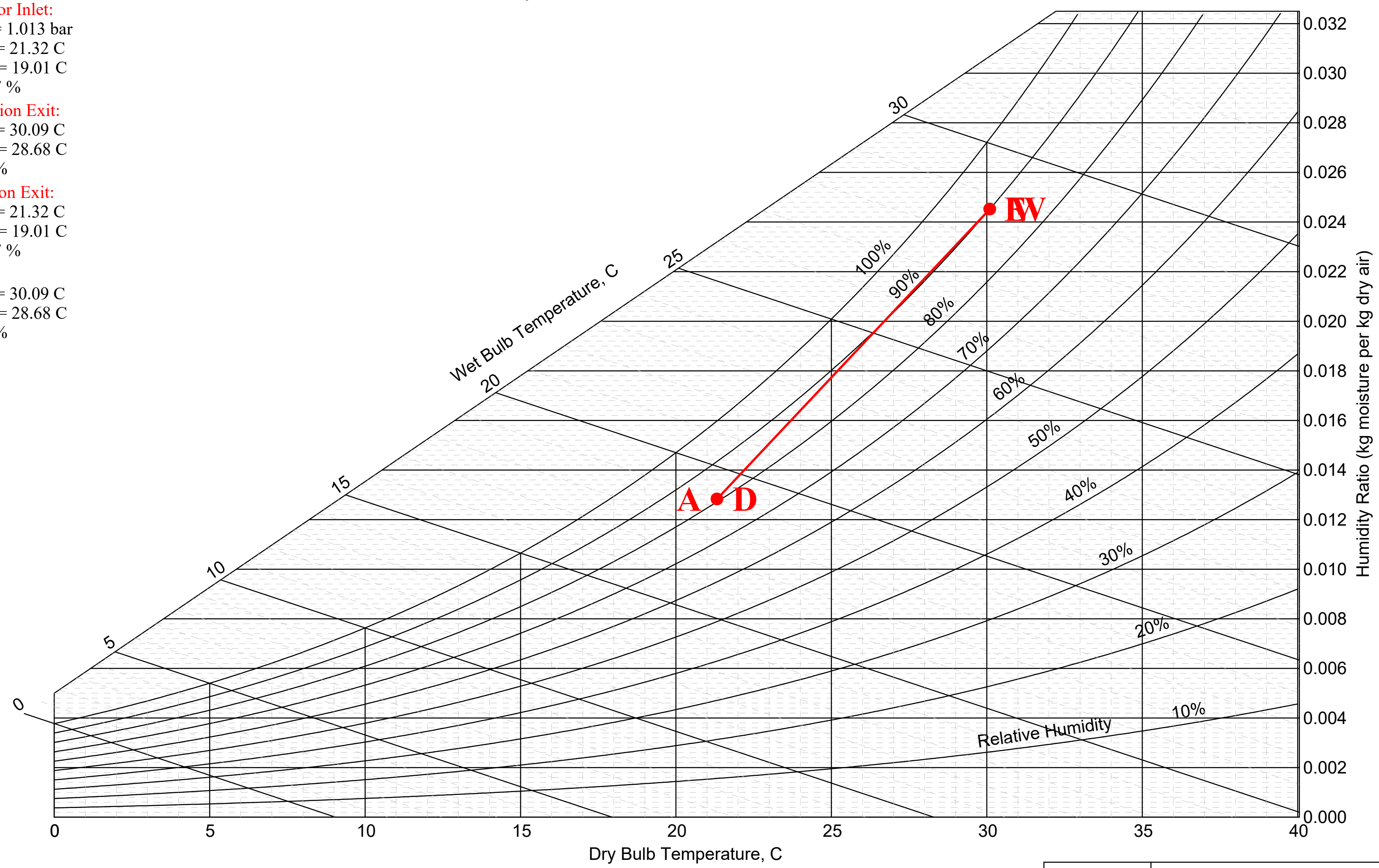
A) Ambient or Inlet:
Pressure = 1.013 bar
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %

W) Wet Section Exit:
Dry bulb = 30.09 C
Wet bulb = 28.68 C
RH = 90 %

D) Dry Section Exit:
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %

E) Air Exit:
Dry bulb = 30.09 C
Wet bulb = 28.68 C
RH = 90 %

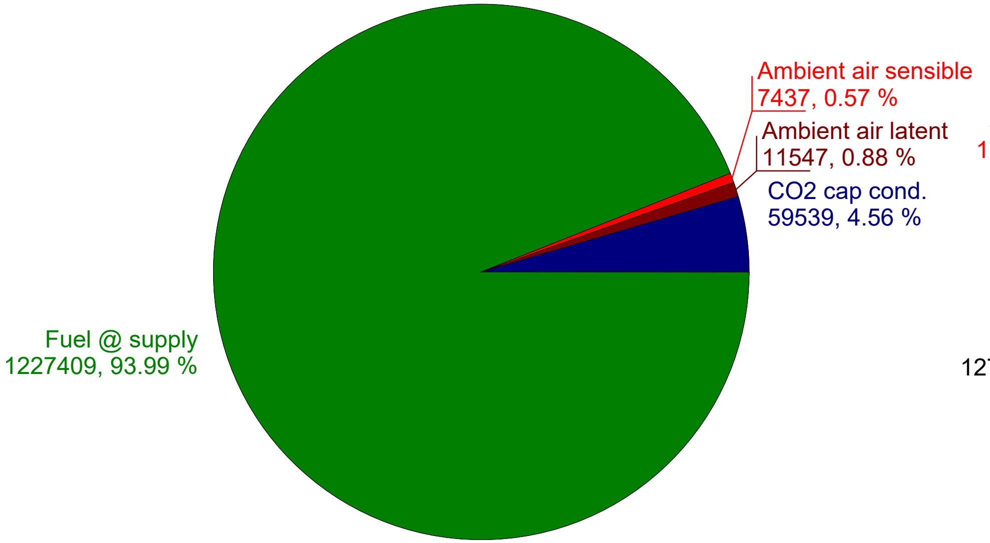
Psychrometric Chart



Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Cooling Tower
Date: 06/11/20	
Drawing No:	

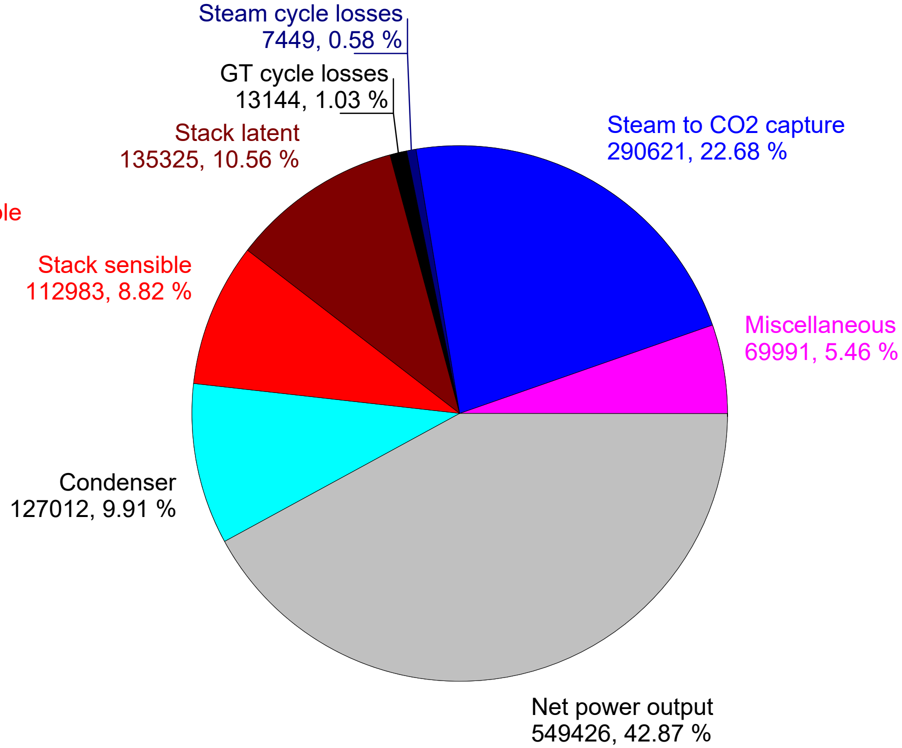
Plant Energy In [kW]

Plant energy in = 1305951 kW
Plant fuel chemical LHV input = 1102549 kW, HHV = 1223403 kW
Plant net LHV elec. eff. = 49.83 % (100% * 549426 / 1102549), Net HHV elec. eff. = 44.91 %



Plant Energy Out [kW]

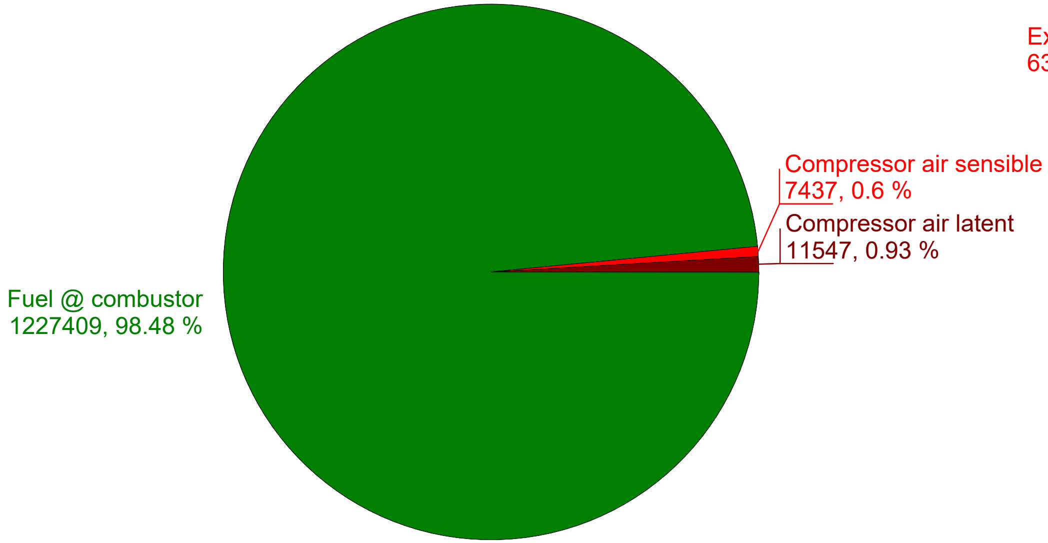
Plant energy out = 1281631 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

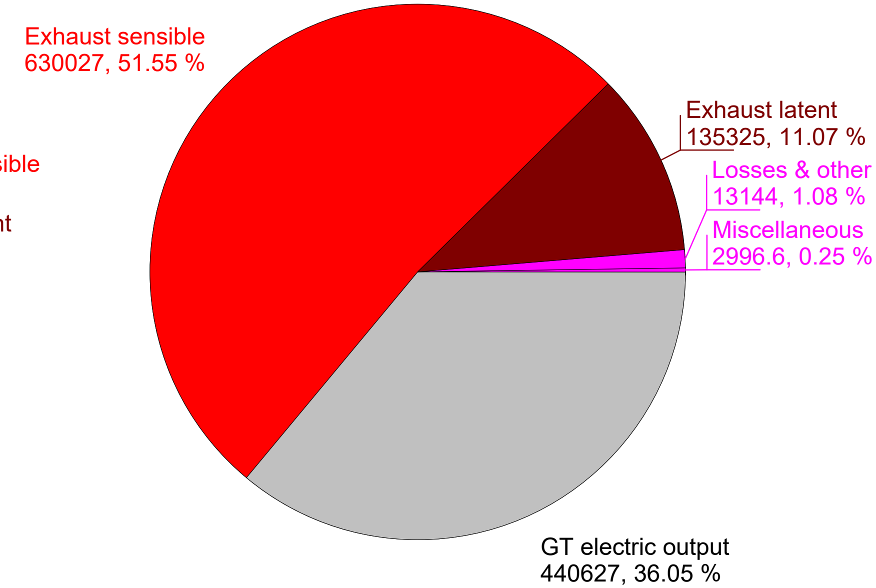
GT Cycle Energy In [kW]

GT cycle energy in = 1246394 kW
GT fuel chemical LHV input = 1102549 kW, HHV = 1223403 kW



GT Cycle Energy Out [kW]

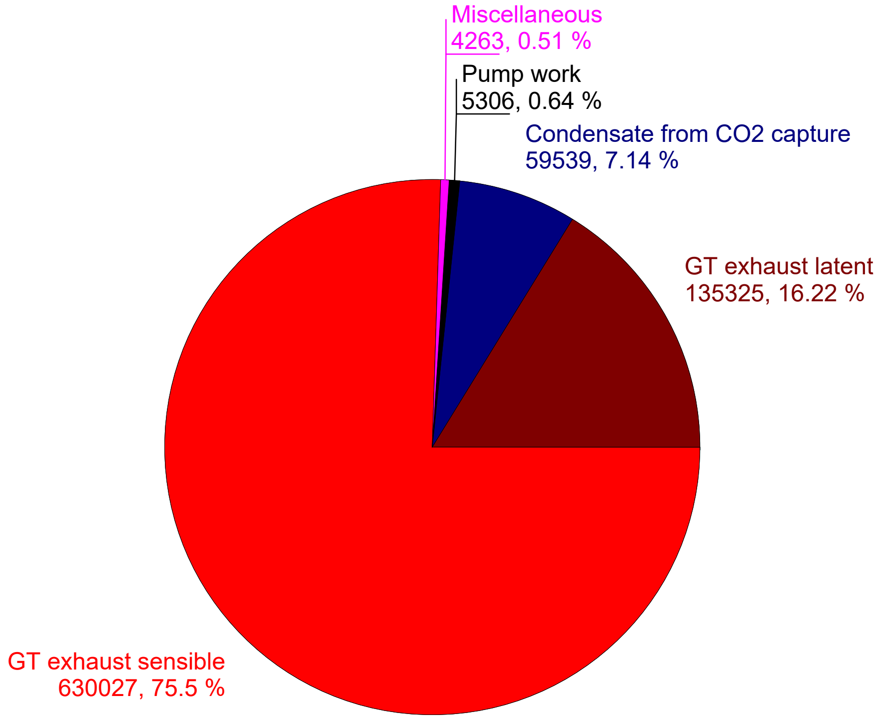
GT cycle energy out = 1222120 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

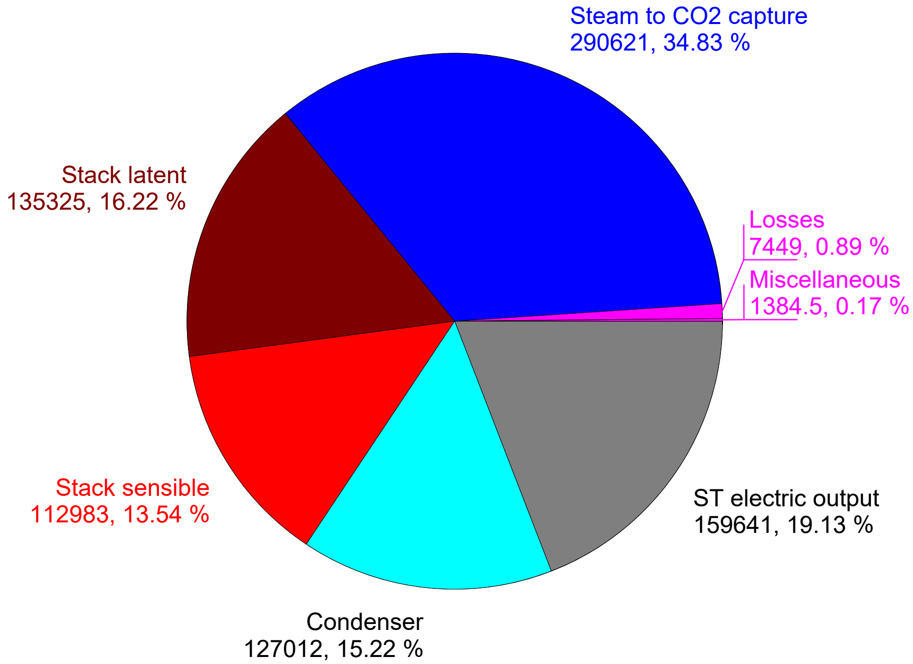
Steam Cycle Energy In [kW]

Steam cycle energy in = 834461 kW



Steam Cycle Energy Out [kW]

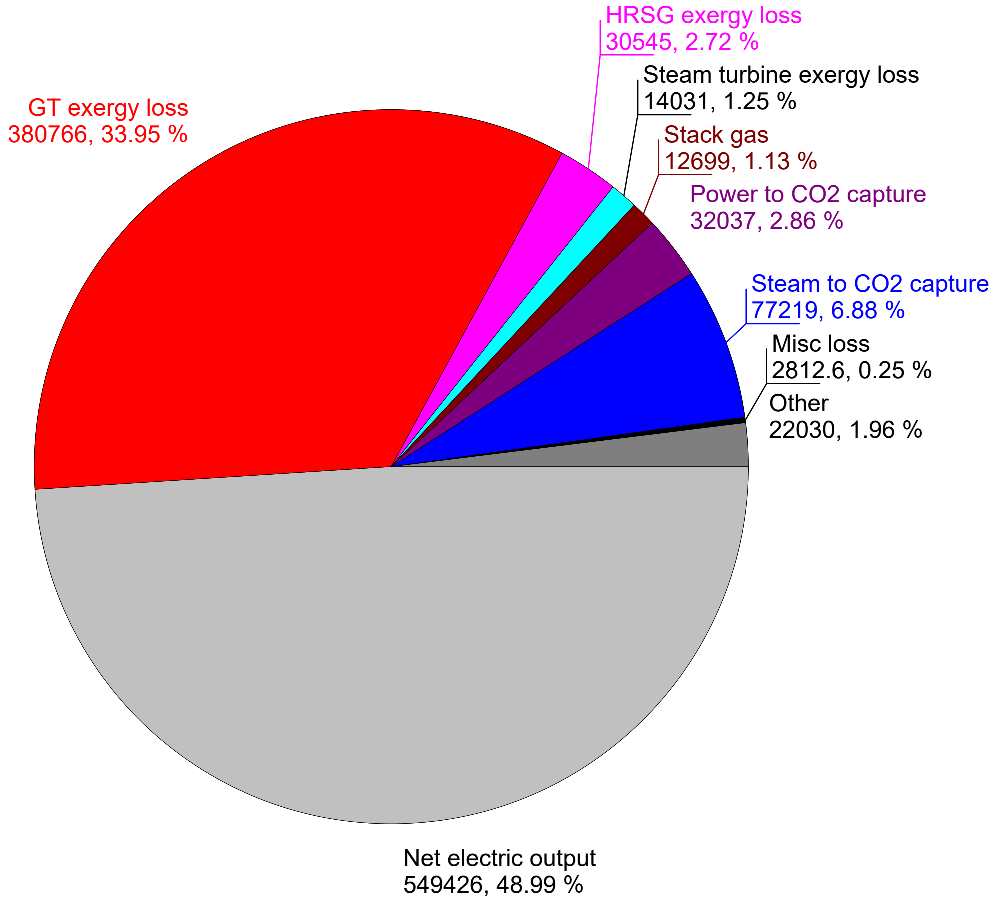
Steam cycle energy out = 834415 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Plant Exergy Analysis [kW]

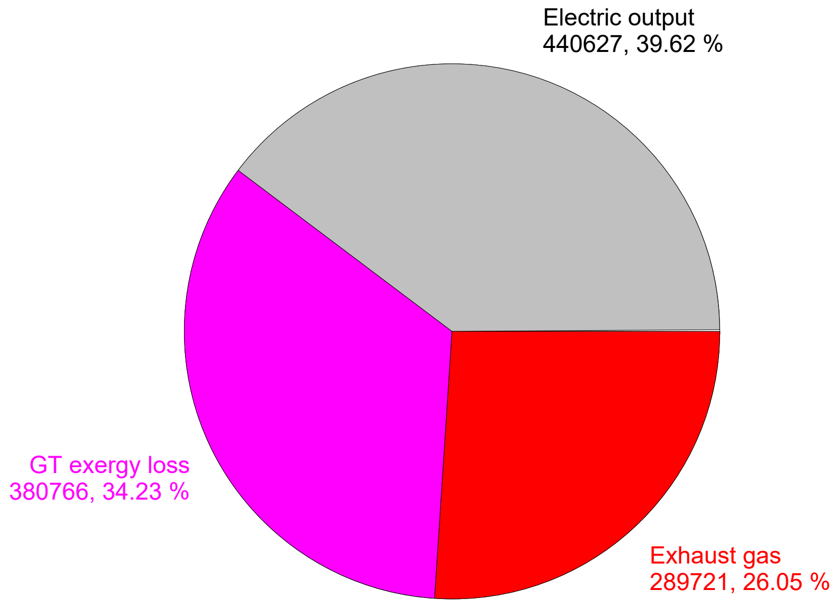
Plant exergy input = 1121567 kW
Fuel exergy input = 1113154 kW
Plant fuel chemical LHV input = 1102549 kW, HHV = 1223403 kW



Reference: 1.013 bar, 25 C, water as vapor.

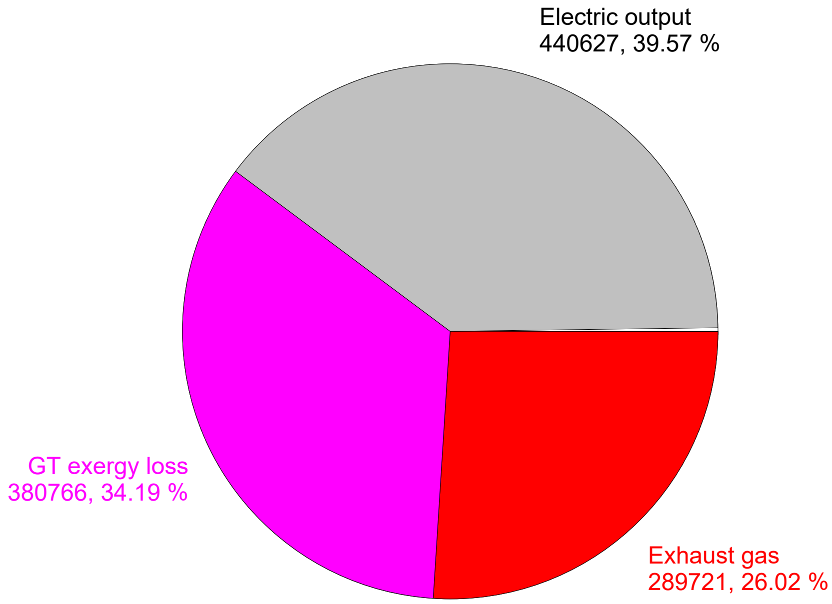
GT Exergy Analysis [kW]

GT exergy in = 1112234 kW



GT & Peripheral Exergy Analysis [kW]

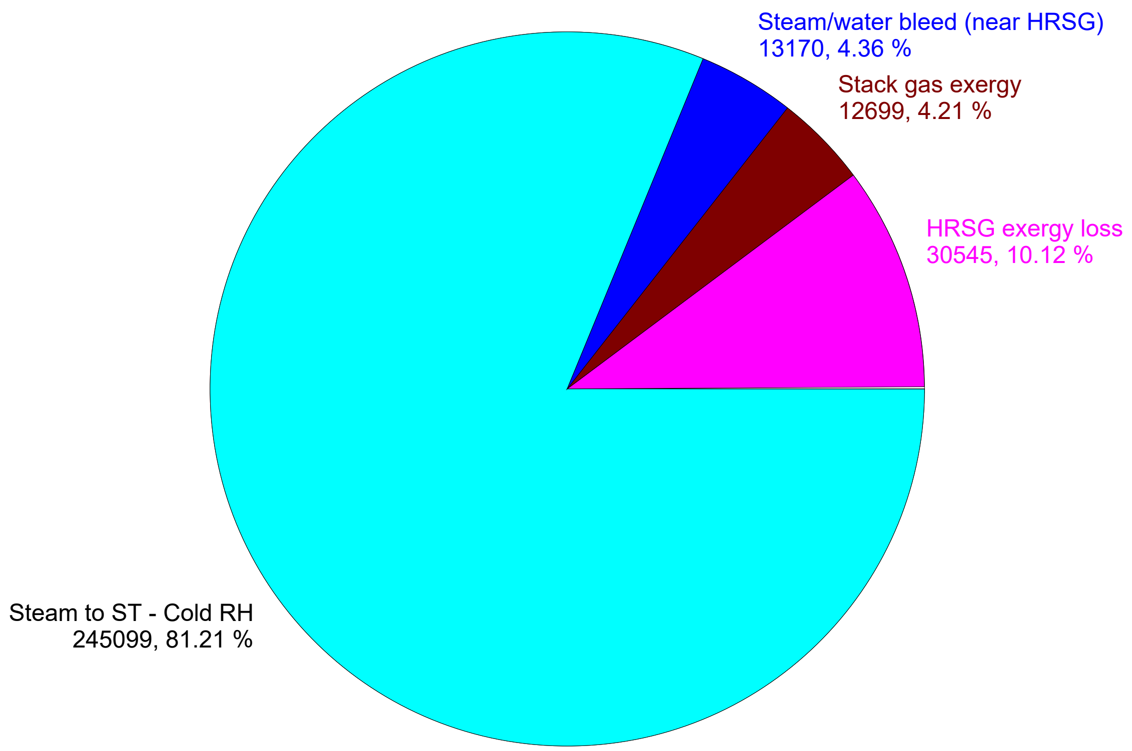
GT & peripheral exergy in = 1113523 kW



Reference: 1.013 bar, 25 C, water as vapor.

HRSG Exergy Analysis [kW]

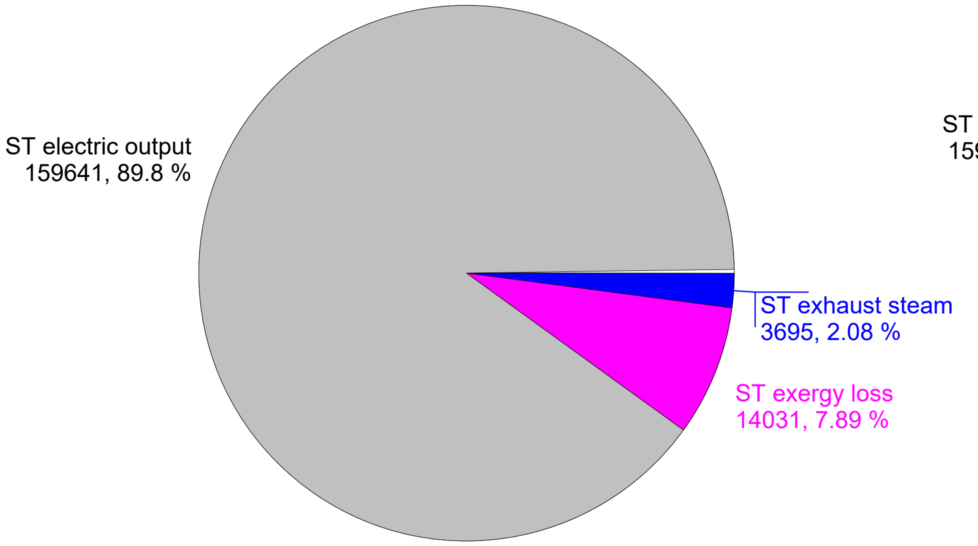
HRSG exergy in = 301825 kW



Reference: 1.013 bar, 25 C, water as vapor.

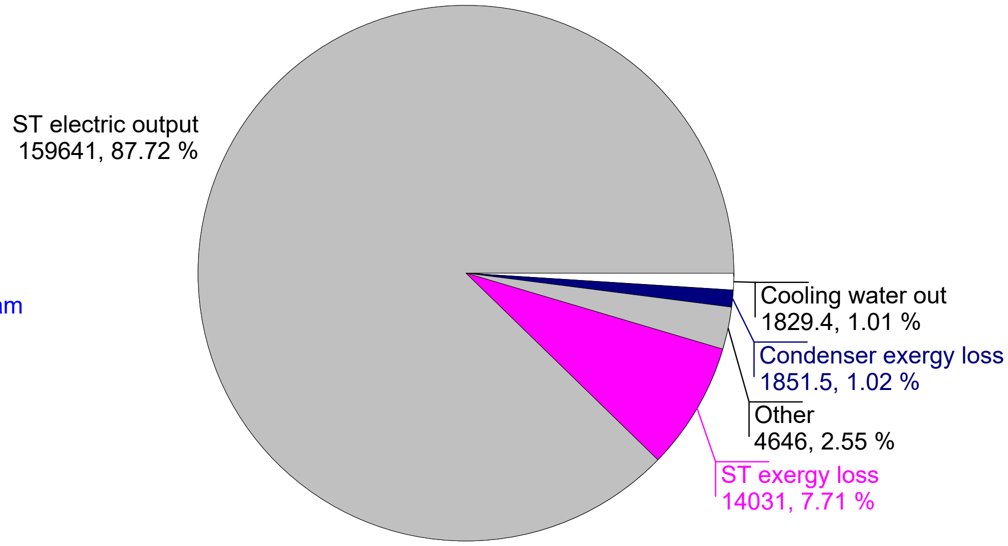
ST Exergy Analysis [kW]

ST exergy in = 177772 kW



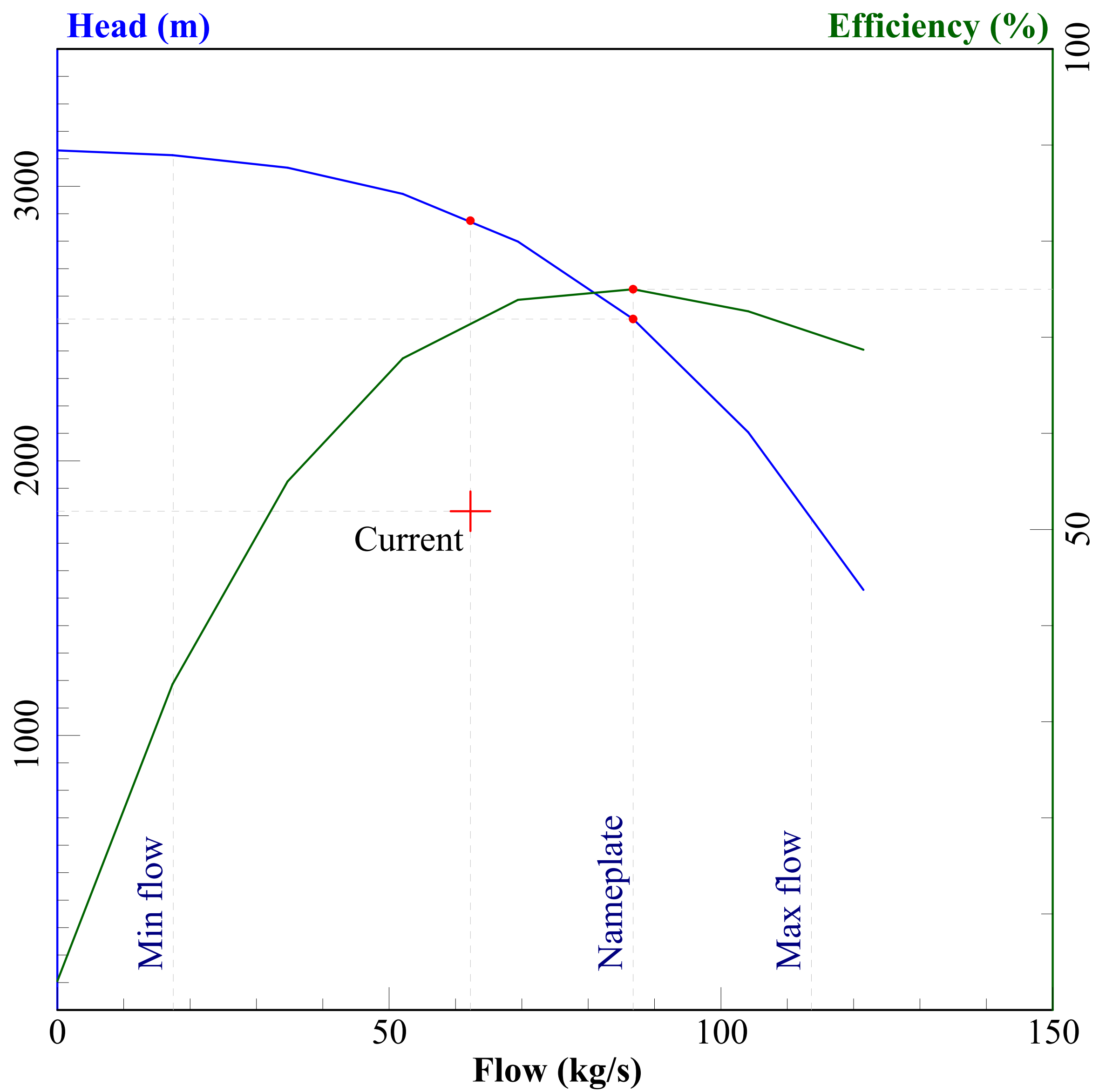
ST & Condenser Exergy Analysis [kW]

ST & condenser exergy in = 181999 kW



Reference: 1.013 bar, 25 C, water as vapor.

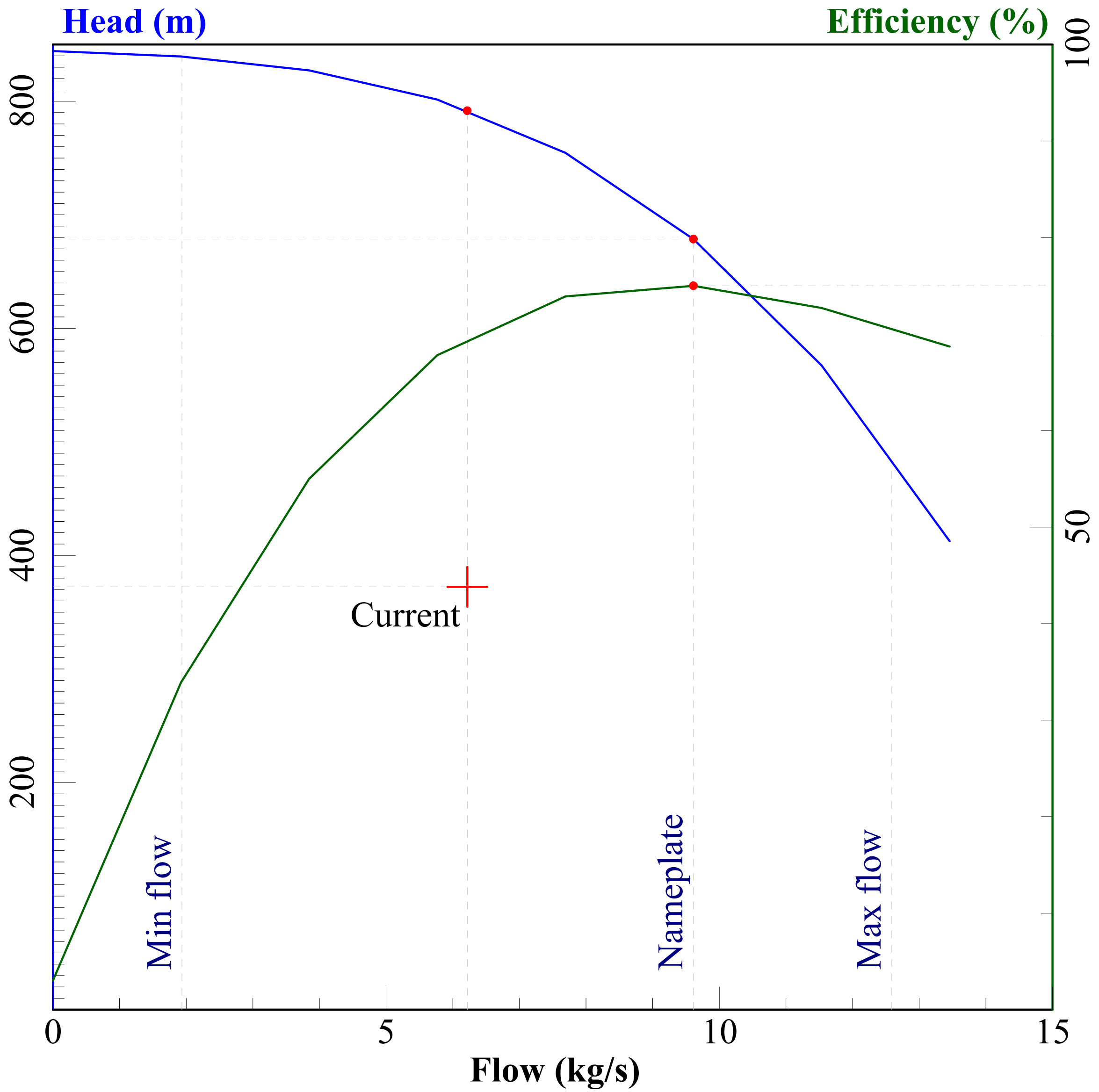
HP Feedwater Pump (P1)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	86.77 kg/s
Nameplate head	2516.5 m
Nameplate flow (nominal)	5678 lpm
Nameplate head (nominal)	2560.3 m
Nameplate RPM	3000
Current pump flow	62.26 kg/s
Current head	2874.5 m
Current head after valve	1816.7 m
Current RPM	3000
Minimum continuous flow	17.48 kg/s
Maximum continuous flow	113.6 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HP Feedwater Pump (P1)
Date: 06/11/20	
Drawing No:	

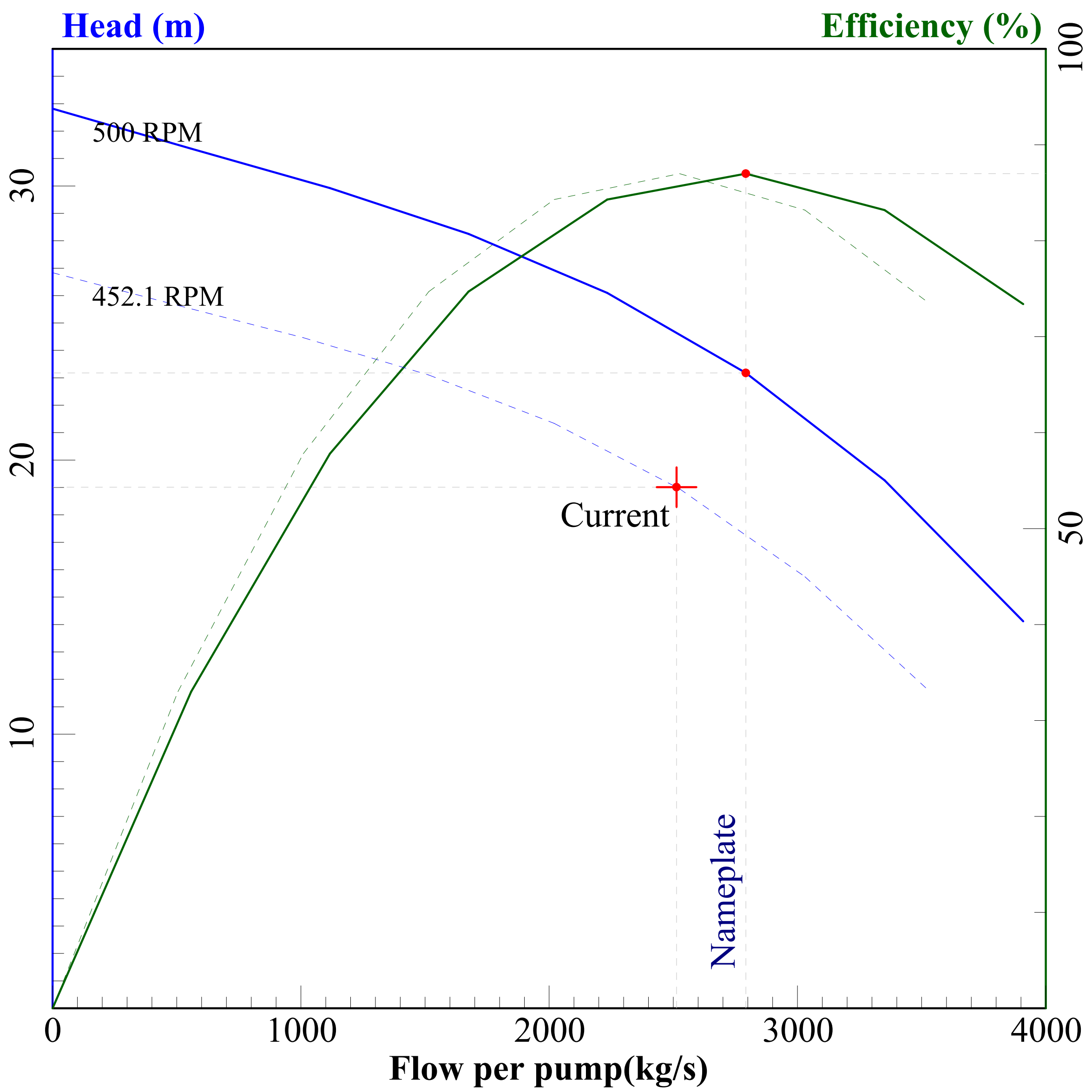
IP Feedwater Pump (P2)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	9.612 kg/s
Nameplate head	678.6 m
Nameplate flow (nominal)	662.4 lpm
Nameplate head (nominal)	701 m
Nameplate RPM	3000
Current pump flow	6.219 kg/s
Current head	791.6 m
Current head after valve	372.4 m
Current RPM	3000
Minimum continuous flow	1.937 kg/s
Maximum continuous flow	12.59 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IP Feedwater Pump (P2)
Date: 06/11/20	
Drawing No:	

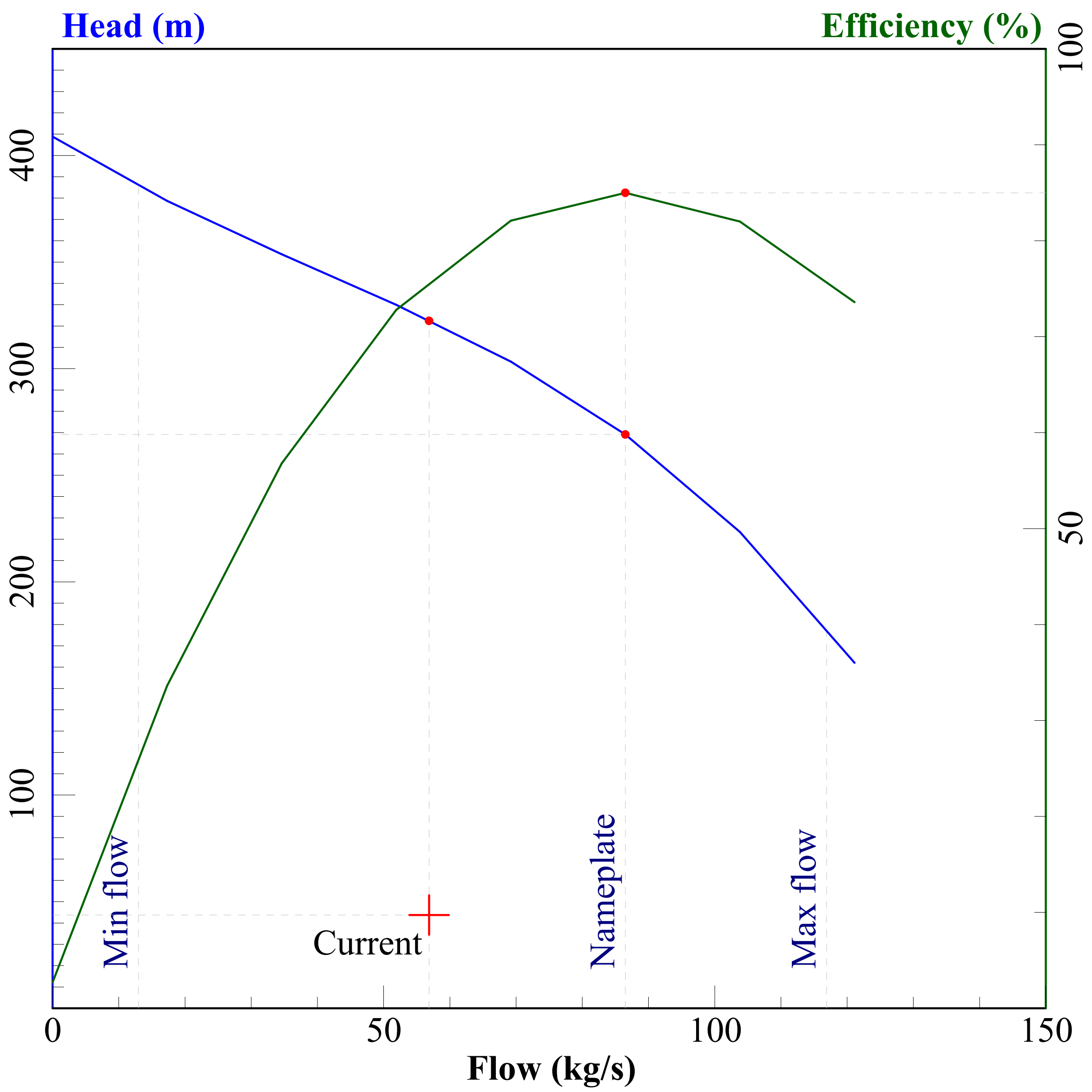
Condenser C.W. Pump (P4)



No. per Condenser	2
No. operating per Condenser	2
Nameplate flow	2792.3 kg/s
Nameplate head	23.18 m
Nameplate flow (nominal)	170344 lpm
Nameplate head (nominal)	24.38 m
Nameplate RPM	500
Current pump flow	2513 kg/s
Current head	19.01 m
Current head after valve	19.01 m
Current RPM	452.1

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condenser C.W. Pump (P4)
Date: 06/11/20	
Drawing No:	

Condensate Forwarding Pump (P6)



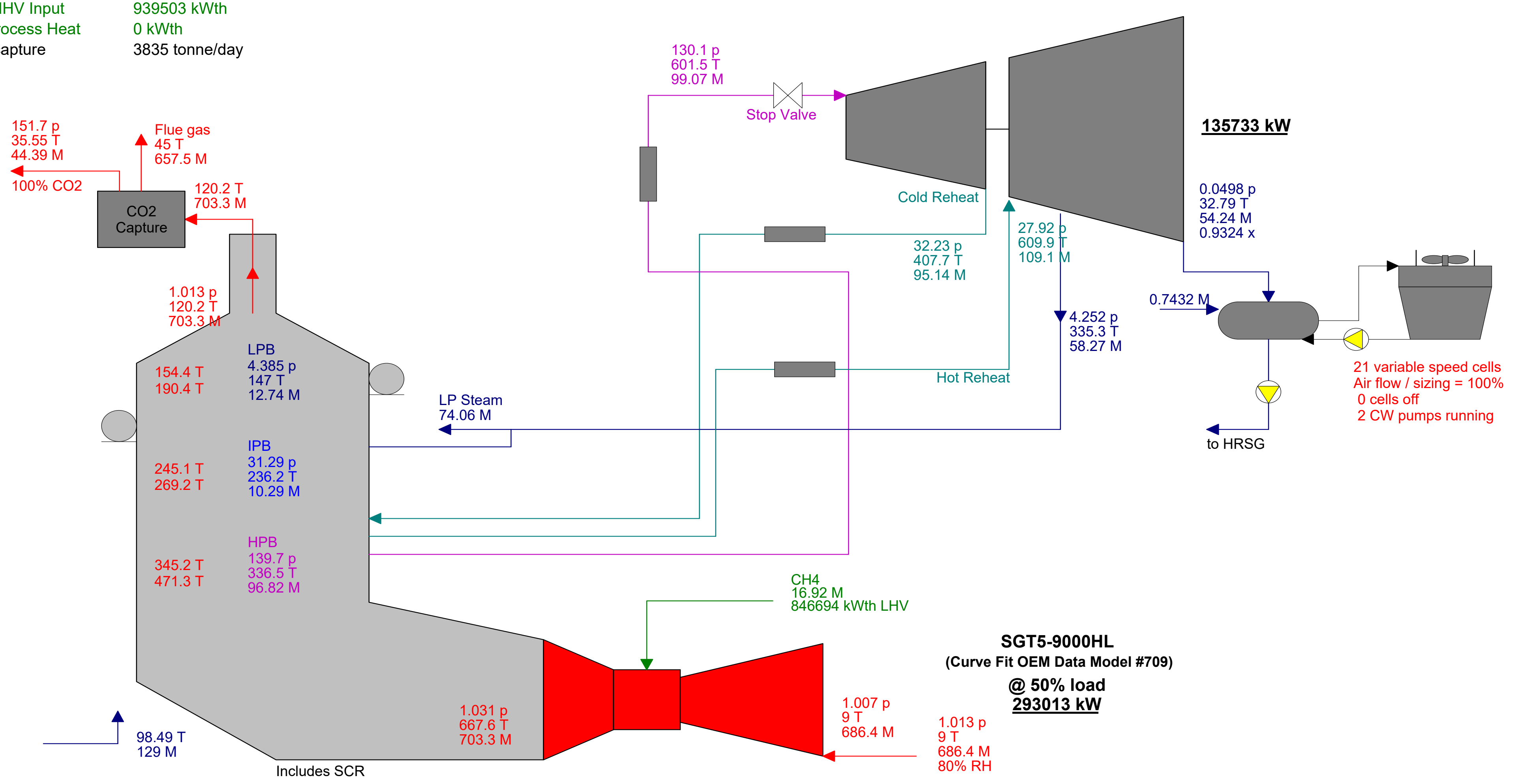
No. per Condenser	2
No. operating per Condenser	1
Nameplate flow	86.51 kg/s
Nameplate head	269.2 m
Nameplate flow (nominal)	5300 lpm
Nameplate head (nominal)	274.3 m
Nameplate RPM	1500
Current pump flow	56.87 kg/s
Current head	322.4 m
Current head after valve	43.77 m
Current RPM	1500
Minimum continuous flow	12.99 kg/s
Maximum continuous flow	116.9 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condensate Forwarding Pump (P6)
Date: 06/11/20	
Drawing No:	

GT MASTER 29.0 AECOM

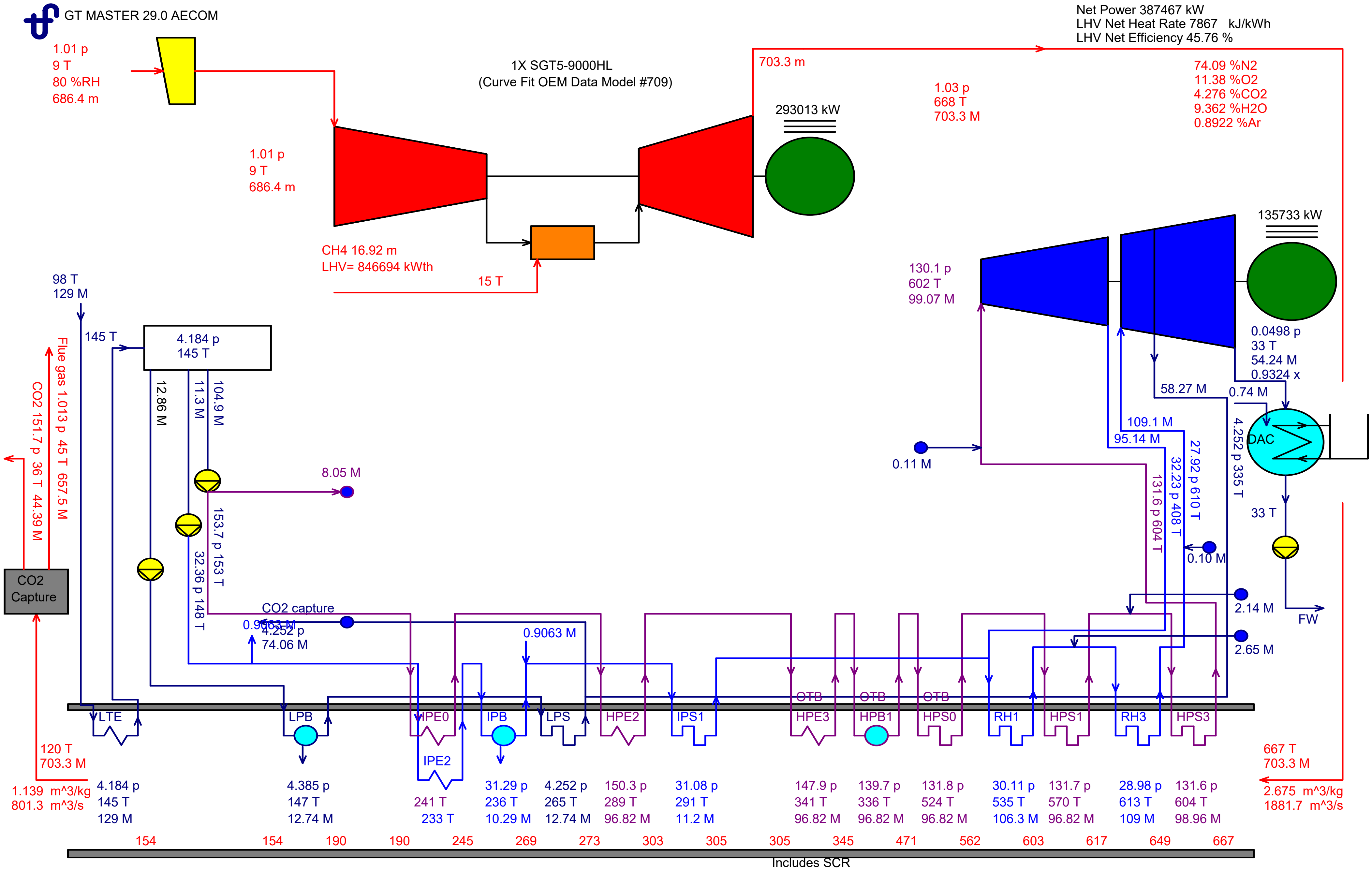
Gross Power	428746 kW
Net Power	387467 kW
Aux. & Losses	41279 kW
LHV Gross Heat Rate	7109 kJ/kWh
LHV Net Heat Rate	7867 kJ/kWh
LHV Gross Electric Eff.	50.64 %
LHV Net Electric Eff.	45.76 %
Fuel LHV Input	846694 kWth
Fuel HHV Input	939503 kWth
Net Process Heat	0 kWth
CO2 capture	3835 tonne/day

Ambient
1.013 P
9 T
80% RH
7.353 Twb



p [bar] T [C] M [kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 20:06:49 file=

GT MASTER 29.0 AECOM
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM



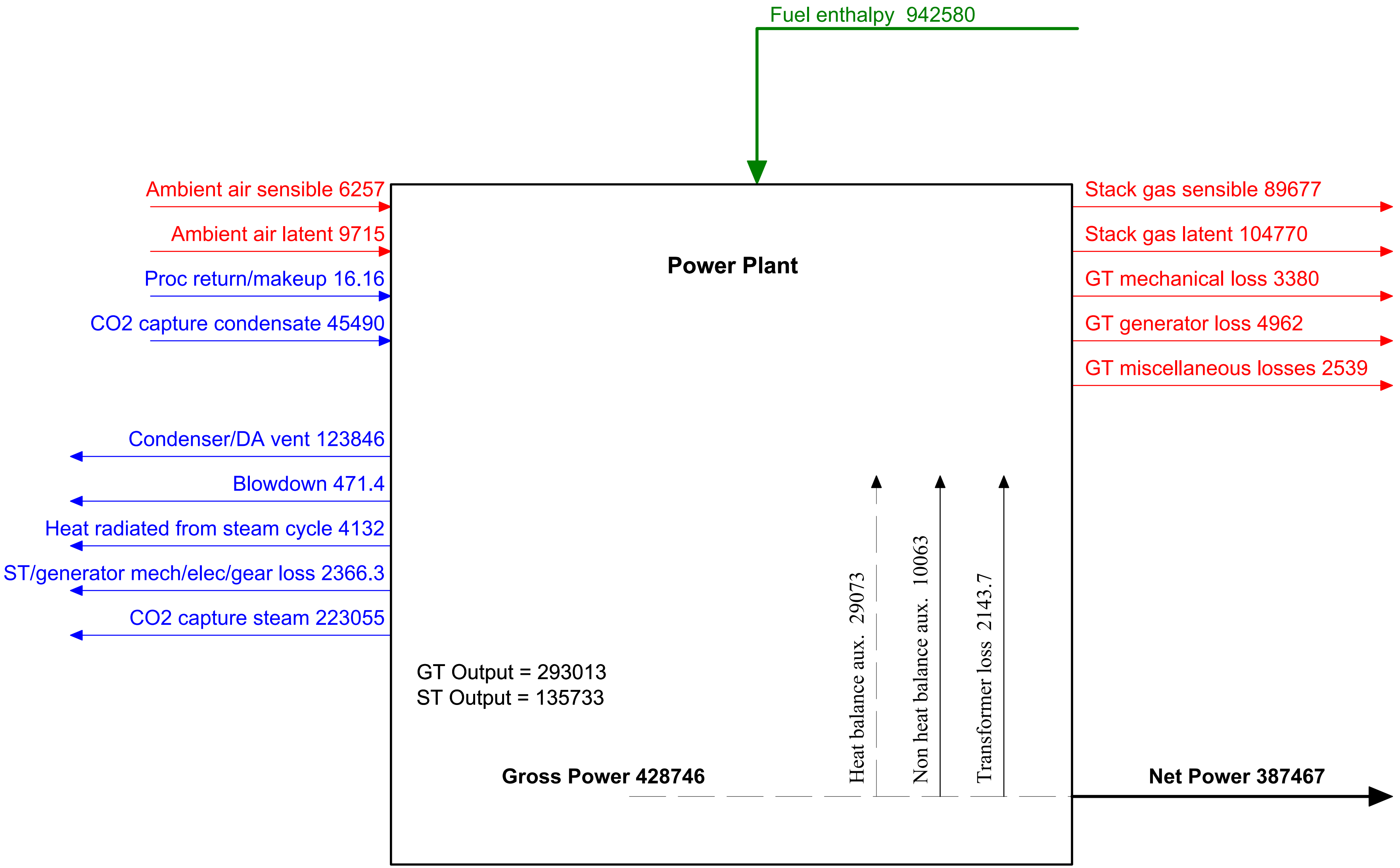
p[bar], T[C], M[kg/s], Steam Properties: IAPWS-IF97

1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Fuel chemical LHV input = 846694 kW
Fuel chemical HHV input = 939503 kW

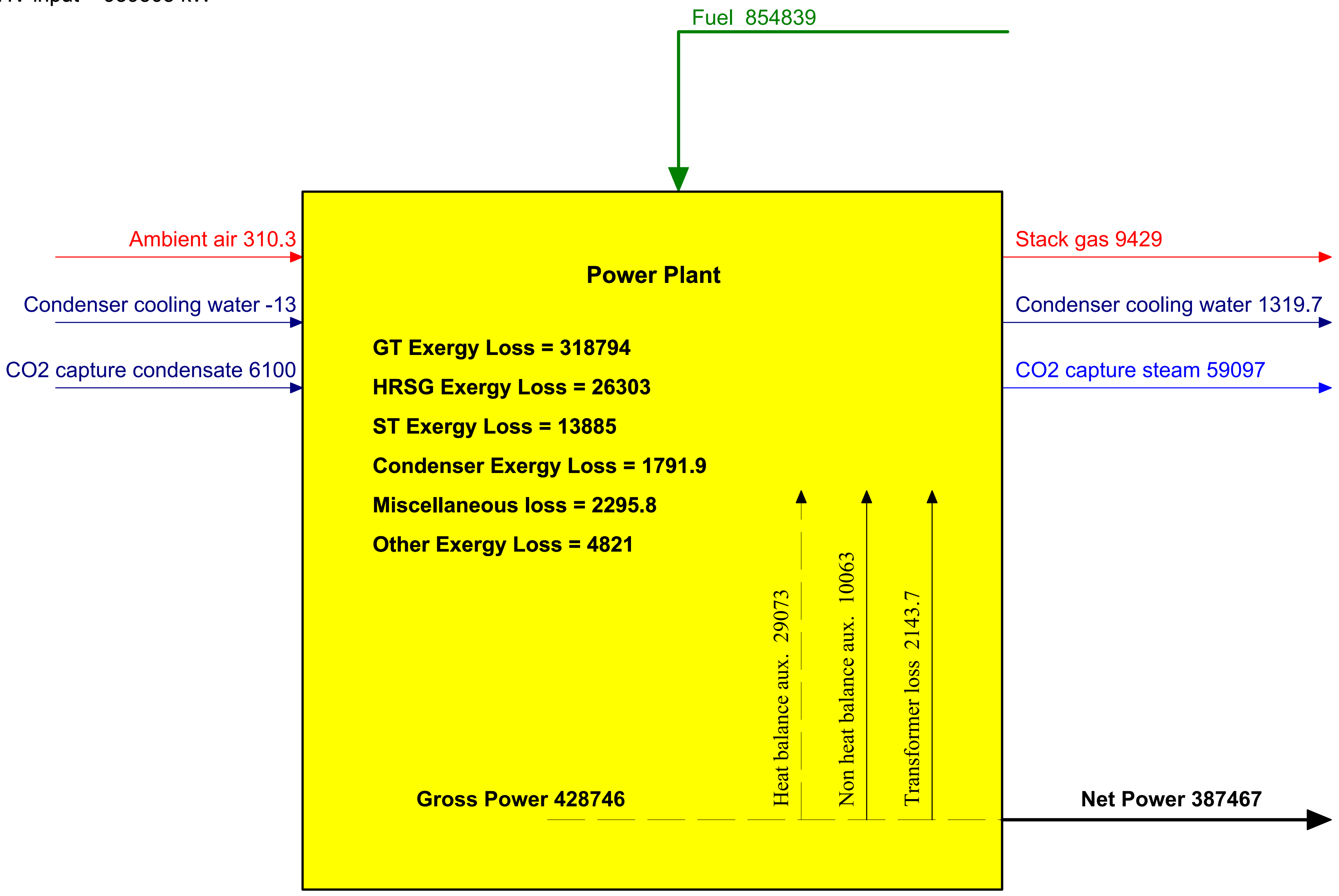
Power Plant Energy Flow Schematic [kW]



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Fuel exergy input = 854839 kW
Fuel chemical LHV input = 846694 kW
Fuel chemical HHV input = 939503 kW

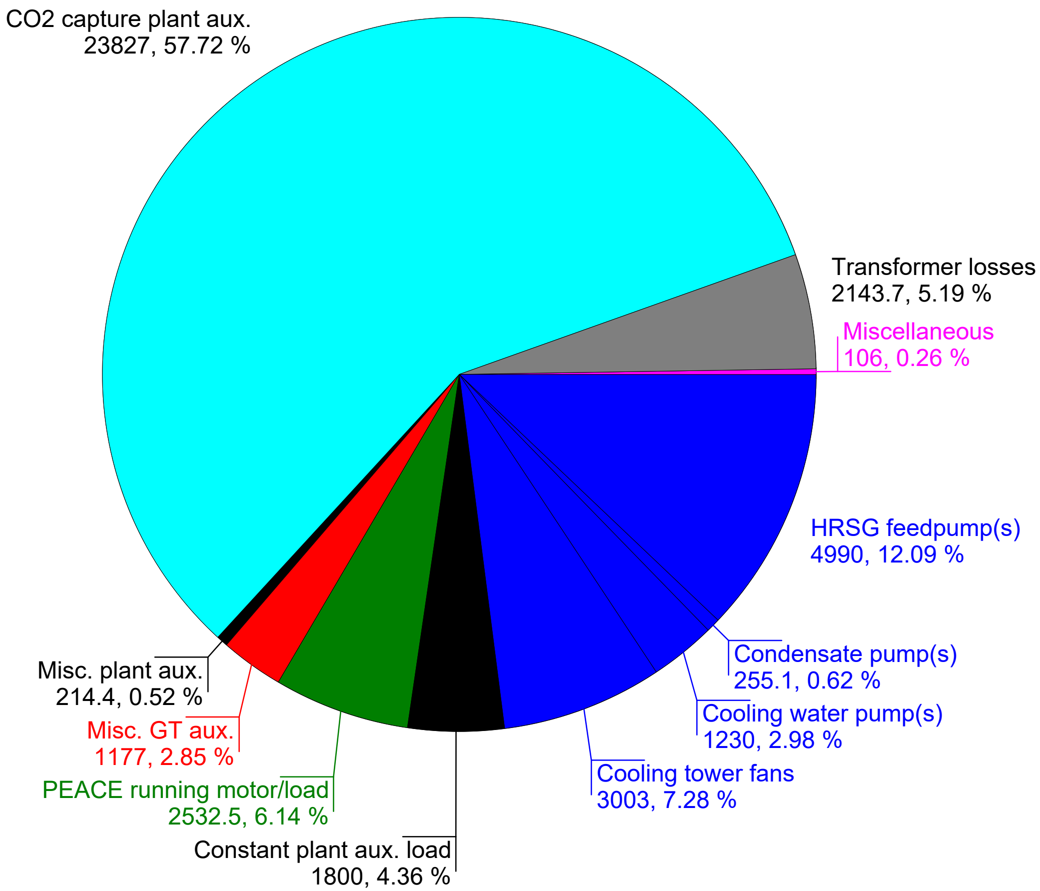
Power Plant Exergy Flow Schematic [kW]



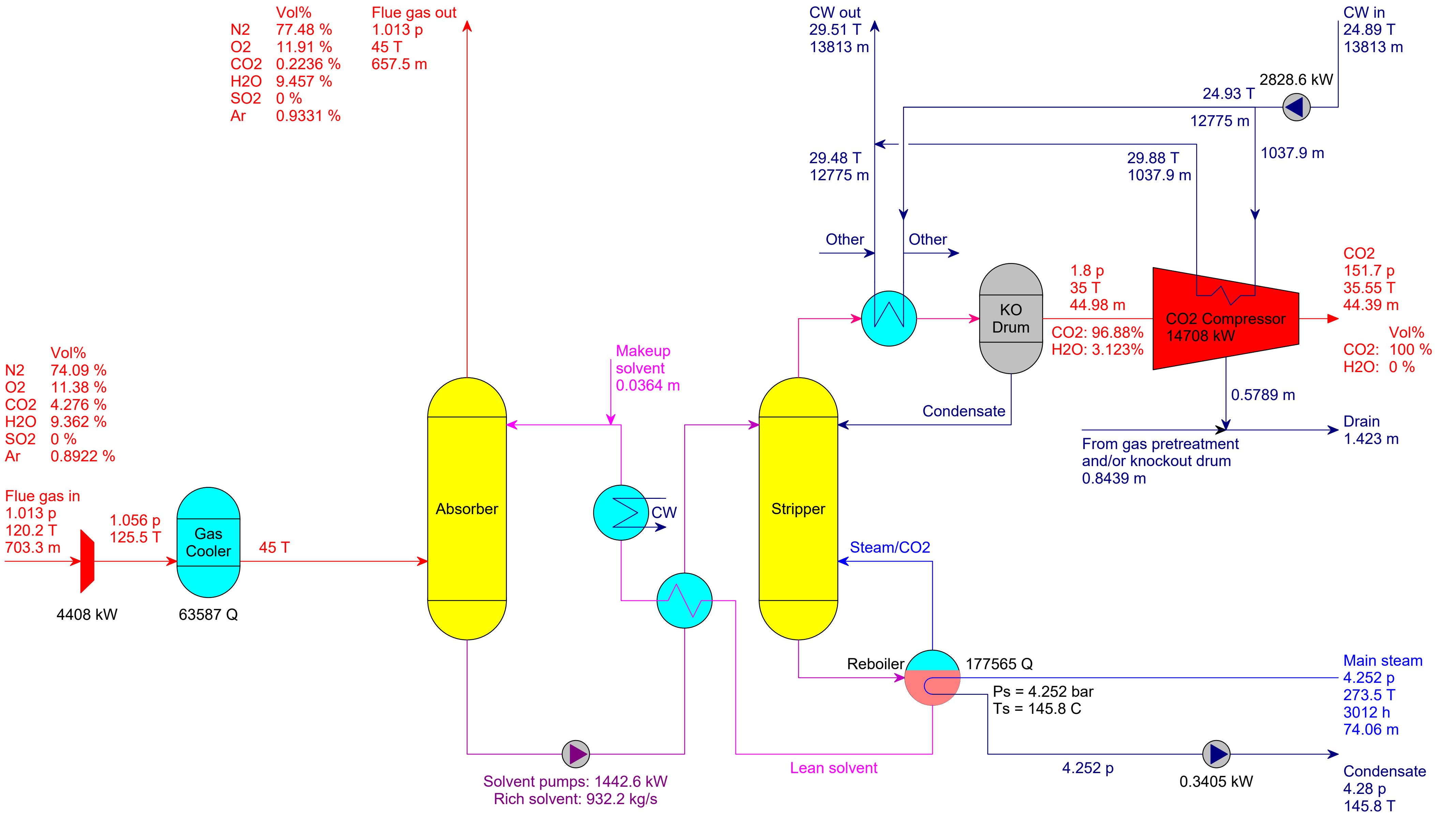
Reference: 1.013 bar, 25 C, water as vapor.

Auxiliaries & Losses [kW]

Total auxiliaries & transformer losses = 41279 kW



CO2 Capture Plant Flow Diagram

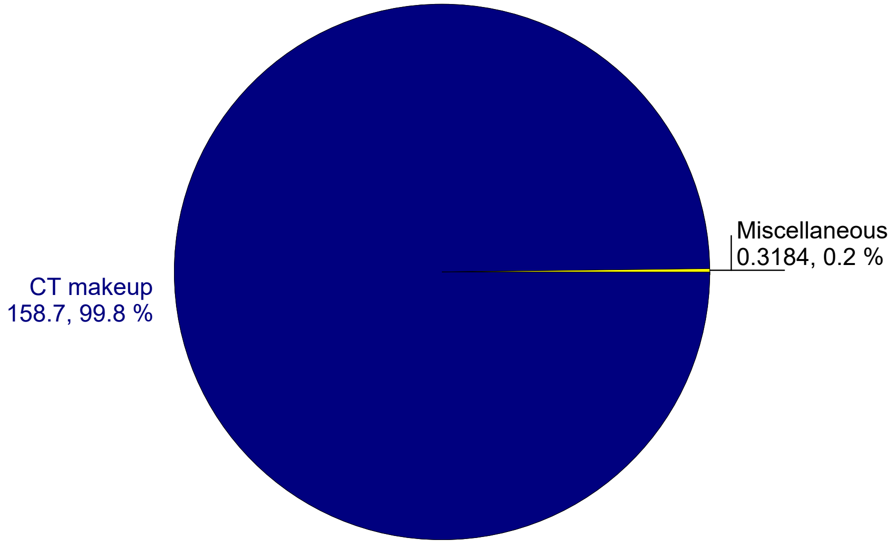


Process: Amine-based
CO2 capture: 44.39 kg/s, 3835 tonne/day
CO2 capture efficiency: 95 %
Heat input: 177565 kW, 177.6 MW, 4000 kJ/kg CO2
Total electrical power consumption: 23827 kW
Solvent consumption: 3.144 tonne/day

p[bar] T[C] h[kJ/kg] m[kg/s] Q[kW]

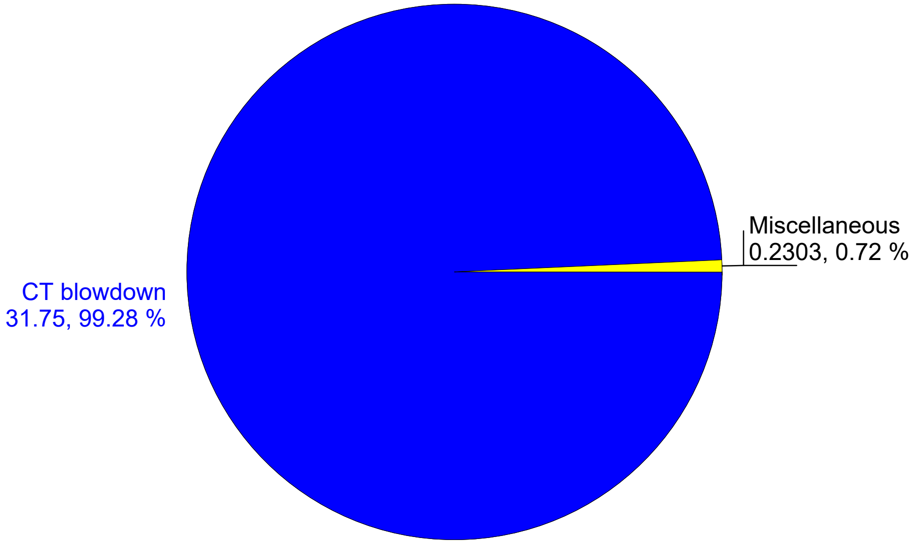
Plant Water Consumption [kg/s]

Plant water consumption = 159 kg/s

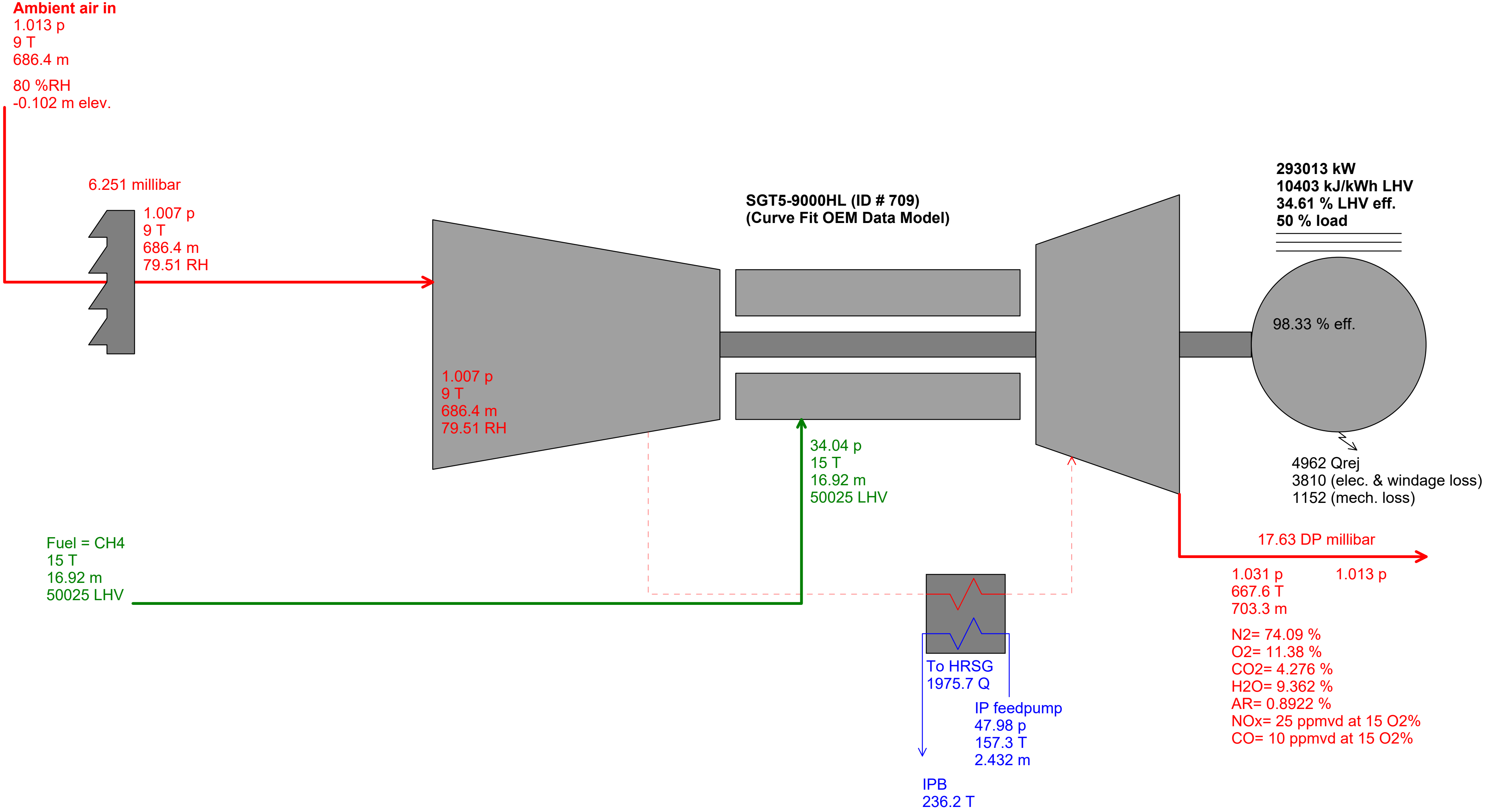


Plant Water Discharge [kg/s]

Plant water discharge = 31.98 kg/s

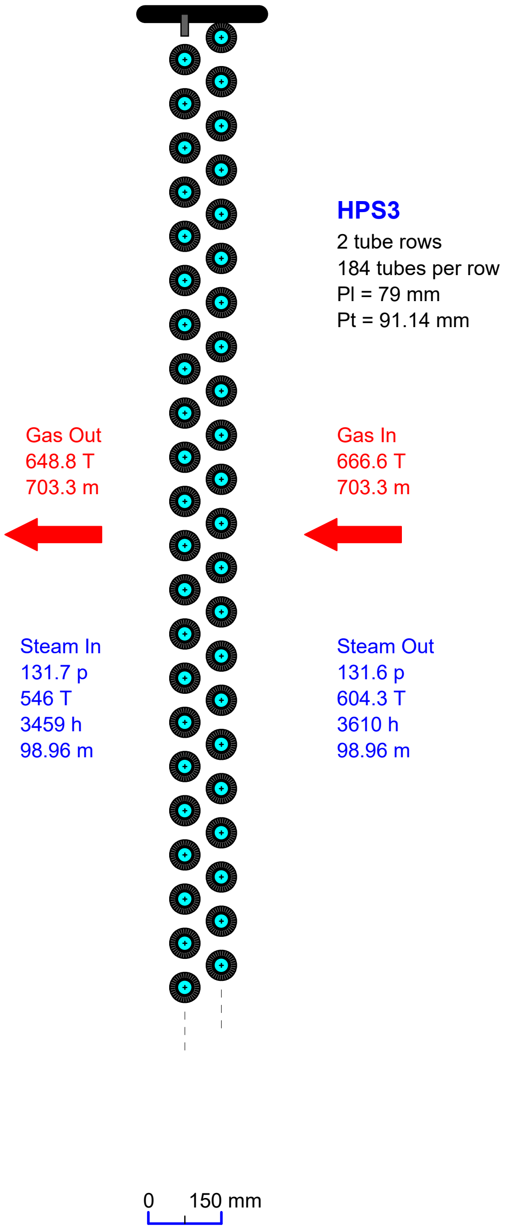


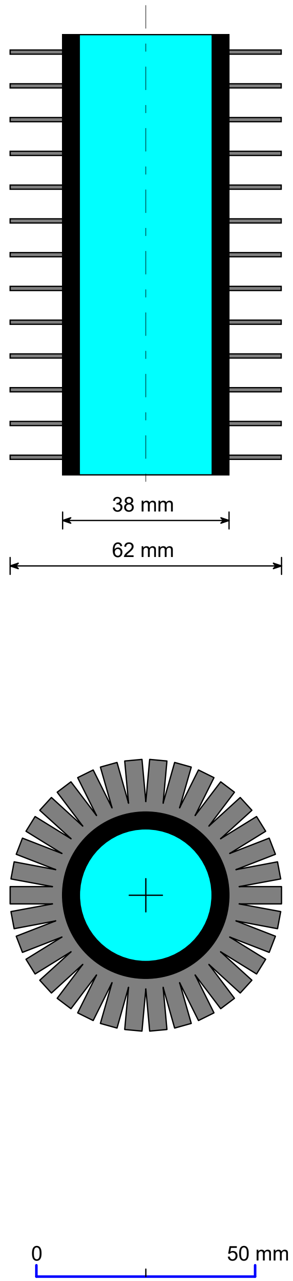
GT generator power = 293013 kW
GT Heat Rate @ gen term = 10403 kJ/kWh
GT efficiency @ gen term = 31.19% HHV = 34.61% LHV
GT @ 50 % rating



p[bar], T[C], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

HPS3 Hardware Design



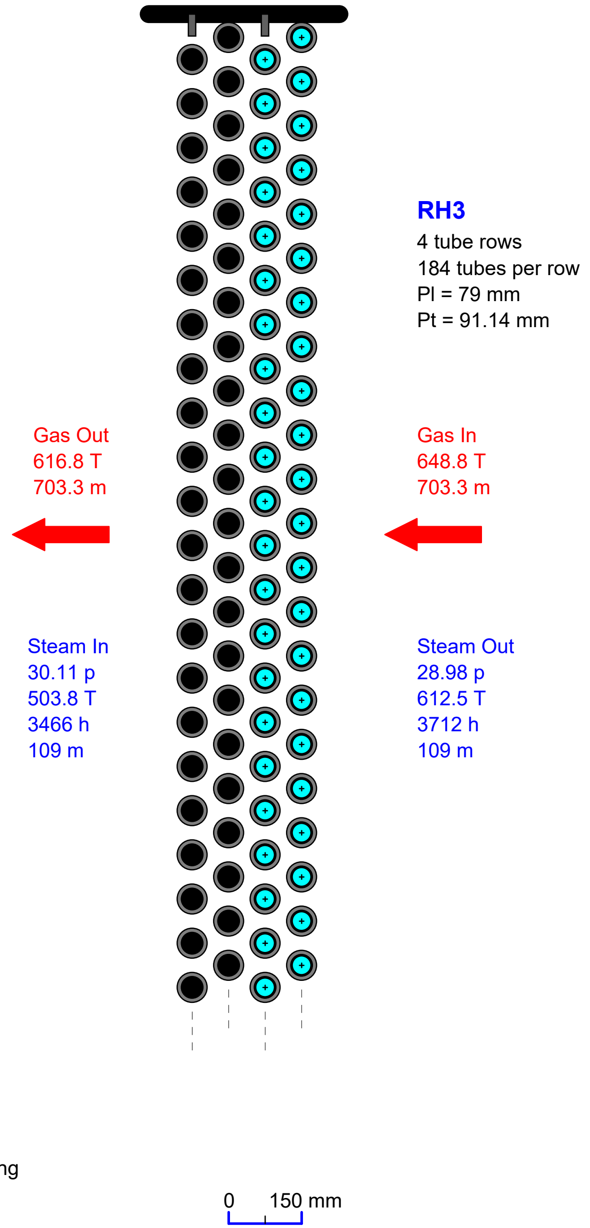


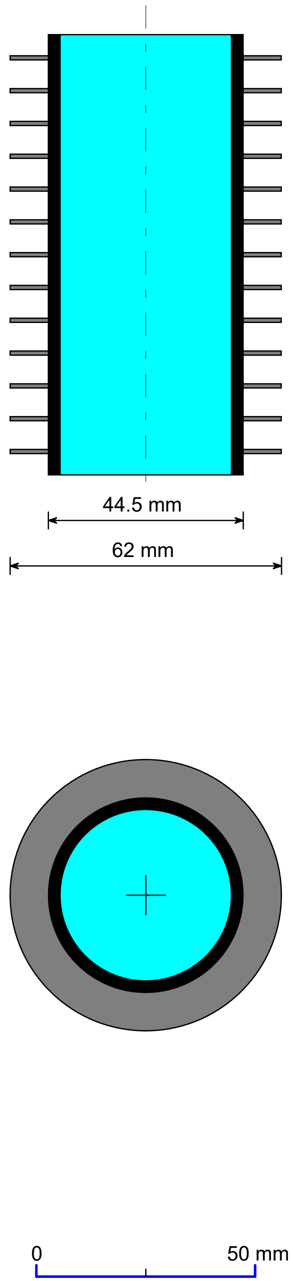
Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP304
Tube material	TP347HFG
Tube outer diameter	38 mm
Tube wall thickness	3.81 mm
Fin height	12 mm
Fin spacing	6.723 mm
Fin thickness	1 mm
Number of fins per meter	129.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4645 m^2
Maximum gas velocity	10.1 m/s
Gas pressure drop	0.2933 millibar
Steam side velocity	10.24 m/s
Steam side pressure drop	0.1062 bar
Heat transfer from gas	15020 kW
Heat transfer to steam	14945 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS3
Date: 06/11/20	
Drawing No:	

RH3 Hardware Design



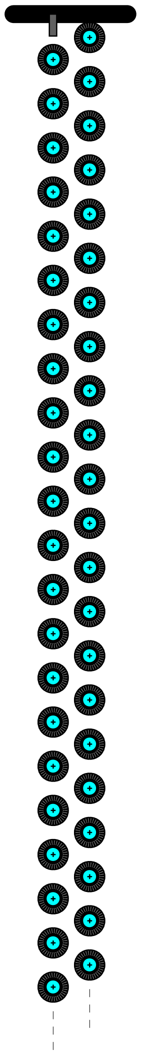


Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	TP347HFG
Tube outer diameter	44.5 mm
Tube wall thickness	2.667 mm
Fin height	8.75 mm
Fin spacing	6.507 mm
Fin thickness	1 mm
Number of fins per meter	133.2
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	8064 m^2
Maximum gas velocity	11.1 m/s
Gas pressure drop	0.58 millibar
Steam side velocity	31.38 m/s
Steam side pressure drop	1.126 bar
Heat transfer from gas	27009 kW
Heat transfer to steam	26875 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH3
Date: 06/11/20	
Drawing No:	

HPS1 Hardware Design



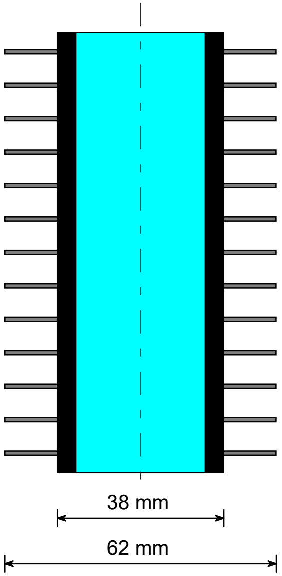
HPS1
2 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

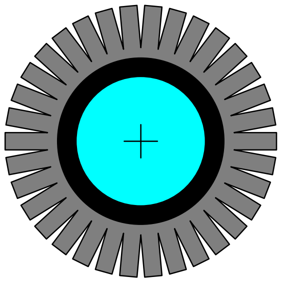
Gas Out
602.9 T
703.3 m

Gas In
616.8 T
703.3 m

Steam In
131.8 p
524.3 T
3401 h
96.82 m

Steam Out
131.7 p
569.7 T
3521 h
96.82 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T91
Tube outer diameter	38 mm
Tube wall thickness	4.191 mm
Fin height	12 mm
Fin spacing	6.65 mm
Fin thickness	1 mm
Number of fins per meter	130.7
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4680 m^2
Maximum gas velocity	9.585 m/s
Gas pressure drop	0.2776 millibar
Steam side velocity	10.06 m/s
Steam side pressure drop	0.1089 bar
Heat transfer from gas	11669 kW
Heat transfer to steam	11611 kW

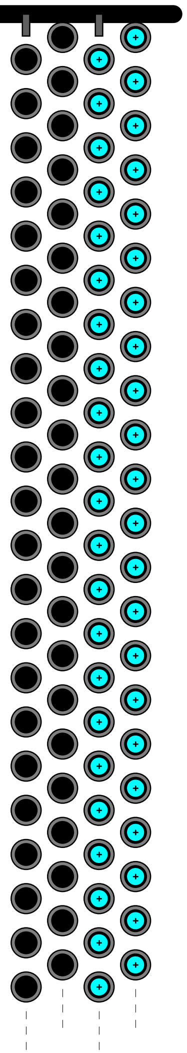
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS1
Date: 06/11/20	
Drawing No:	

RH1 Hardware Design



RH1

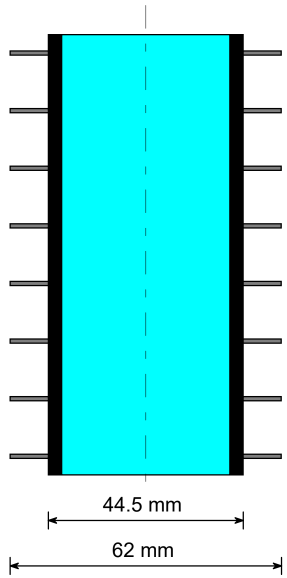
4 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

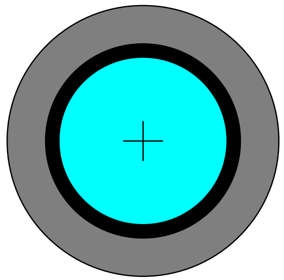
Gas Out
561.6 T
703.3 m

Gas In
602.9 T
703.3 m

Steam In
31.08 p
393.1 T
3214 h
106.3 m

Steam Out
30.11 p
535 T
3536 h
106.3 m





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T22
Tube outer diameter	44.5 mm
Tube wall thickness	3.048 mm
Fin height	8.75 mm
Fin spacing	12.19 mm
Fin thickness	1 mm
Number of fins per meter	75.8
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	5493 m^2
Maximum gas velocity	10.25 m/s
Gas pressure drop	0.419 millibar
Steam side velocity	26.95 m/s
Steam side pressure drop	0.976 bar
Heat transfer from gas	34391 kW
Heat transfer to steam	34220 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

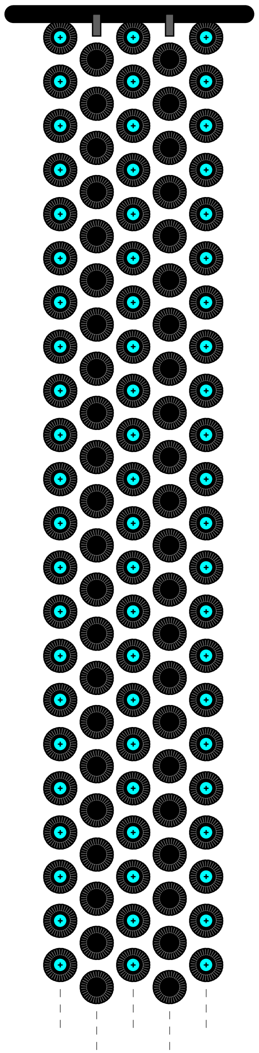
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH1
Date: 06/11/20	
Drawing No:	

HPS0 (OTB) Hardware Design

Gas Out
471.3 T
703.3 m

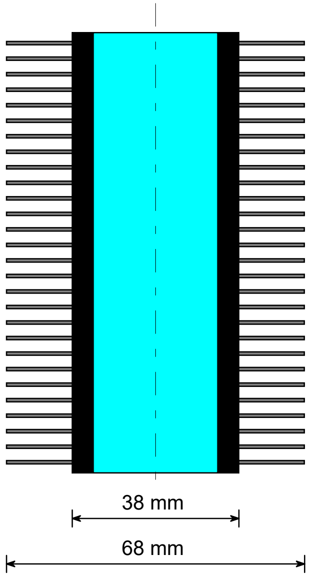
Steam In
139.7 p
336.5 T
2638.9 h
96.82 m

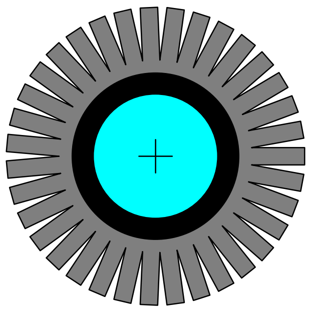


HPS0 (OTB)
5 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
561.6 T
703.3 m

Steam Out
131.8 p
524.3 T
3401 h
96.82 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	5
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	27939 m^2
Maximum gas velocity	9.239 m/s
Gas pressure drop	1.118 millibar
Steam side velocity	16.39 m/s
Steam side pressure drop	7.893 bar
Heat transfer from gas	74170 kW
Heat transfer to steam	73801 kW

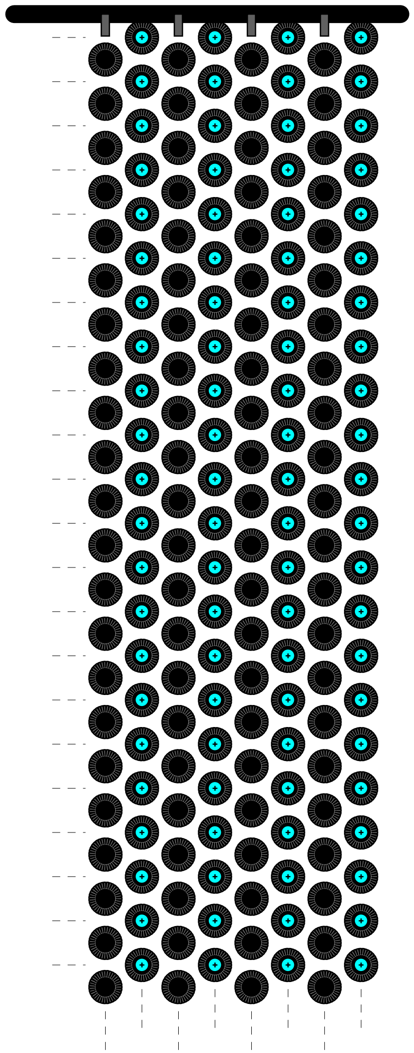
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS0 (OTB)
Date: 06/11/20	
Drawing No:	

HPB1 (OTB) Hardware Design



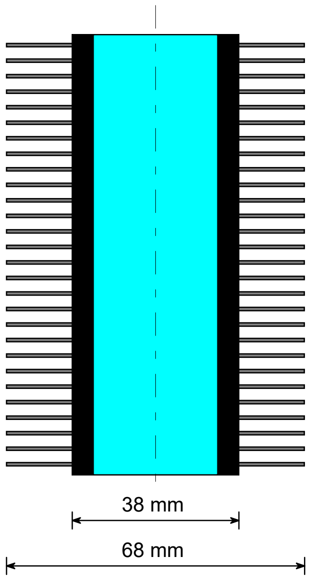
HPB1 (OTB)
11.31 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

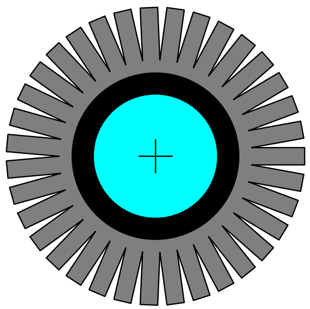
Gas Out
345.2 T
703.3 m

Gas In
471.3 T
703.3 m

Water In
147.9 p
341 T
1601.9 h
96.82 m

Steam Out
139.7 p
336.5 T
2638.9 h
96.82 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	11.31
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	62045 m^2
Maximum gas velocity	7.973 m/s
Gas pressure drop	2.086 millibar
Water side velocity	1.347 m/s
Water side pressure drop	8.207 bar
Heat transfer from gas	100915 kW
Heat transfer to steam/water	100413 kW

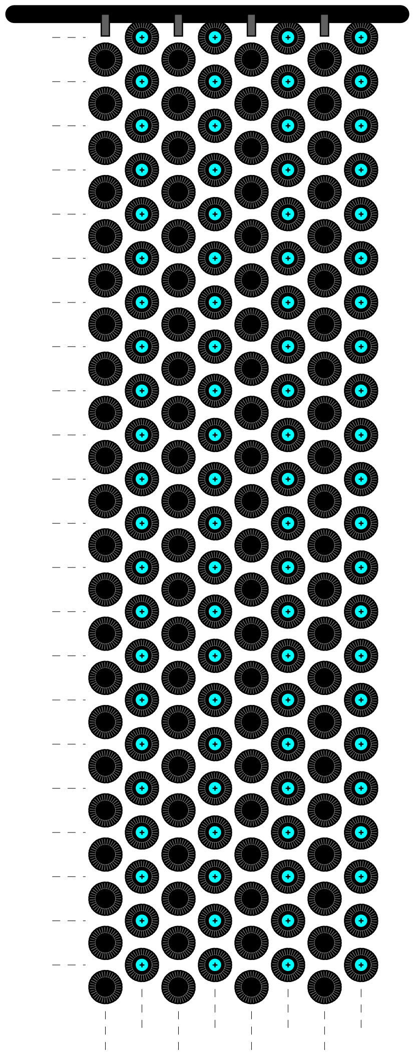
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPB1 (OTB)
Date: 06/11/20	
Drawing No:	

HPE3 (OTB) Hardware Design



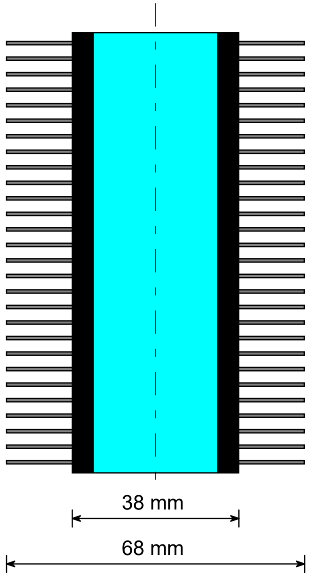
Gas Out
305 T
703.3 m

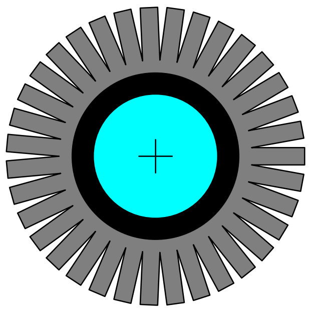
HPE3 (OTB)
17.6 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
345.2 T
703.3 m

Water In
150.3 p
288.7 T
1277.5 h
96.82 m

Water Out
147.9 p
341 T
1601.9 h
96.82 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	17.6
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	96580 m^2
Maximum gas velocity	6.999 m/s
Gas pressure drop	2.83 millibar
Water side velocity	1.197 m/s
Water side pressure drop	2.418 bar
Heat transfer from gas	31565 kW
Heat transfer to water	31408 kW

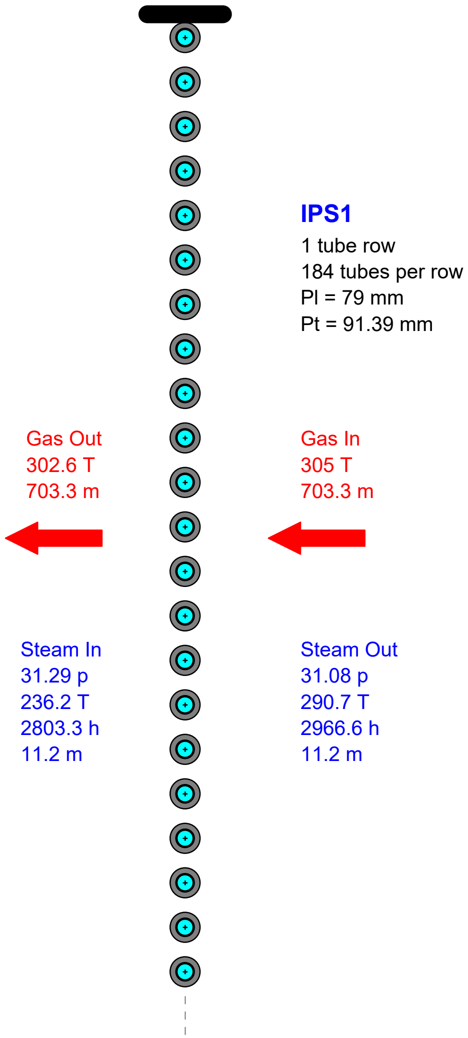
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

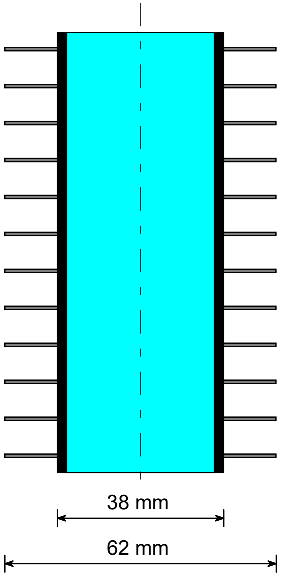
0 150 mm

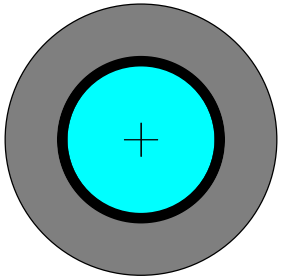
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE3 (OTB)
Date: 06/11/20	
Drawing No:	

IPS1 Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	7.626 mm
Fin thickness	0.8 mm
Number of fins per meter	118.7
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.39 mm
# of tube rows (longitudinal)	1
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2154.4 m^2
Maximum gas velocity	6.127 m/s
Gas pressure drop	0.0761 millibar
Steam side velocity	4.782 m/s
Steam side pressure drop	0.2047 bar
Heat transfer from gas	1838.5 kW
Heat transfer to steam	1829.3 kW

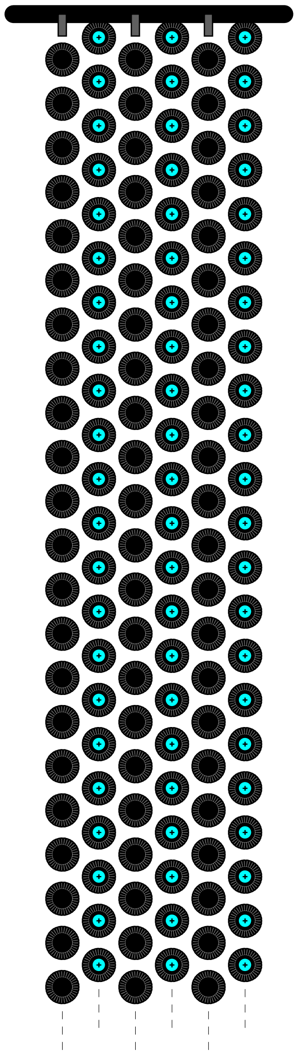
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPS1
Date: 06/11/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

HPE2 Hardware Design



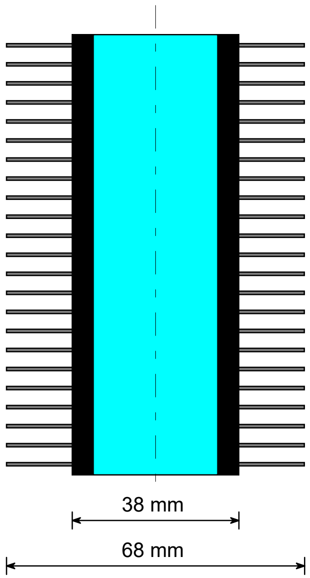
HPE2
6 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

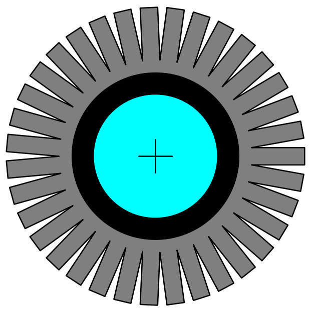
Gas Out
273.4 T
703.3 m

Gas In
302.6 T
703.3 m

Water In
151.3 p
241 T
1044 h
96.82 m

Water Out
150.3 p
288.7 T
1277.5 h
96.82 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	3.555 mm
Fin thickness	0.8 mm
Number of fins per meter	229.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	27374 m^2
Maximum gas velocity	6.394 m/s
Gas pressure drop	0.7465 millibar
Water side velocity	1.049 m/s
Water side pressure drop	0.9461 bar
Heat transfer from gas	22724 kW
Heat transfer to water	22611 kW

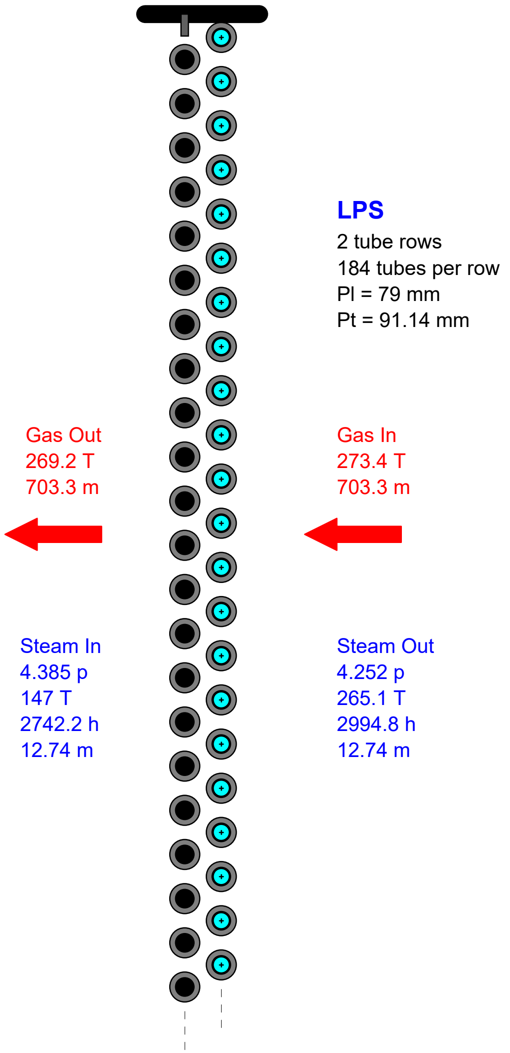
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

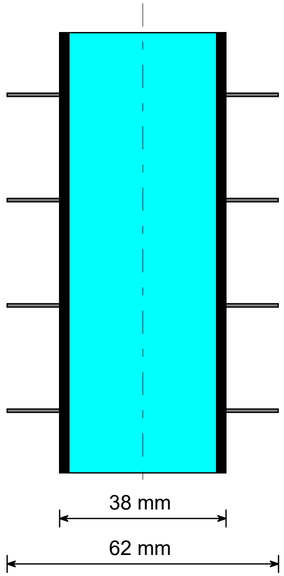
0 150 mm

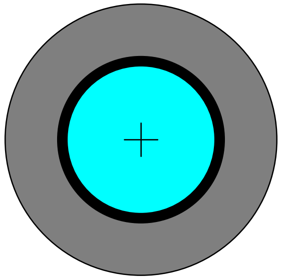
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE2
Date: 06/11/20	
Drawing No:	

LPS Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	23.26 mm
Fin thickness	0.8 mm
Number of fins per meter	41.56
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2091.2 m^2
Maximum gas velocity	5.645 m/s
Gas pressure drop	0.0948 millibar
Steam side velocity	38.69 m/s
Steam side pressure drop	0.1327 bar
Heat transfer from gas	3234 kW
Heat transfer to steam	3217 kW

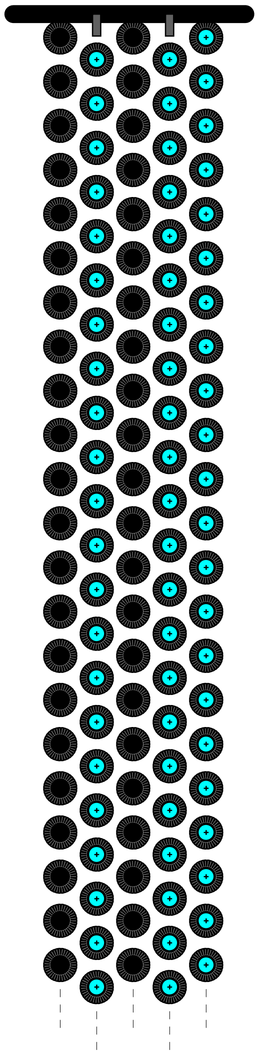
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0   150 mm

0   50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPS
Date: 06/11/20	
Drawing No:	

IPB Hardware Design



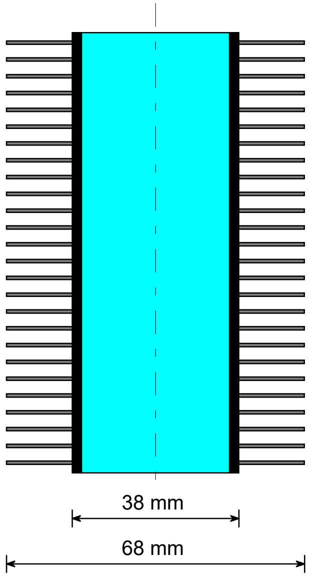
Gas Out
245.1 T
703.3 m

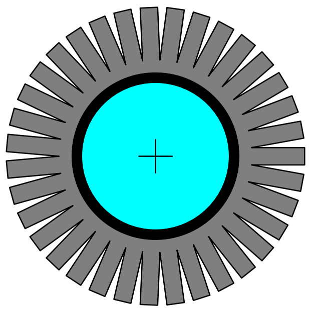
Water In
31.29 p
232.8 T
1003.6 h
10.29 m

IPB
5 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
269.2 T
703.3 m

Steam Out
31.29 p
236.2 T
2803.3 h
10.29 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.045 mm
Fin thickness	0.8 mm
Number of fins per meter	260
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	5
# of rows per pass	1.251
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	25540 m^2
Maximum gas velocity	6.137 m/s
Gas pressure drop	0.6423 millibar
Water side velocity	1.097 m/s
Water side pressure drop	0 bar
Heat transfer from gas	18615 kW
Heat transfer to steam/water	18523 kW

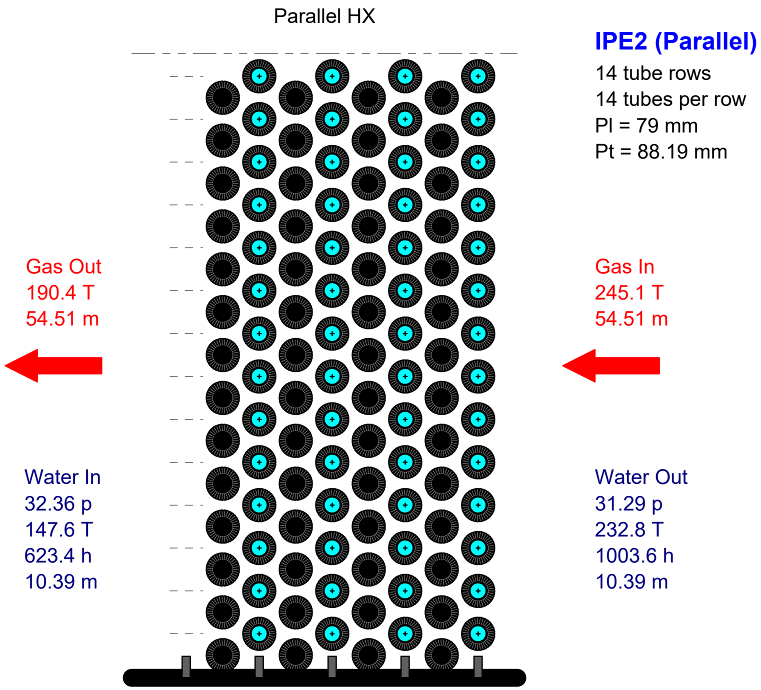
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

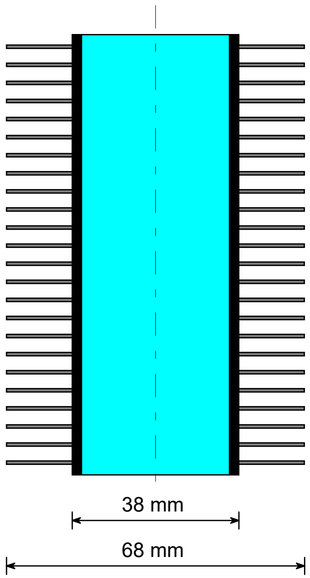
0 150 mm

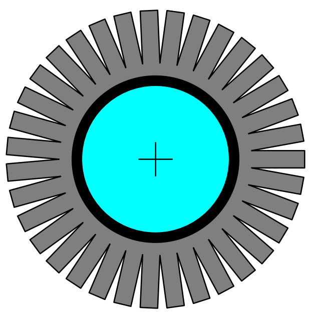
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPB
Date: 06/11/20	
Drawing No:	

IPE2 Hardware Design







Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.339 mm
Fin thickness	0.8 mm
Number of fins per meter	241.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	88.19 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	14
Tube length	20.4 m
Gas path transverse width	1.279 m
Gas path frontal area	26.09 m^2
HX total outside surface area	5089 m^2
Maximum gas velocity	6.035 m/s
Gas pressure drop	1.778 millibar
Water side velocity	0.9441 m/s
Water side pressure drop	1.071 bar
Heat transfer from gas	3971 kW
Heat transfer to water	3952 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

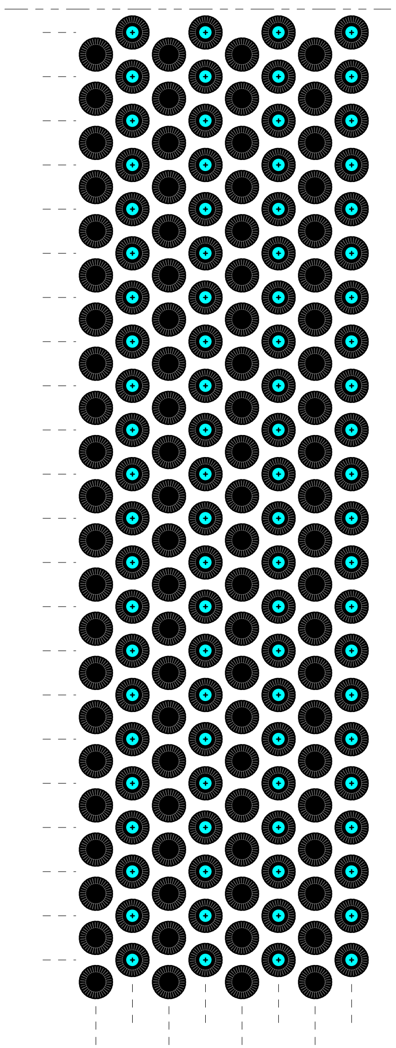
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPE2 (Parallel)
Date: 06/11/20	
Drawing No:	

HPE0 Hardware Design

Parallel HX



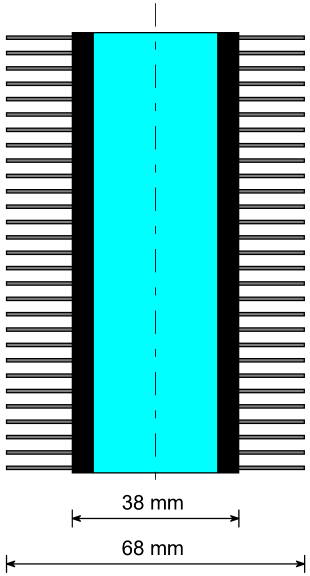
HPE0 (Parallel)
14 tube rows
170 tubes per row
Pl = 79 mm
Pt = 91.12 mm

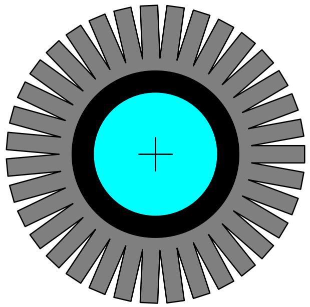
Gas Out
190.4 T
648.8 m

Gas In
245.1 T
648.8 m

Water In
153.7 p
153.1 T
654.7 h
96.82 m

Water Out
151.3 p
241 T
1044 h
96.82 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.699 mm
Fin thickness	0.8 mm
Number of fins per meter	285.8
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.12 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	170
Tube length	20.4 m
Gas path transverse width	15.54 m
Gas path frontal area	316.9 m^2
HX total outside surface area	72030 m^2
Maximum gas velocity	5.756 m/s
Gas pressure drop	1.778 millibar
Water side velocity	1.02 m/s
Water side pressure drop	2.396 bar
Heat transfer from gas	37883 kW
Heat transfer to water	37694 kW

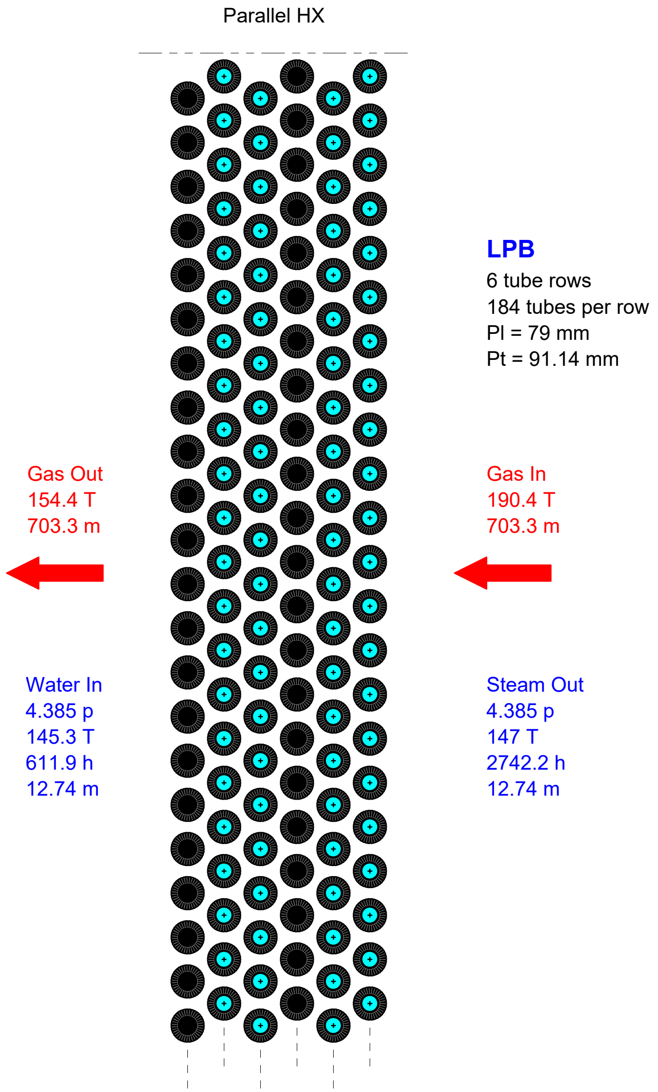
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

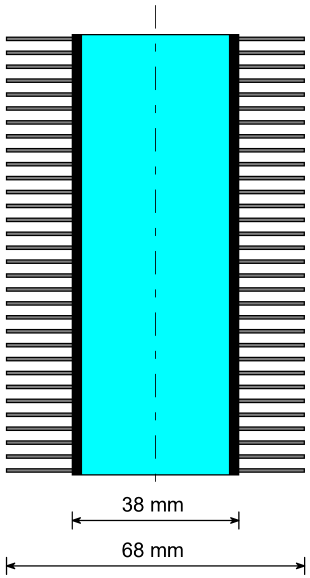
0 150 mm

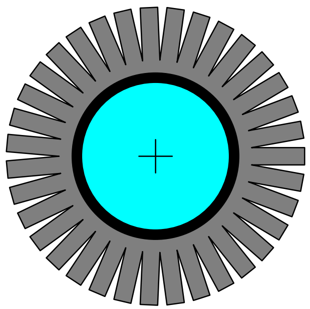
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE0 (Parallel)
Date: 06/11/20	
Drawing No:	

LPB Hardware Design







Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	2.359 mm
Fin thickness	0.8 mm
Number of fins per meter	316.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1.501
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	36720 m^2
Maximum gas velocity	5.31 m/s
Gas pressure drop	0.7402 millibar
Water side velocity	1.007 m/s
Water side pressure drop	0 bar
Heat transfer from gas	27269 kW
Heat transfer to steam/water	27134 kW

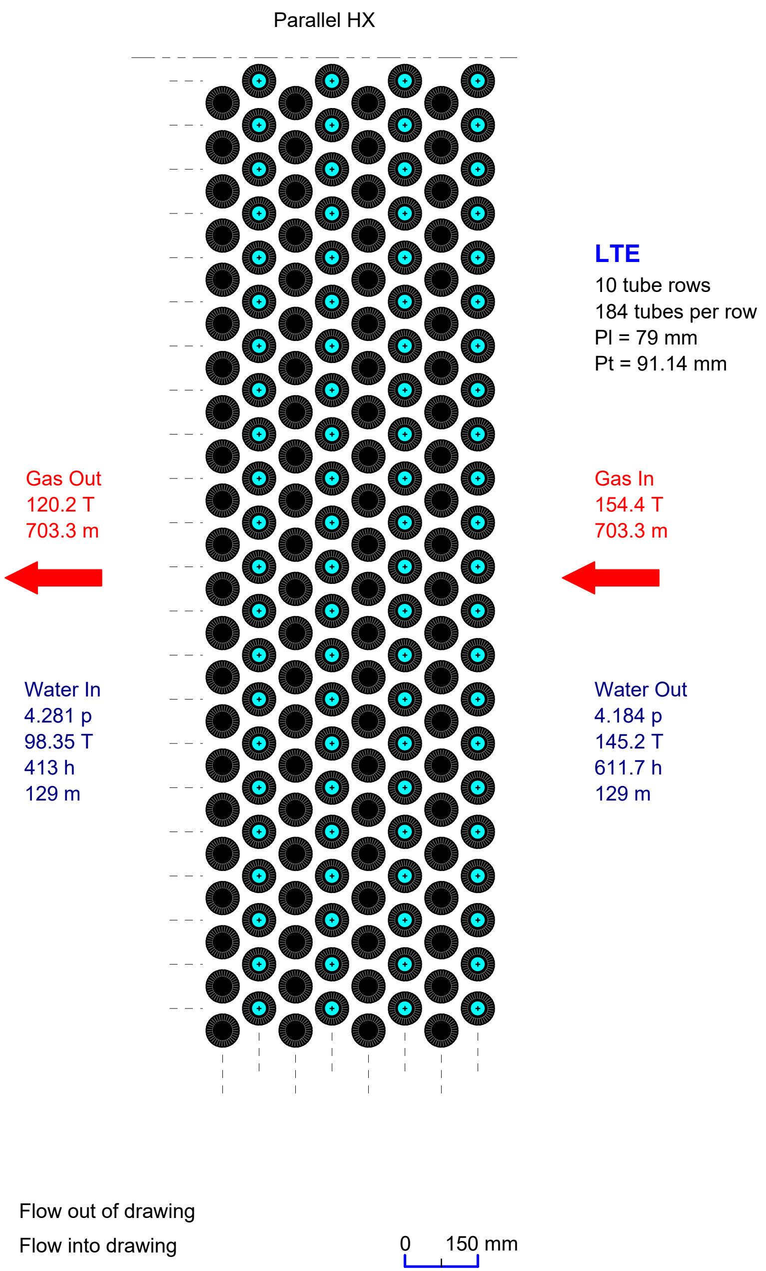
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

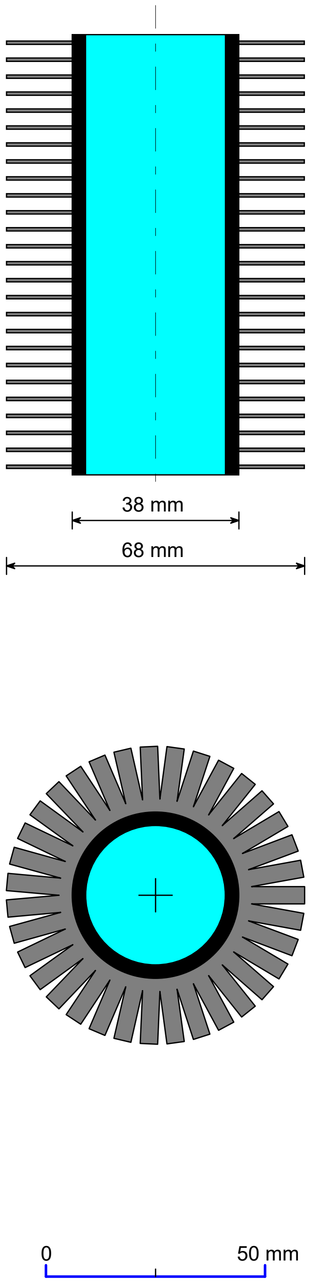
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPB
Date: 06/11/20	
Drawing No:	

LTE Hardware Design



LTE
10 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm



Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	3.048 mm
Fin height	15 mm
Fin spacing	3.077 mm
Fin thickness	0.8 mm
Number of fins per meter	257.9
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	10
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	50703 m^2
Maximum gas velocity	4.745 m/s
Gas pressure drop	0.9312 millibar
Water side velocity	0.9314 m/s
Water side pressure drop	0.097 bar
Heat transfer from gas	25776 kW
Heat transfer to water	25648 kW

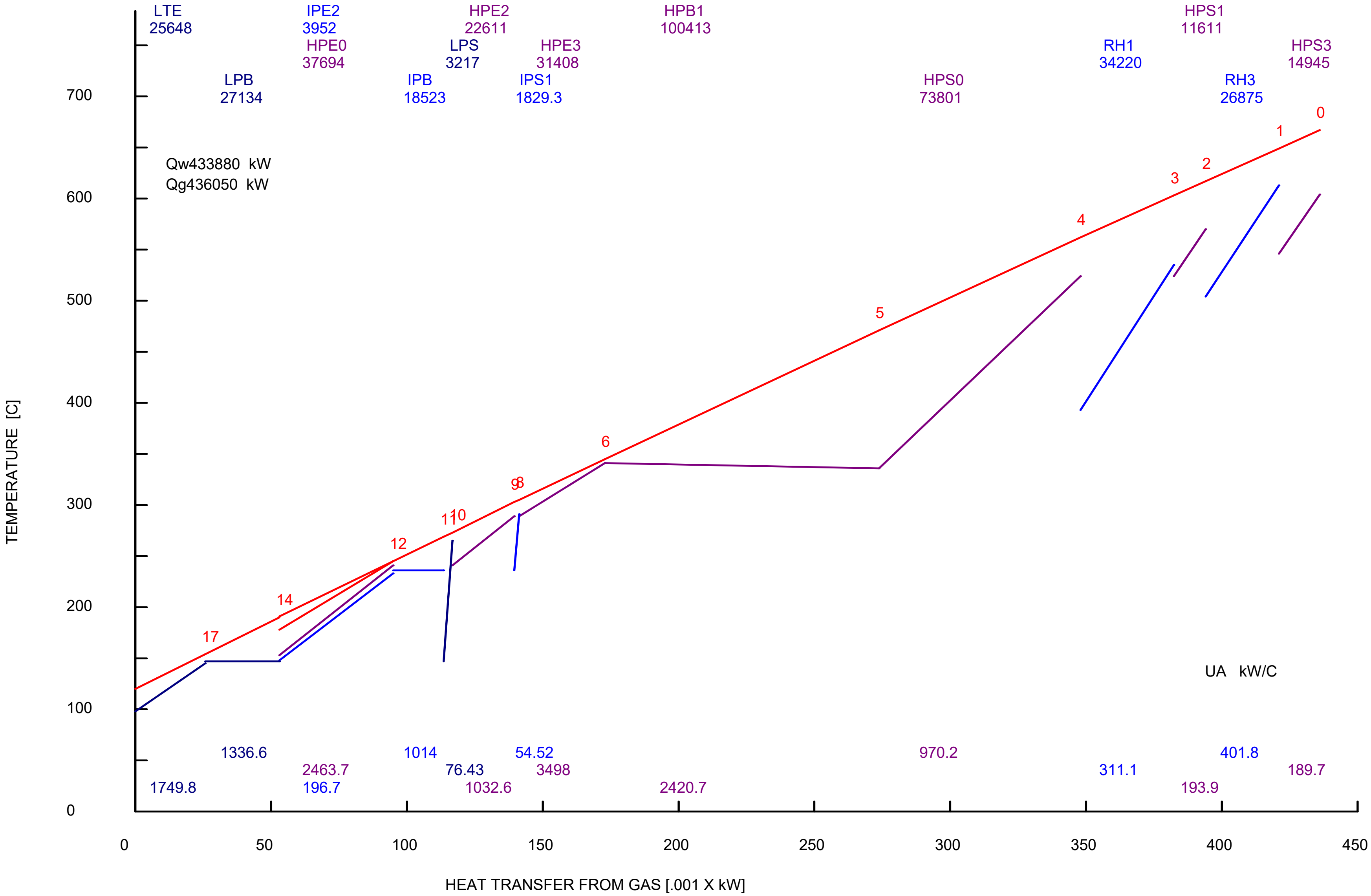
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LTE
Date: 06/11/20	
Drawing No:	

GT MASTER 29.0 AECOM

Net Power 387467 kW
LHV Net Heat Rate 7867 kJ/kWh
LHV Net Efficiency 45.76 %

HRSG Temperature Profile



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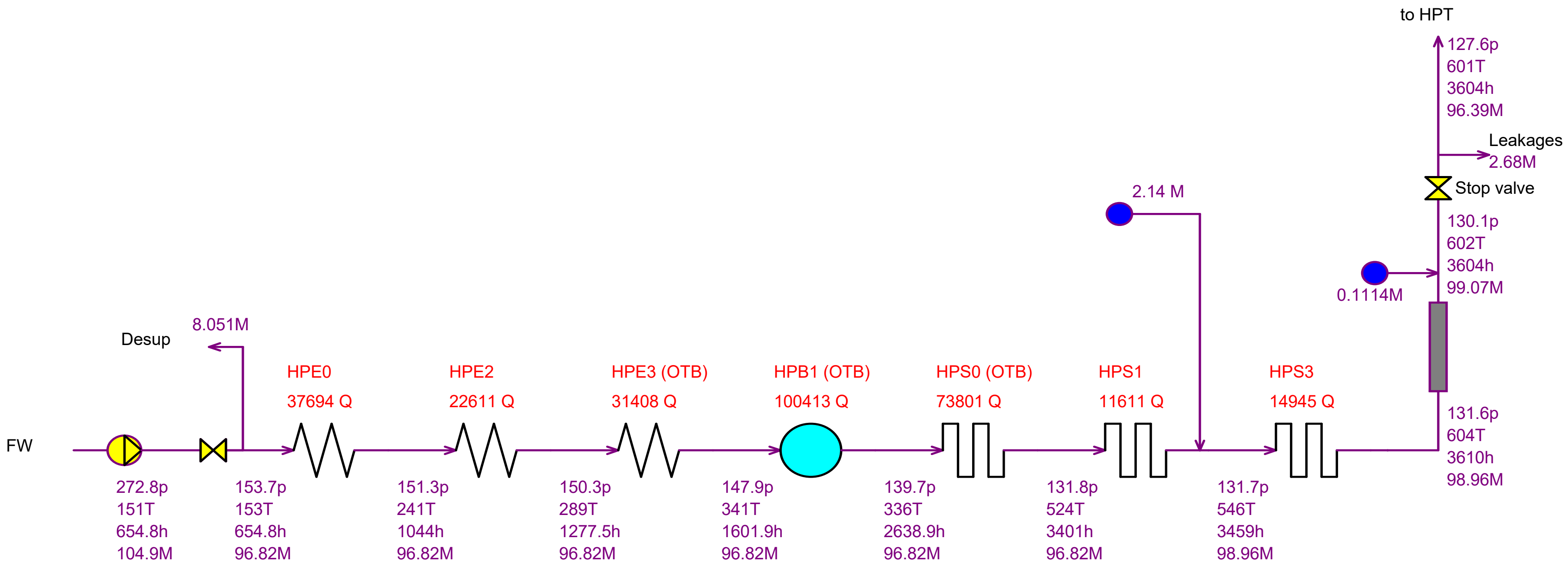
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

HP Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

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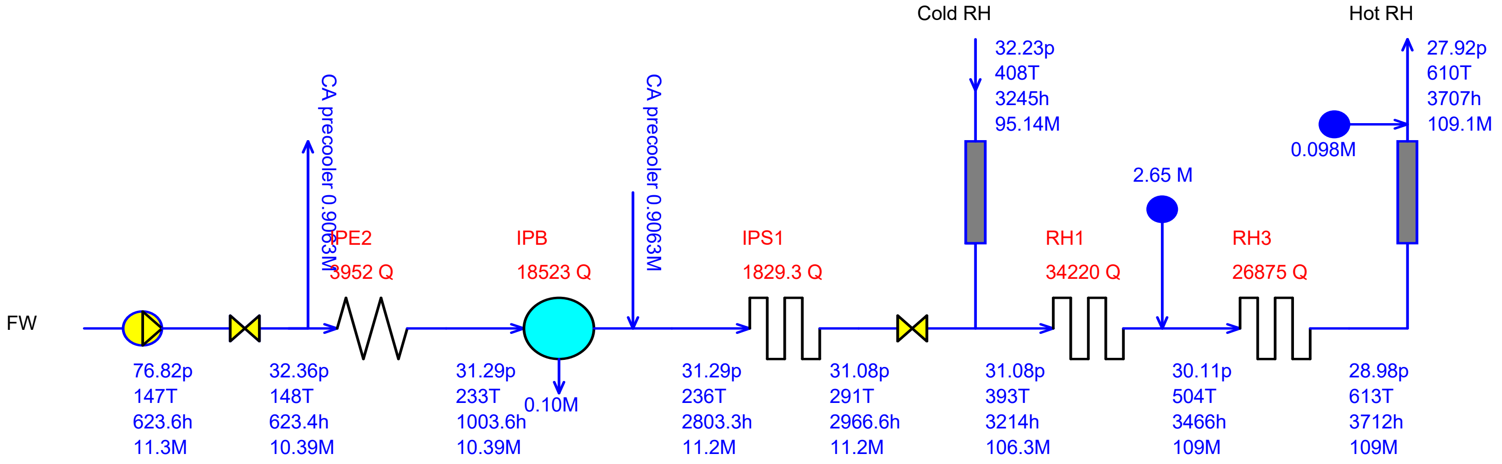
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

IP & Reheat Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

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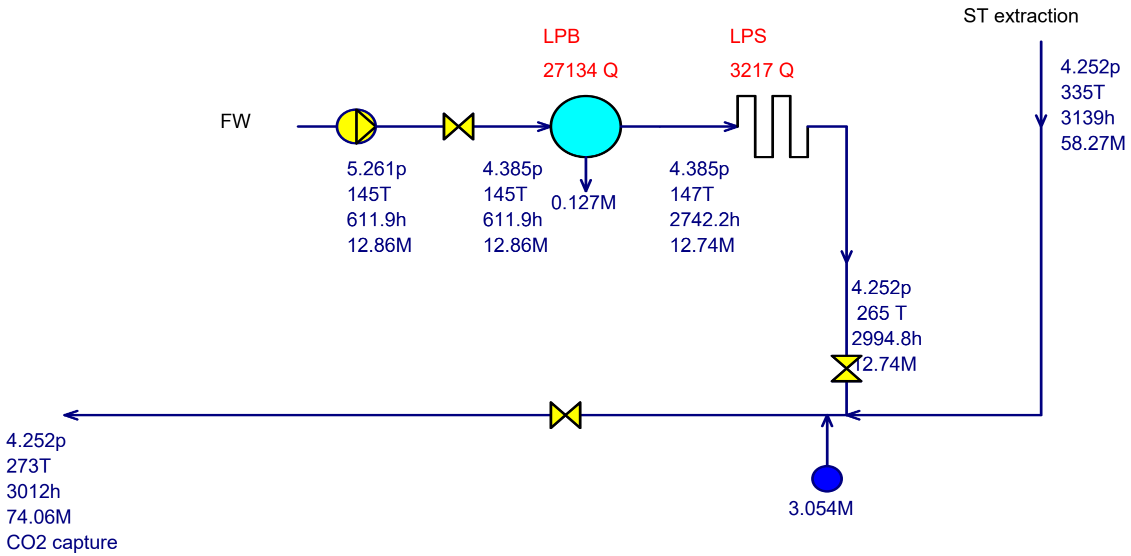
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

LP Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

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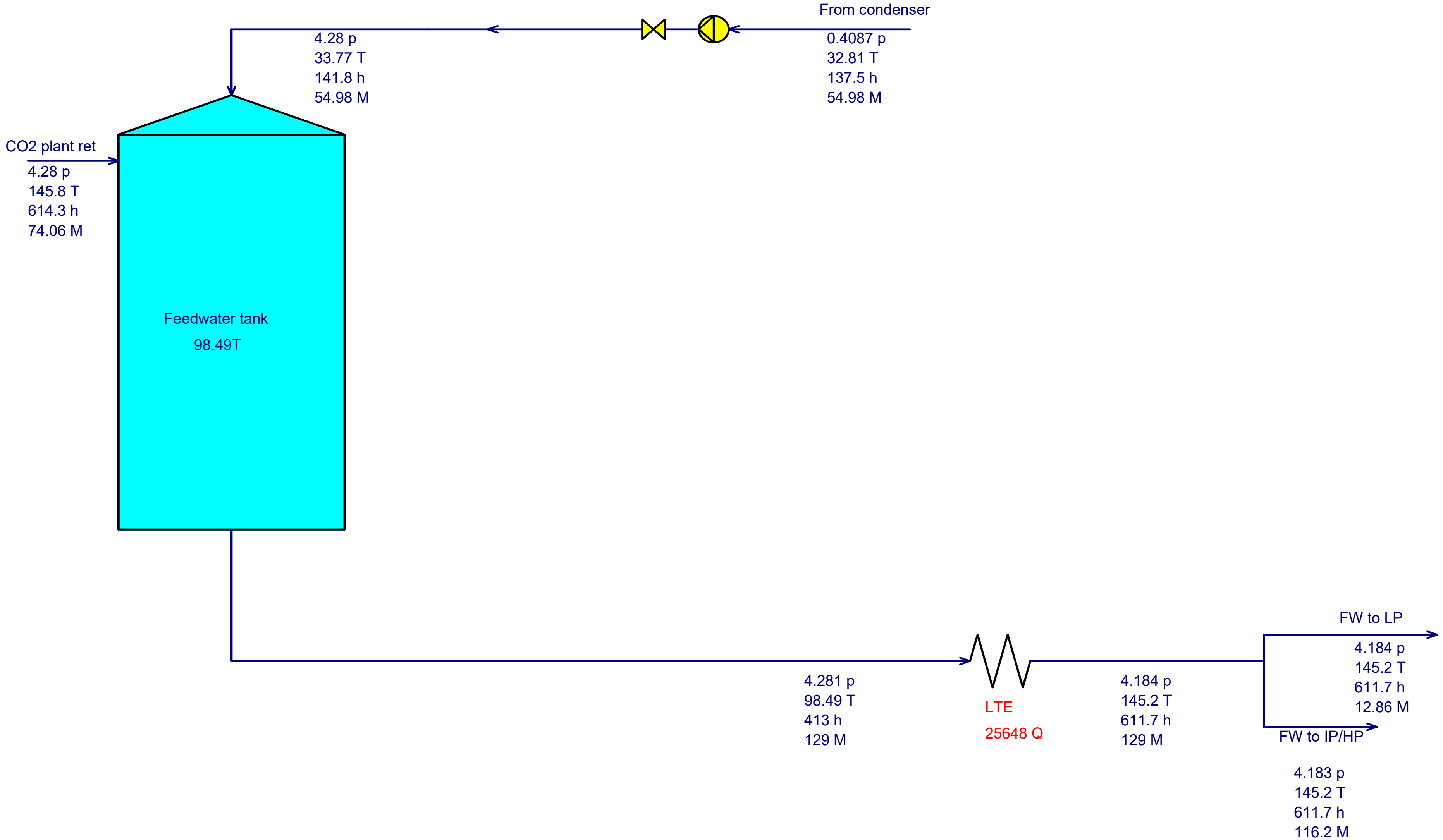
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Feedwater Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

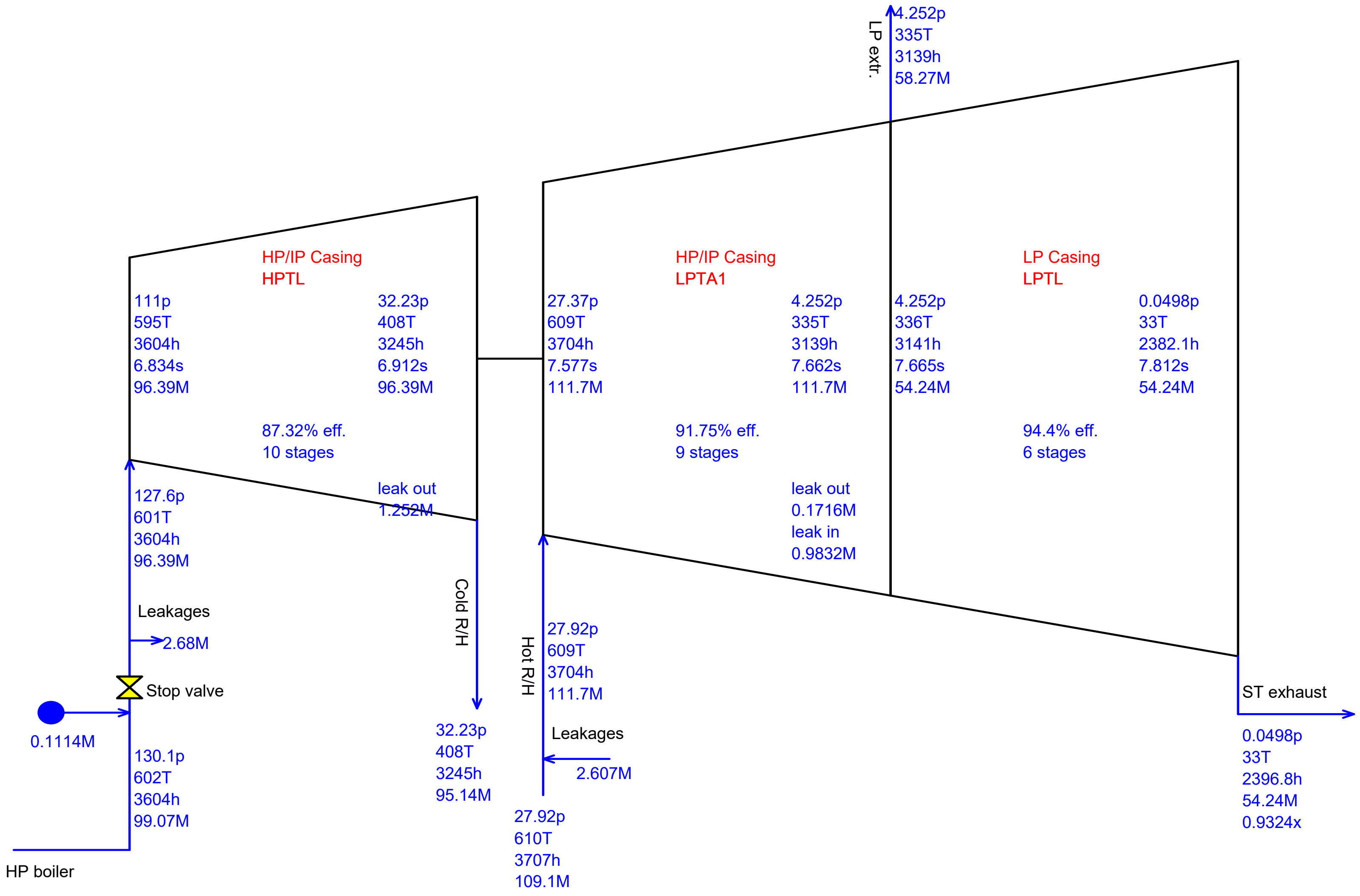
1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

GT MASTER 29.0 AECOM

ST Expansion Power 138099 kW
ST Generator Output 135733 kW

Steam Turbine Group Data



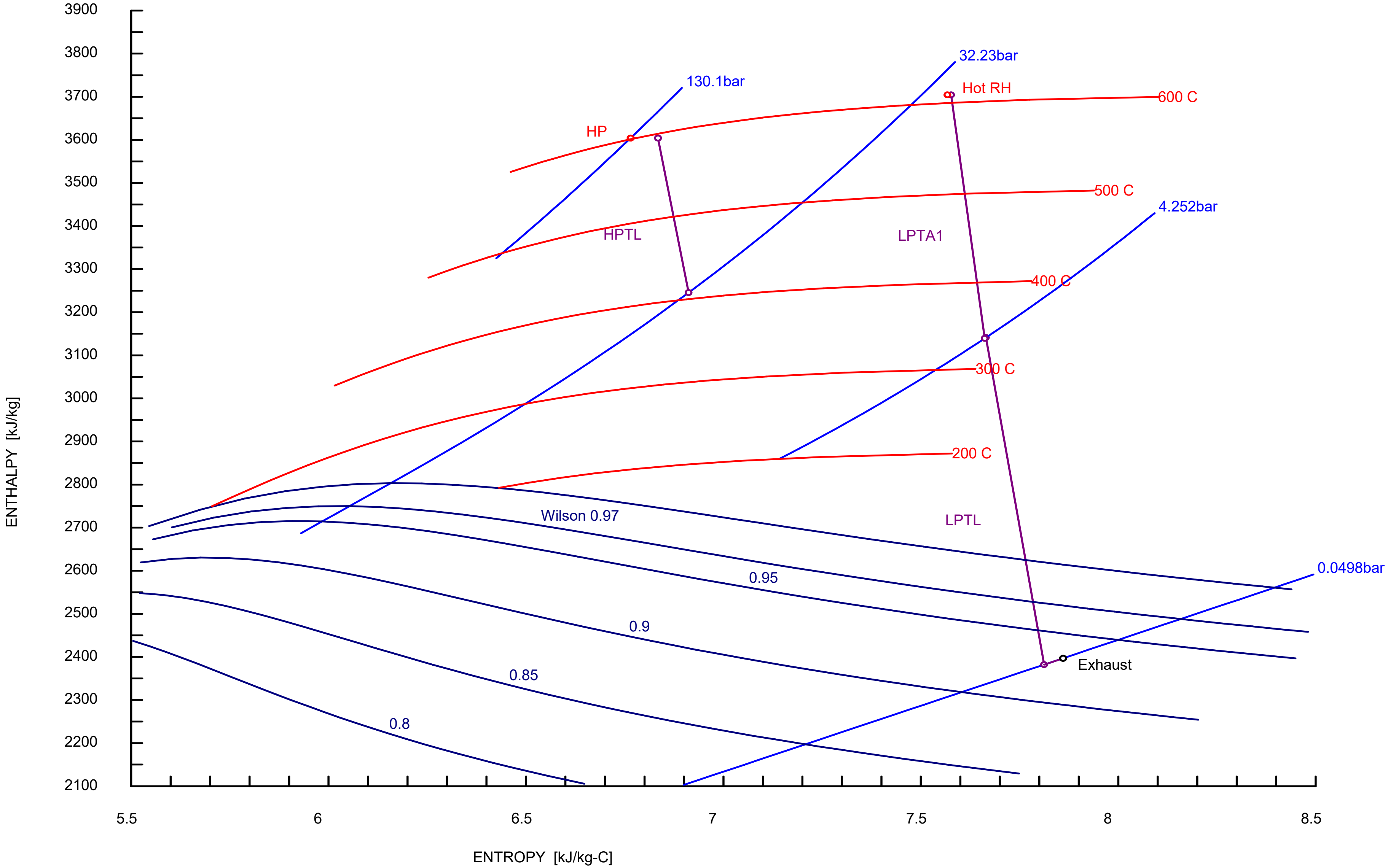
ST Model Adjustments: Disabled
p[bar], T[C], h[kJ/kg], s[kJ/kg-C], M[kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

GT MASTER 29.0 AECOM

ST Expansion Power 138099 kW
ST Generator Output 135733 kW

Steam Turbine Expansion Path



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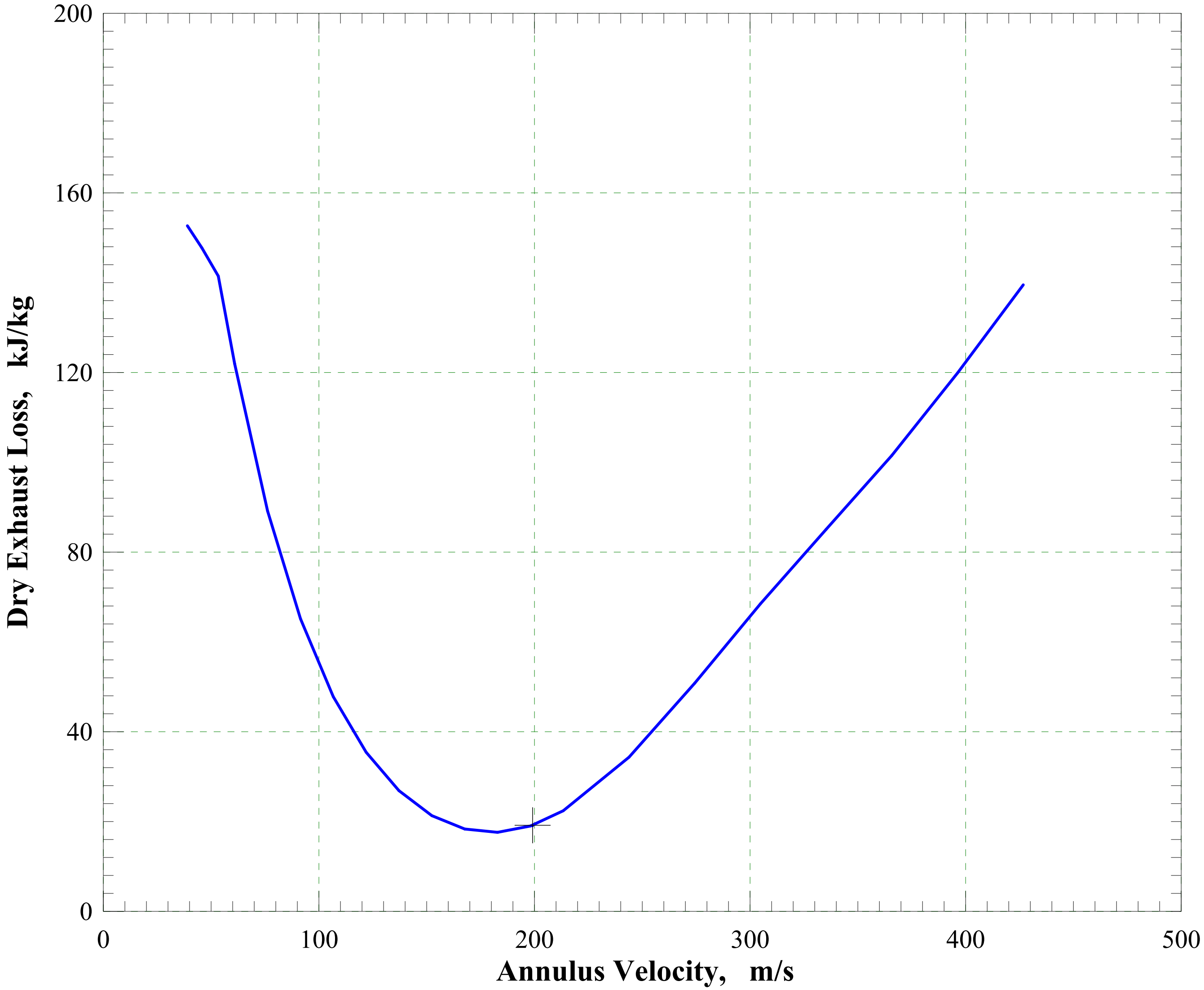
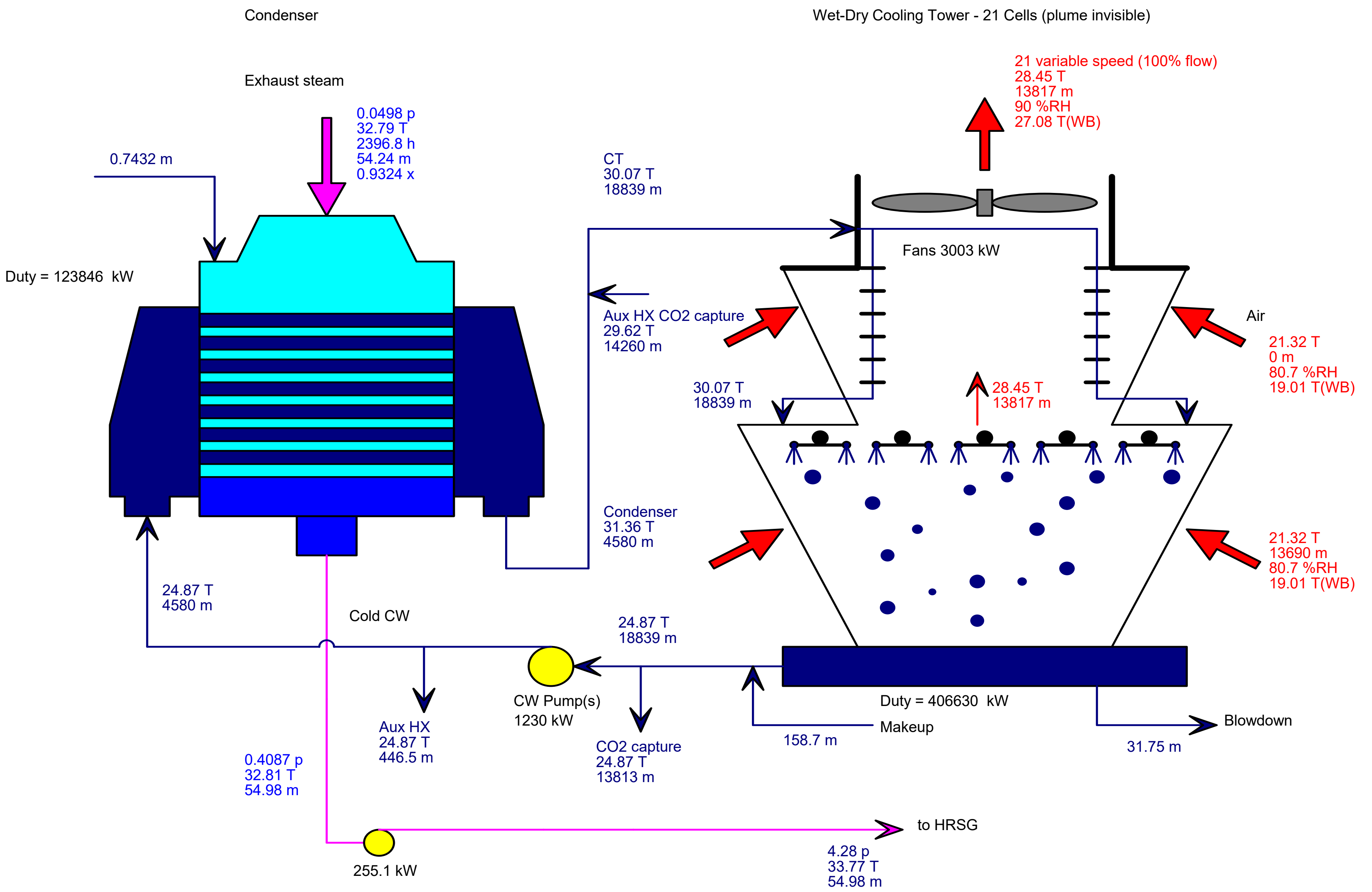
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Steam Turbine Exhaust Loss



Cooling System



p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

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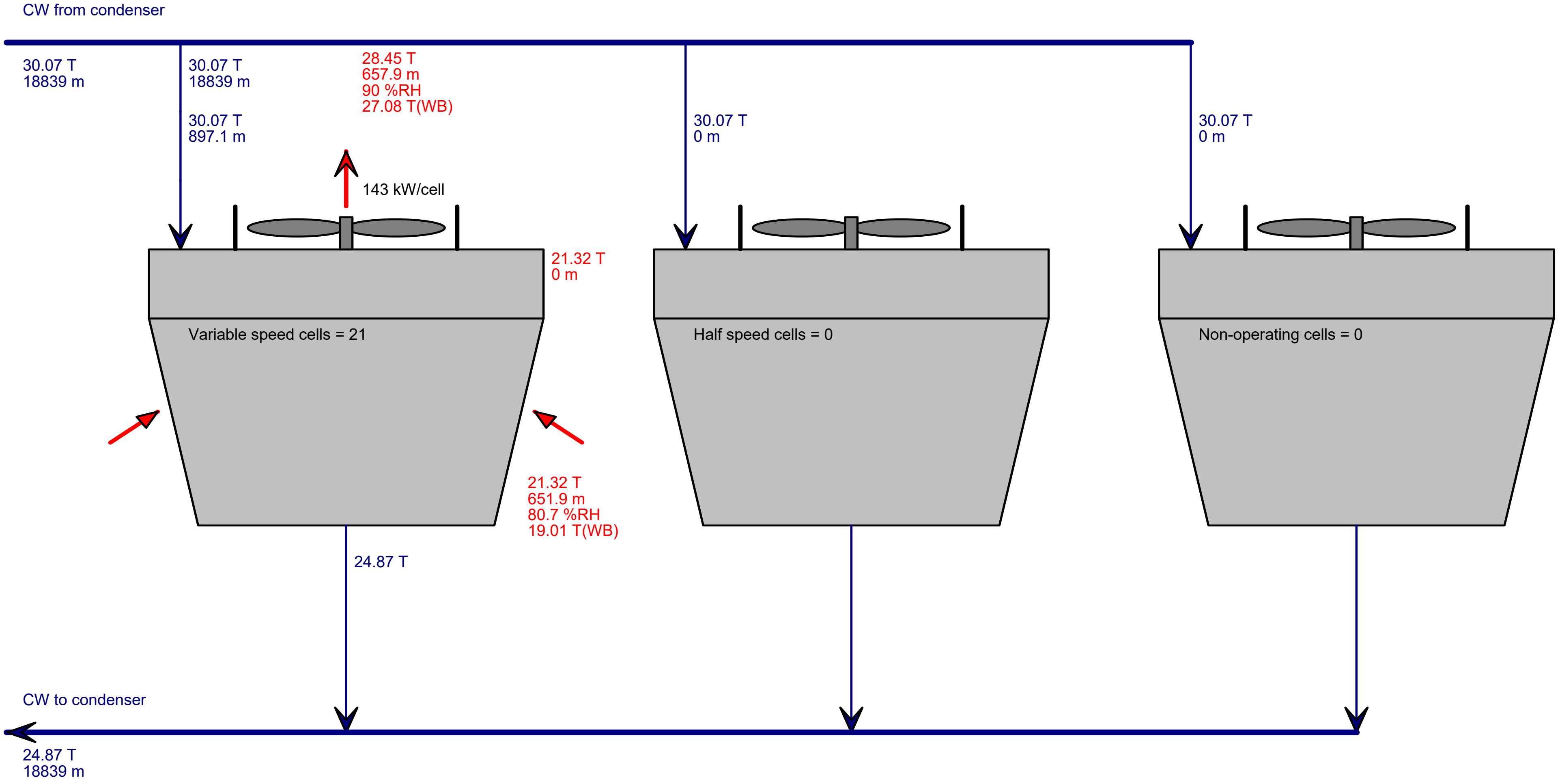
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Cooling Tower Cells - 21 existing cells



p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

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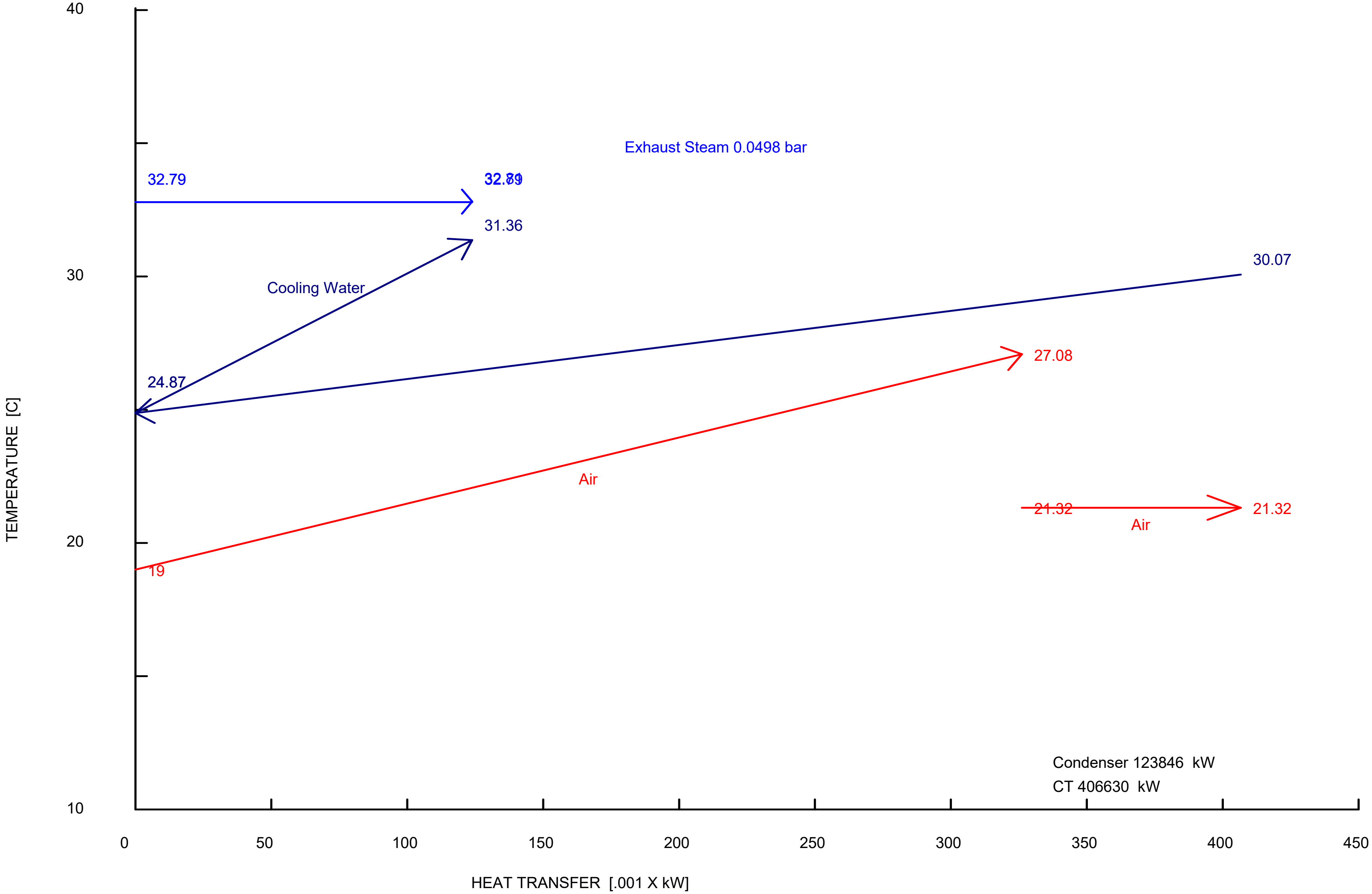
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Water Cooled Condenser and Wet-Dry Cooling Tower T-Q Diagram



AIR STATES:

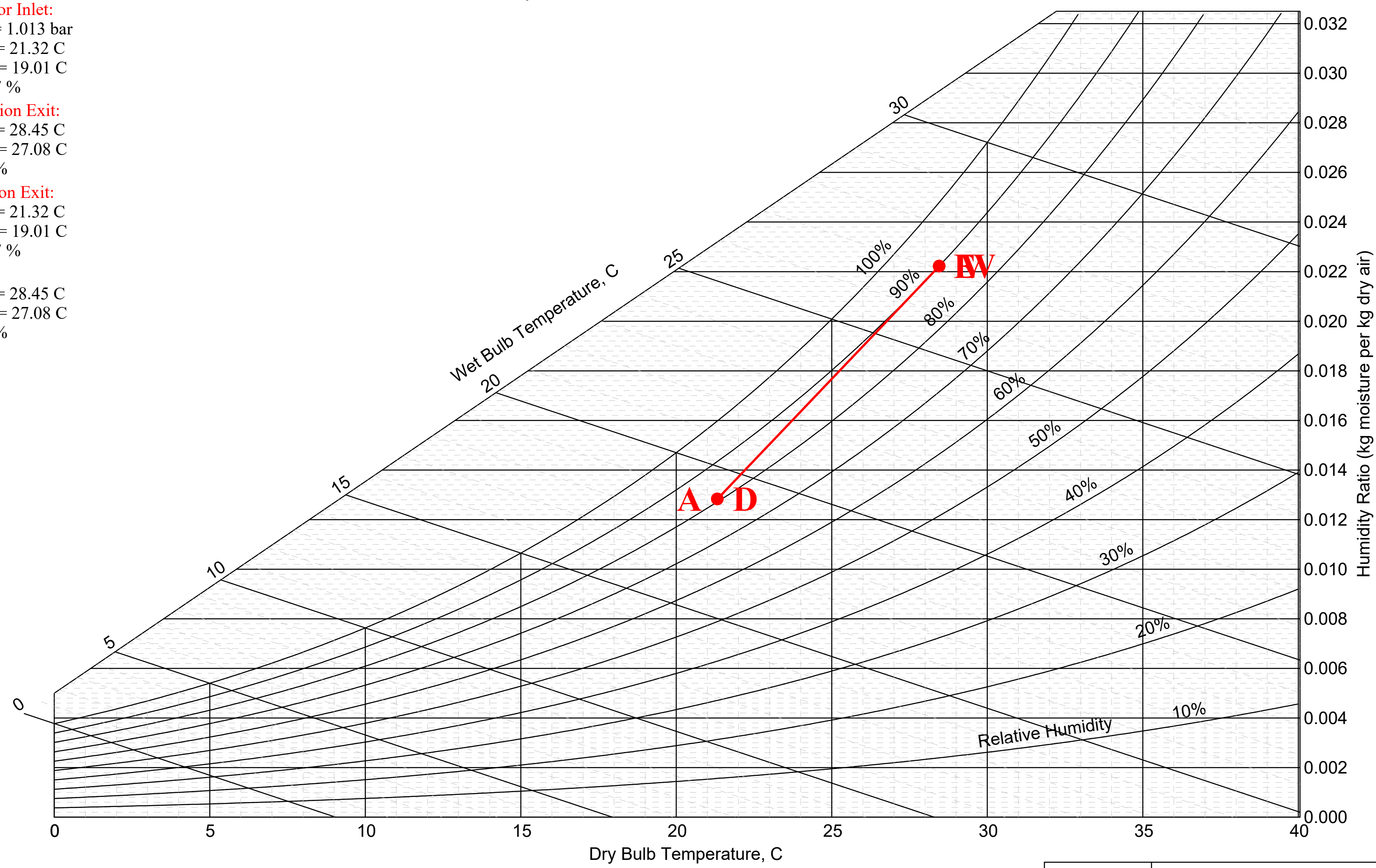
A) Ambient or Inlet:
Pressure = 1.013 bar
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %

W) Wet Section Exit:
Dry bulb = 28.45 C
Wet bulb = 27.08 C
RH = 90 %

D) Dry Section Exit:
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %

E) Air Exit:
Dry bulb = 28.45 C
Wet bulb = 27.08 C
RH = 90 %

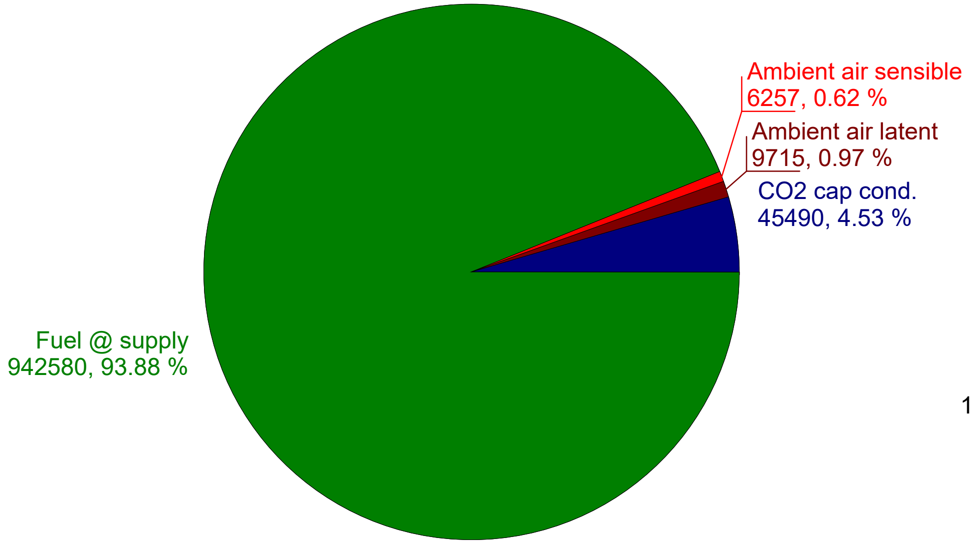
Psychrometric Chart



Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Cooling Tower
Date: 06/11/20	
Drawing No:	

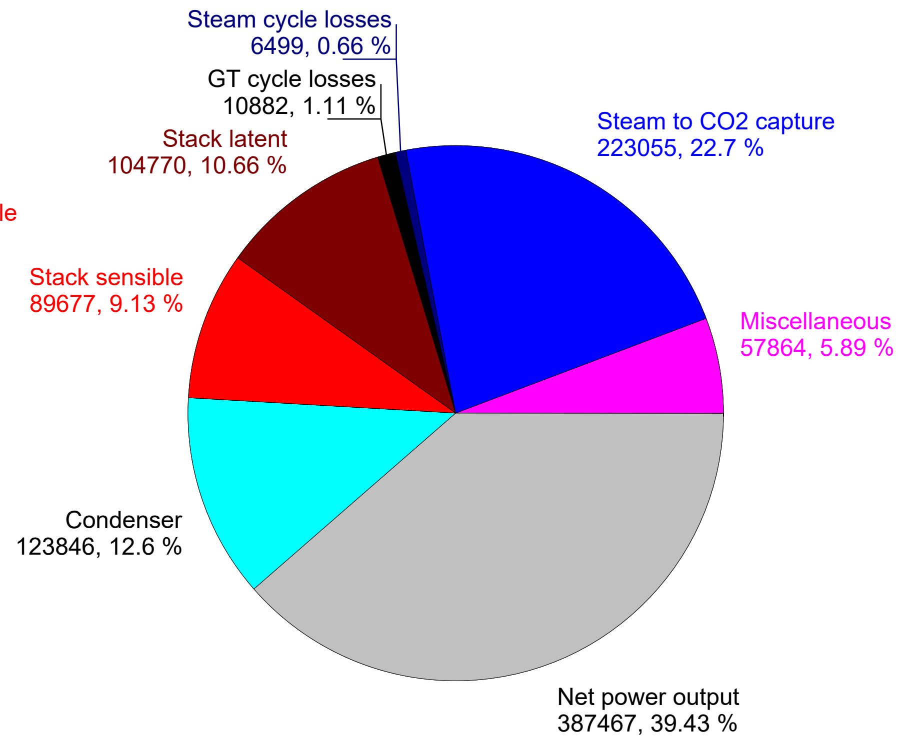
Plant Energy In [kW]

Plant energy in = 1004058 kW
Plant fuel chemical LHV input = 846694 kW, HHV = 939503 kW
Plant net LHV elec. eff. = 45.76 % (100% * 387467 / 846694), Net HHV elec. eff. = 41.24 %



Plant Energy Out [kW]

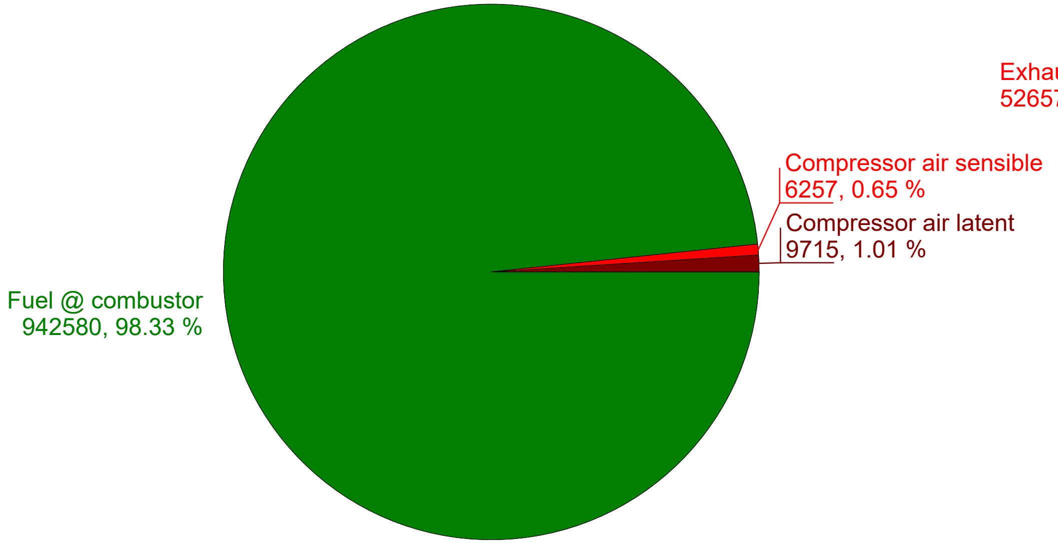
Plant energy out = 982700 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

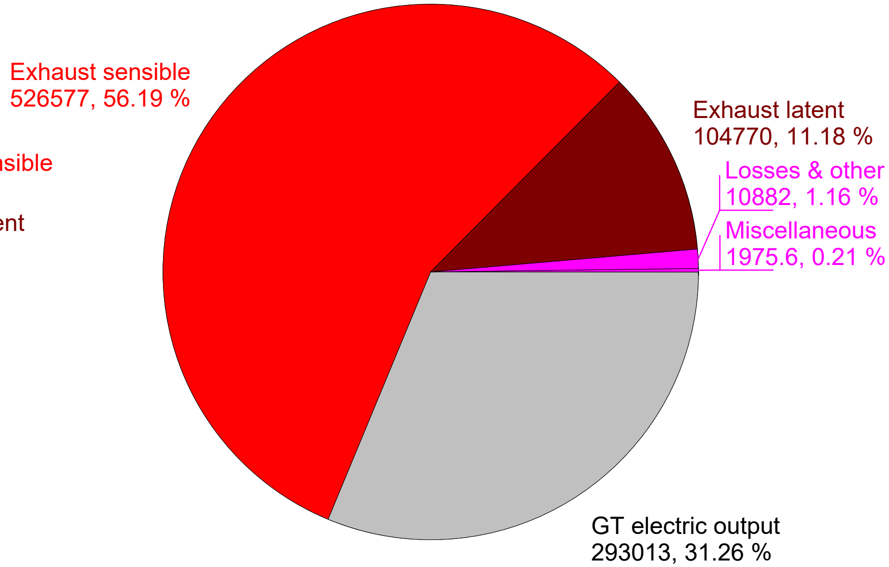
GT Cycle Energy In [kW]

GT cycle energy in = 958552 kW
GT fuel chemical LHV input = 846694 kW, HHV = 939503 kW



GT Cycle Energy Out [kW]

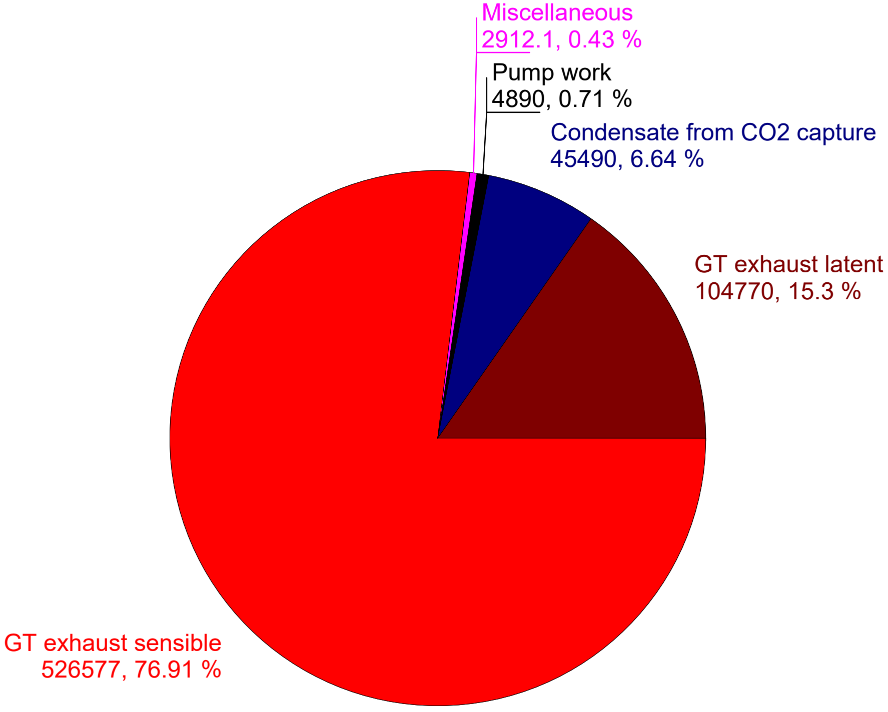
GT cycle energy out = 937217 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

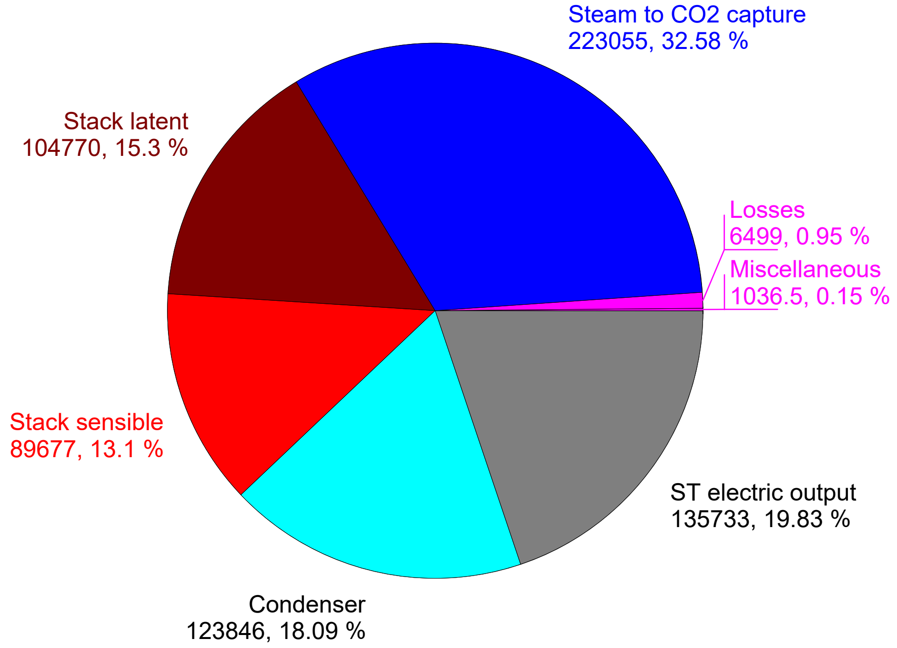
Steam Cycle Energy In [kW]

Steam cycle energy in = 684639 kW



Steam Cycle Energy Out [kW]

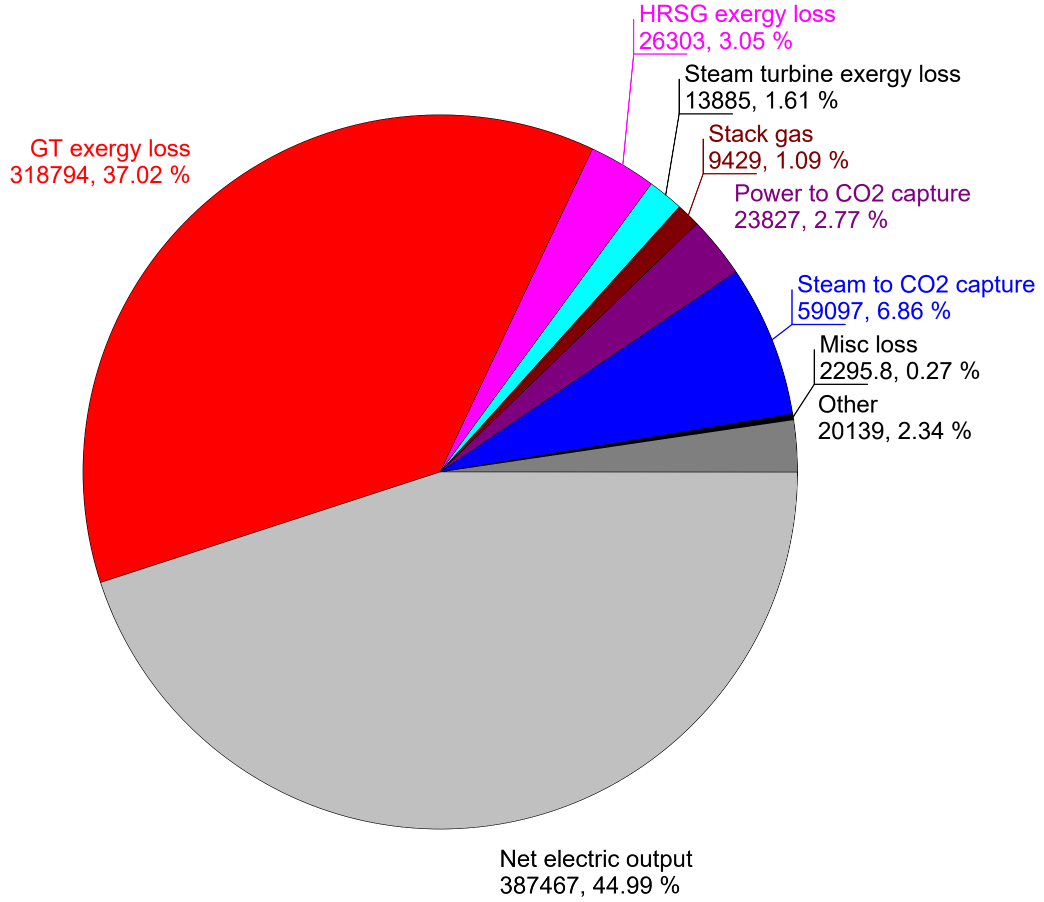
Steam cycle energy out = 684615 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Plant Exergy Analysis [kW]

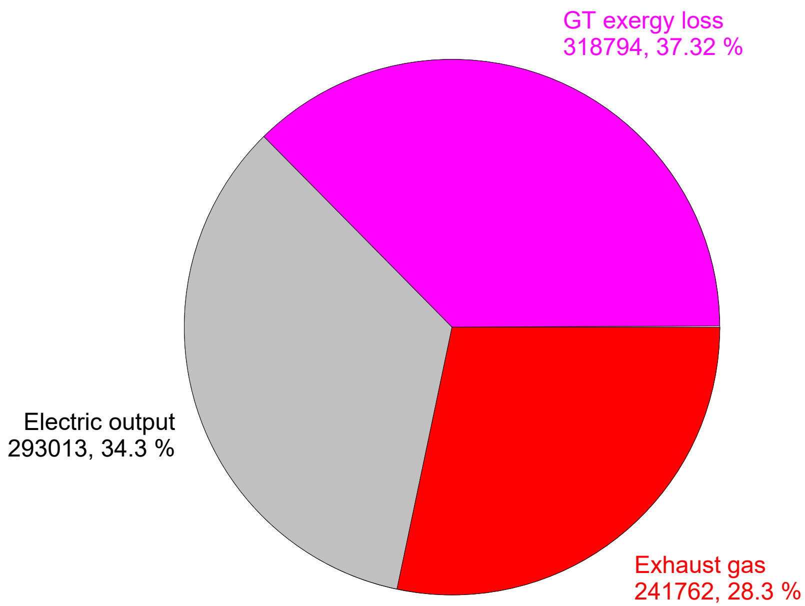
Plant exergy input = 861237 kW
Fuel exergy input = 854839 kW
Plant fuel chemical LHV input = 846694 kW, HHV = 939503 kW



Reference: 1.013 bar, 25 C, water as vapor.

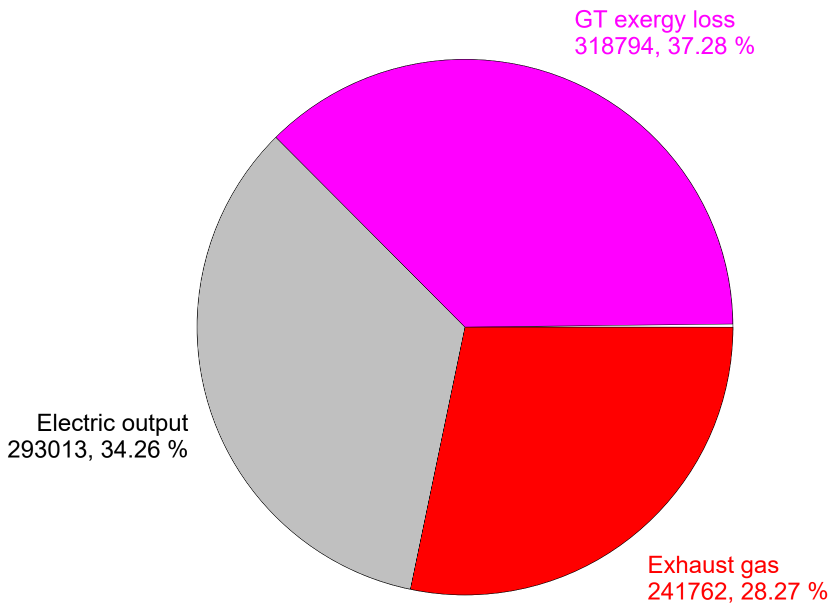
GT Exergy Analysis [kW]

GT exergy in = 854201 kW



GT & Peripheral Exergy Analysis [kW]

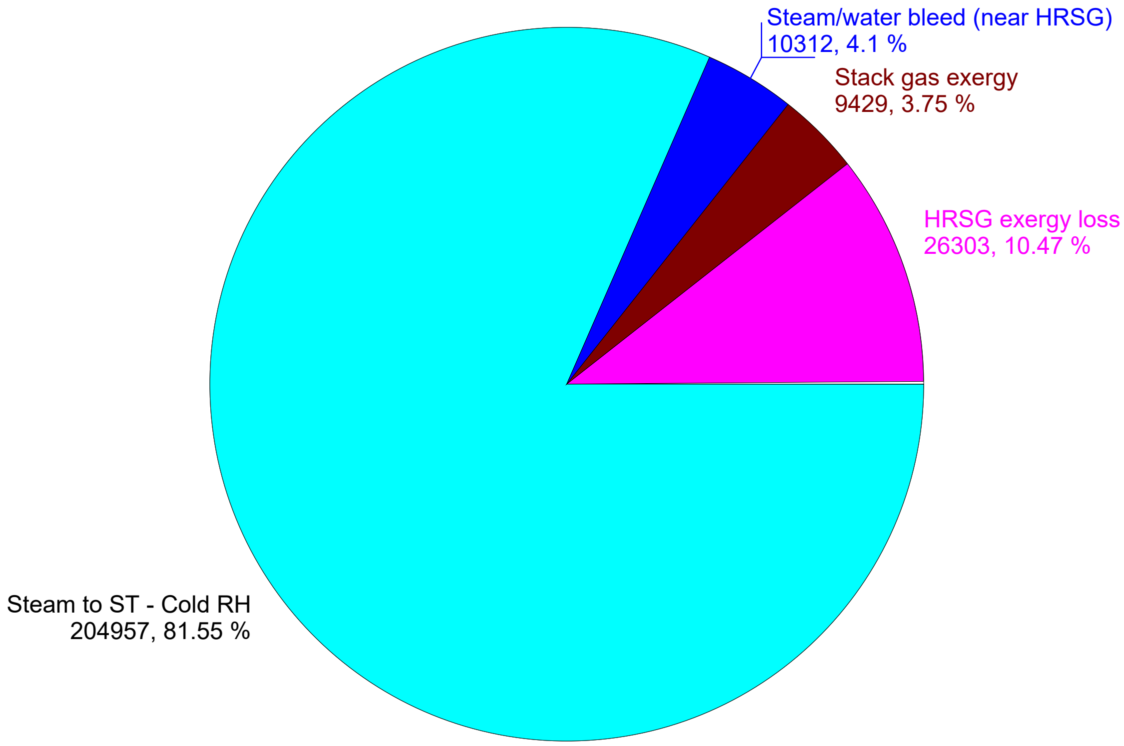
GT & peripheral exergy in = 855149 kW



Reference: 1.013 bar, 25 C, water as vapor.

HRSG Exergy Analysis [kW]

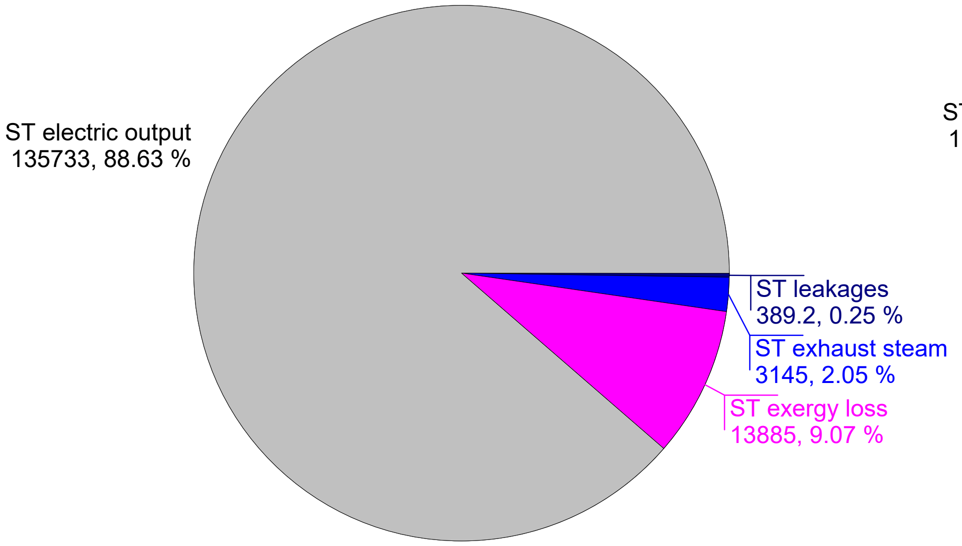
HRSG exergy in = 251323 kW



Reference: 1.013 bar, 25 C, water as vapor.

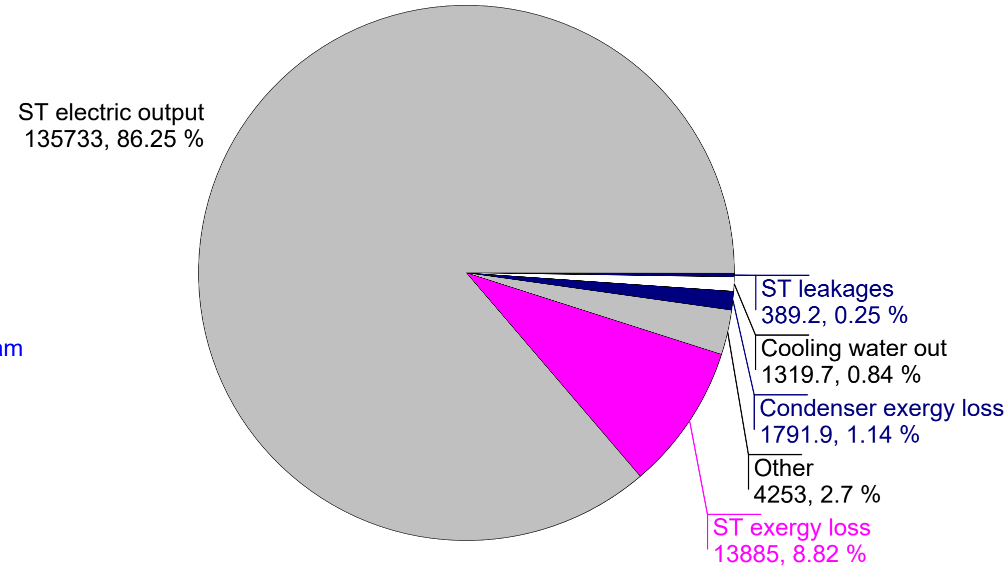
ST Exergy Analysis [kW]

ST exergy in = 153152 kW



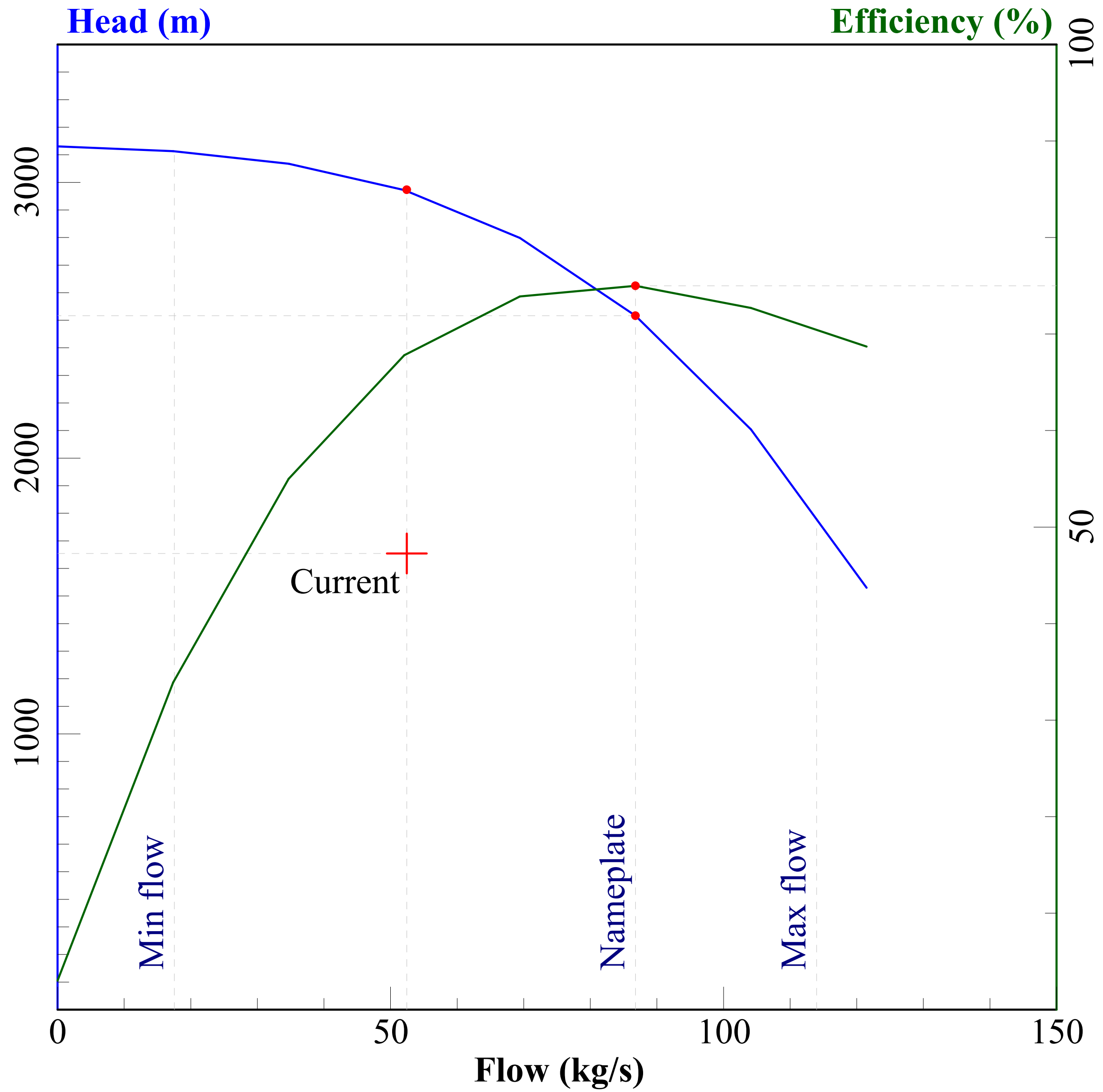
ST & Condenser Exergy Analysis [kW]

ST & condenser exergy in = 157372 kW



Reference: 1.013 bar, 25 C, water as vapor.

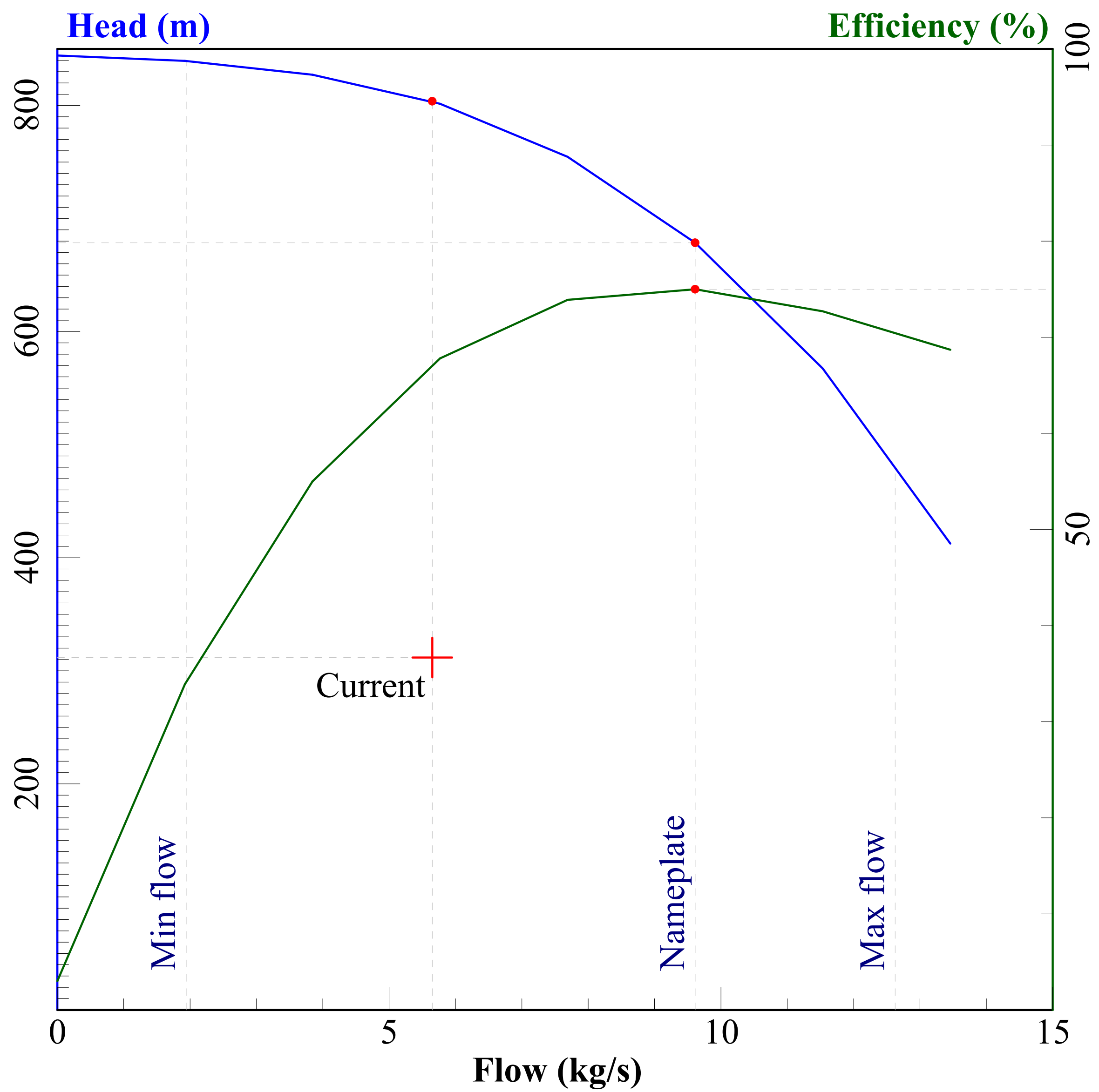
HP Feedwater Pump (P1)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	86.77 kg/s
Nameplate head	2516.5 m
Nameplate flow (nominal)	5678 lpm
Nameplate head (nominal)	2560.3 m
Nameplate RPM	3000
Current pump flow	52.44 kg/s
Current head	2973 m
Current head after valve	1654.1 m
Current RPM	3000
Minimum continuous flow	17.54 kg/s
Maximum continuous flow	114 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HP Feedwater Pump (P1)
Date: 06/11/20	
Drawing No:	

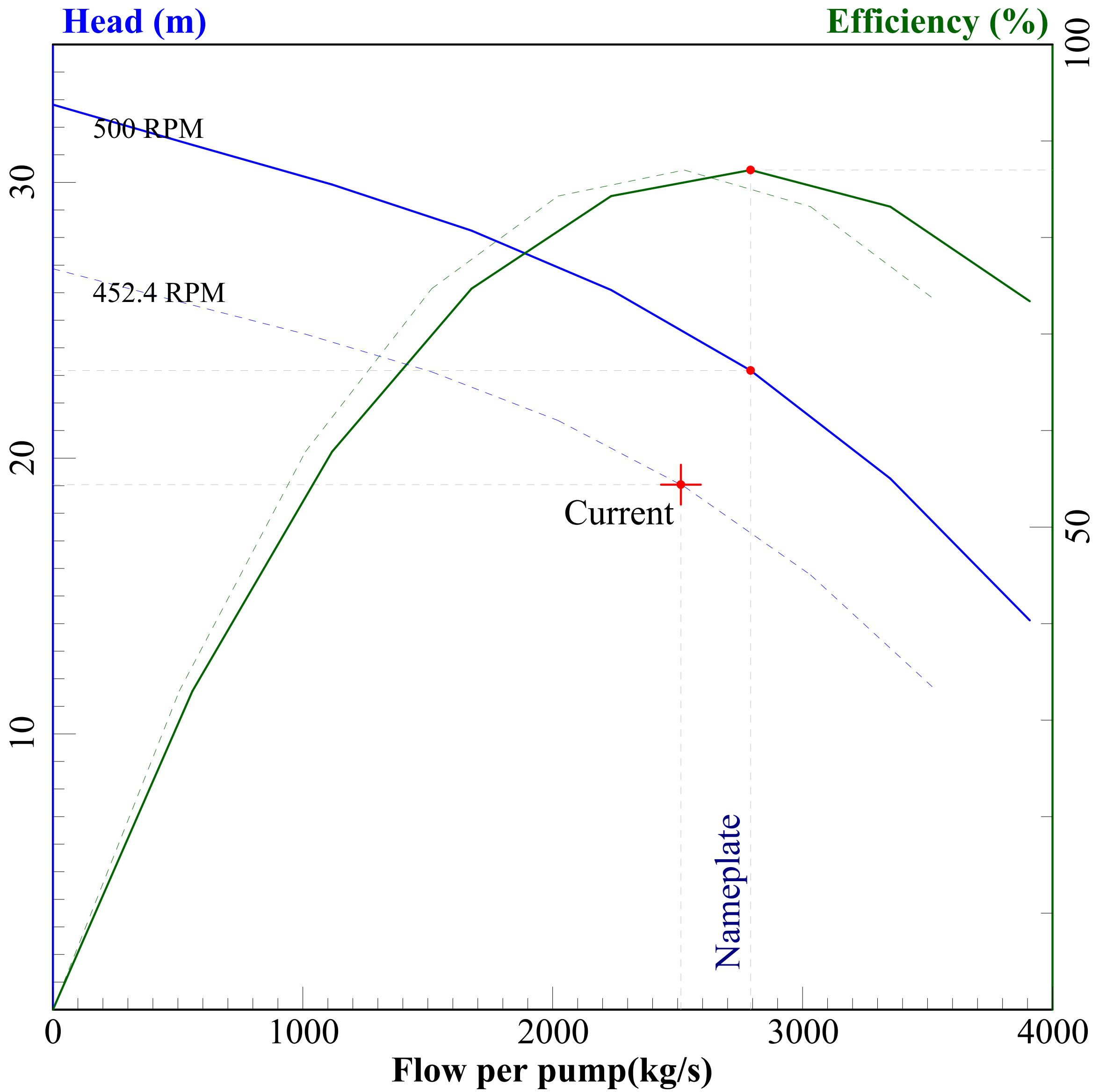
IP Feedwater Pump (P2)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	9.612 kg/s
Nameplate head	678.6 m
Nameplate flow (nominal)	662.4 lpm
Nameplate head (nominal)	701 m
Nameplate RPM	3000
Current pump flow	5.65 kg/s
Current head	803.8 m
Current head after valve	311.8 m
Current RPM	3000
Minimum continuous flow	1.942 kg/s
Maximum continuous flow	12.63 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IP Feedwater Pump (P2)
Date: 06/11/20	
Drawing No:	

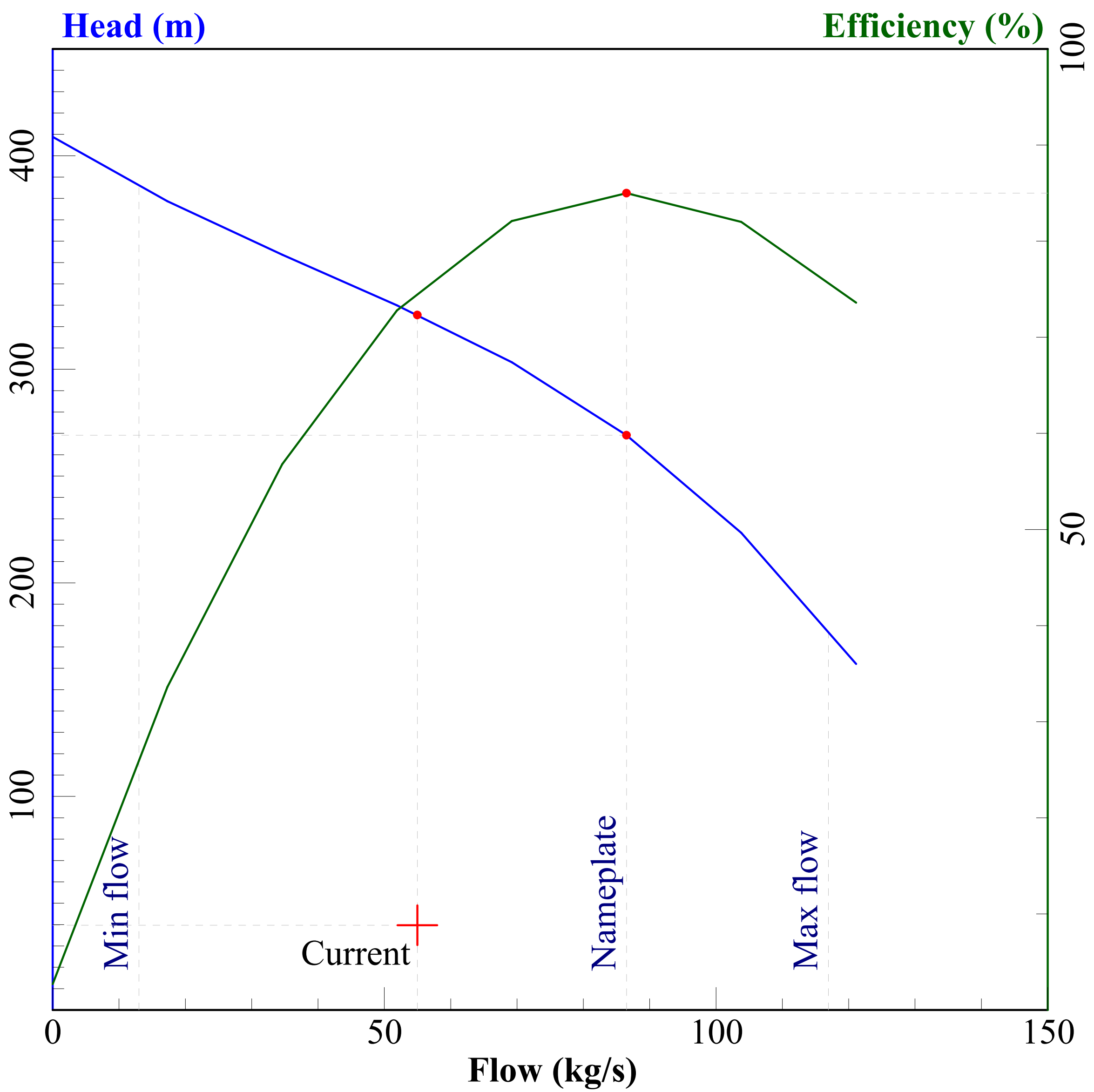
Condenser C.W. Pump (P4)



No. per Condenser	2
No. operating per Condenser	2
Nameplate flow	2792.3 kg/s
Nameplate head	23.18 m
Nameplate flow (nominal)	170344 lpm
Nameplate head (nominal)	24.38 m
Nameplate RPM	500
Current pump flow	2513 kg/s
Current head	19.04 m
Current head after valve	19.04 m
Current RPM	452.4

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condenser C.W. Pump (P4)
Date: 06/11/20	
Drawing No:	

Condensate Forwarding Pump (P6)



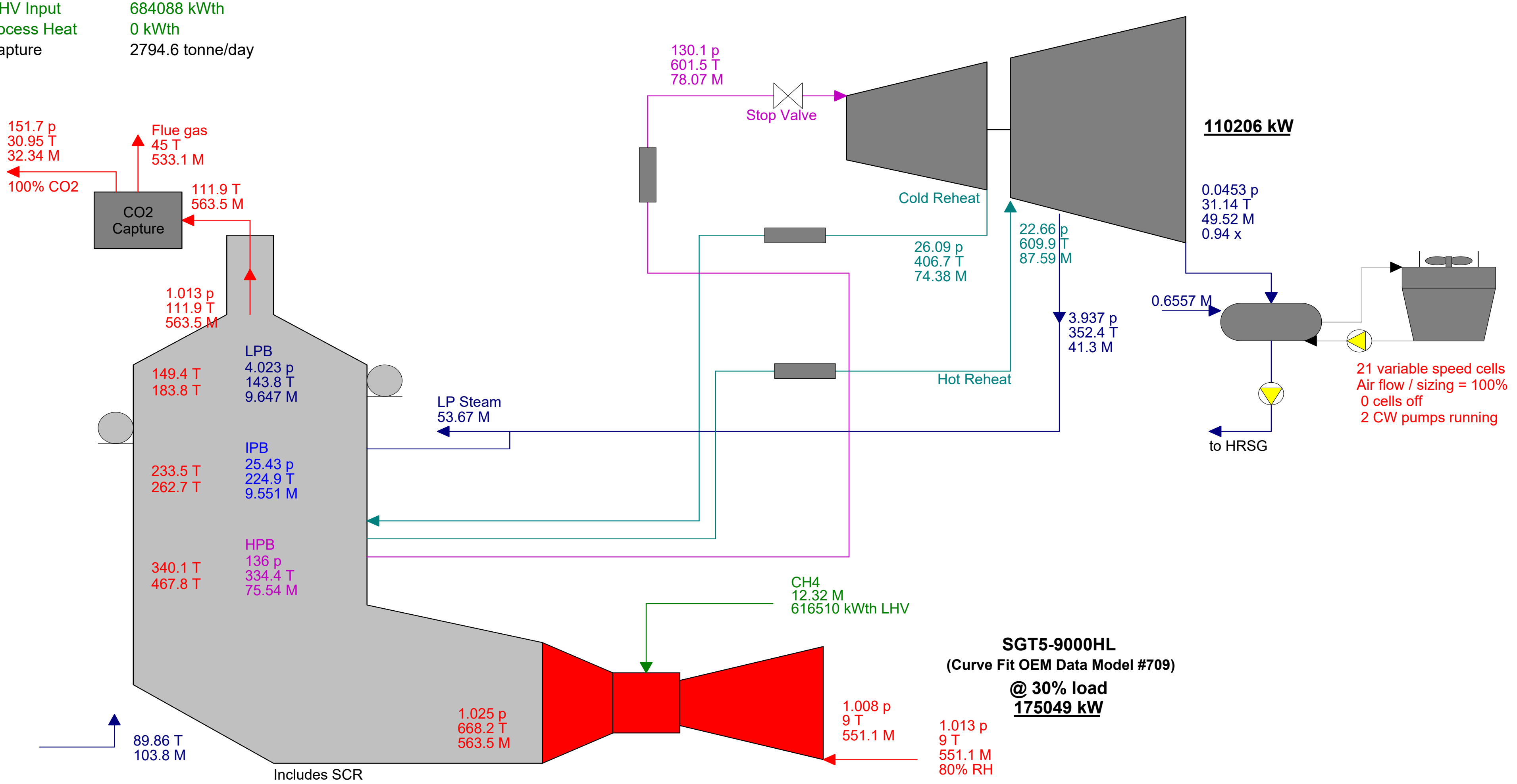
No. per Condenser	2
No. operating per Condenser	1
Nameplate flow	86.51 kg/s
Nameplate head	269.2 m
Nameplate flow (nominal)	5300 lpm
Nameplate head (nominal)	274.3 m
Nameplate RPM	1500
Current pump flow	54.98 kg/s
Current head	325.4 m
Current head after valve	39.69 m
Current RPM	1500
Minimum continuous flow	12.99 kg/s
Maximum continuous flow	116.9 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condensate Forwarding Pump (P6)
Date: 06/11/20	
Drawing No:	

GT MASTER 29.0 AECOM

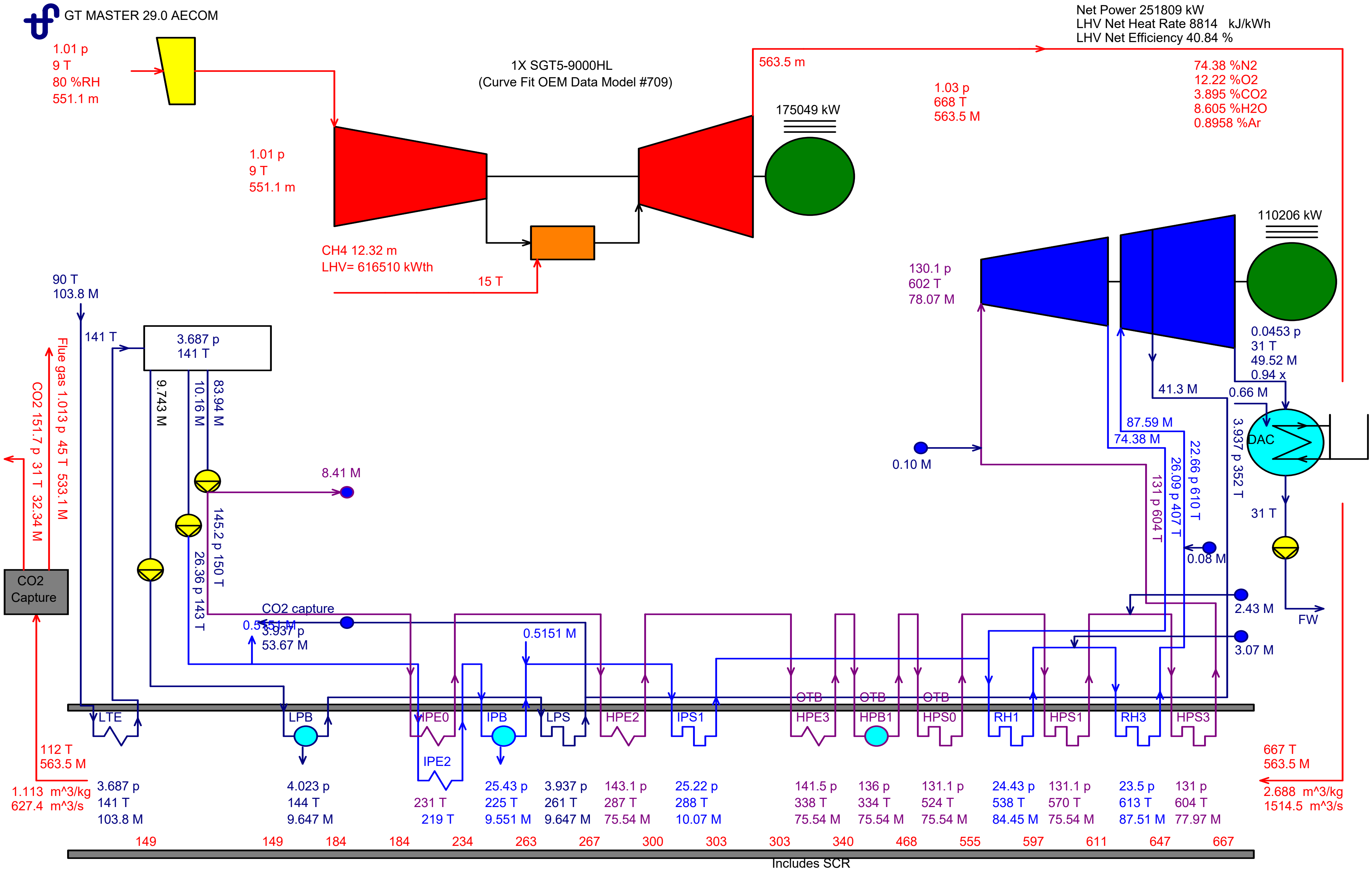
Gross Power	285255 kW
Net Power	251809 kW
Aux. & Losses	33446 kW
LHV Gross Heat Rate	7781 kJ/kWh
LHV Net Heat Rate	8814 kJ/kWh
LHV Gross Electric Eff.	46.27 %
LHV Net Electric Eff.	40.84 %
Fuel LHV Input	616511 kWth
Fuel HHV Input	684088 kWth
Net Process Heat	0 kWth
CO2 capture	2794.6 tonne/day

Ambient
1.013 P
9 T
80% RH
7.353 Twb



p [bar] T [C] M [kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 19:56:02 file=

GT MASTER 29.0 AECOM
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

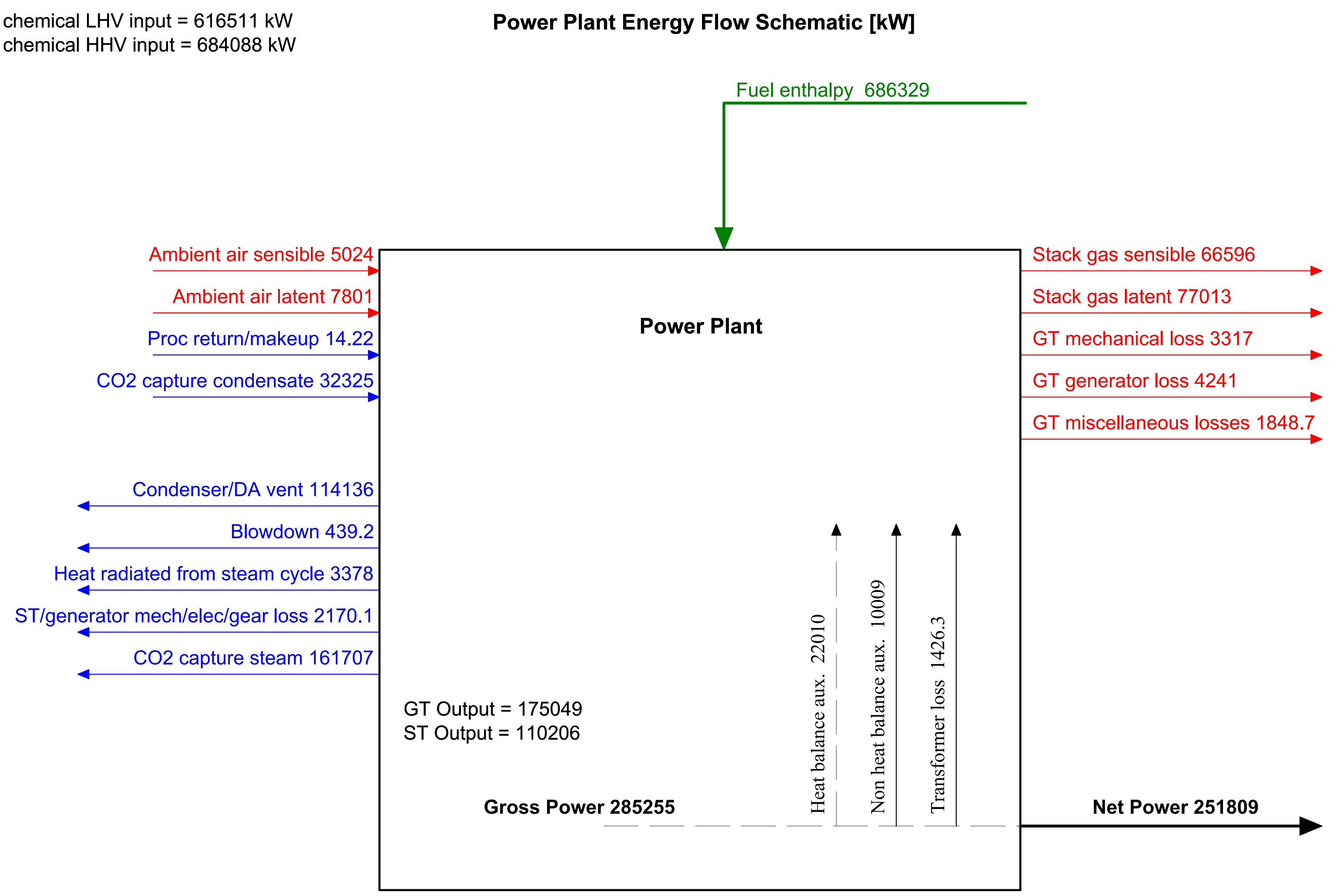


p[bar], T[C], M[kg/s], Steam Properties: IAPWS-IF97

1220 06-11-2020 19:56:02 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

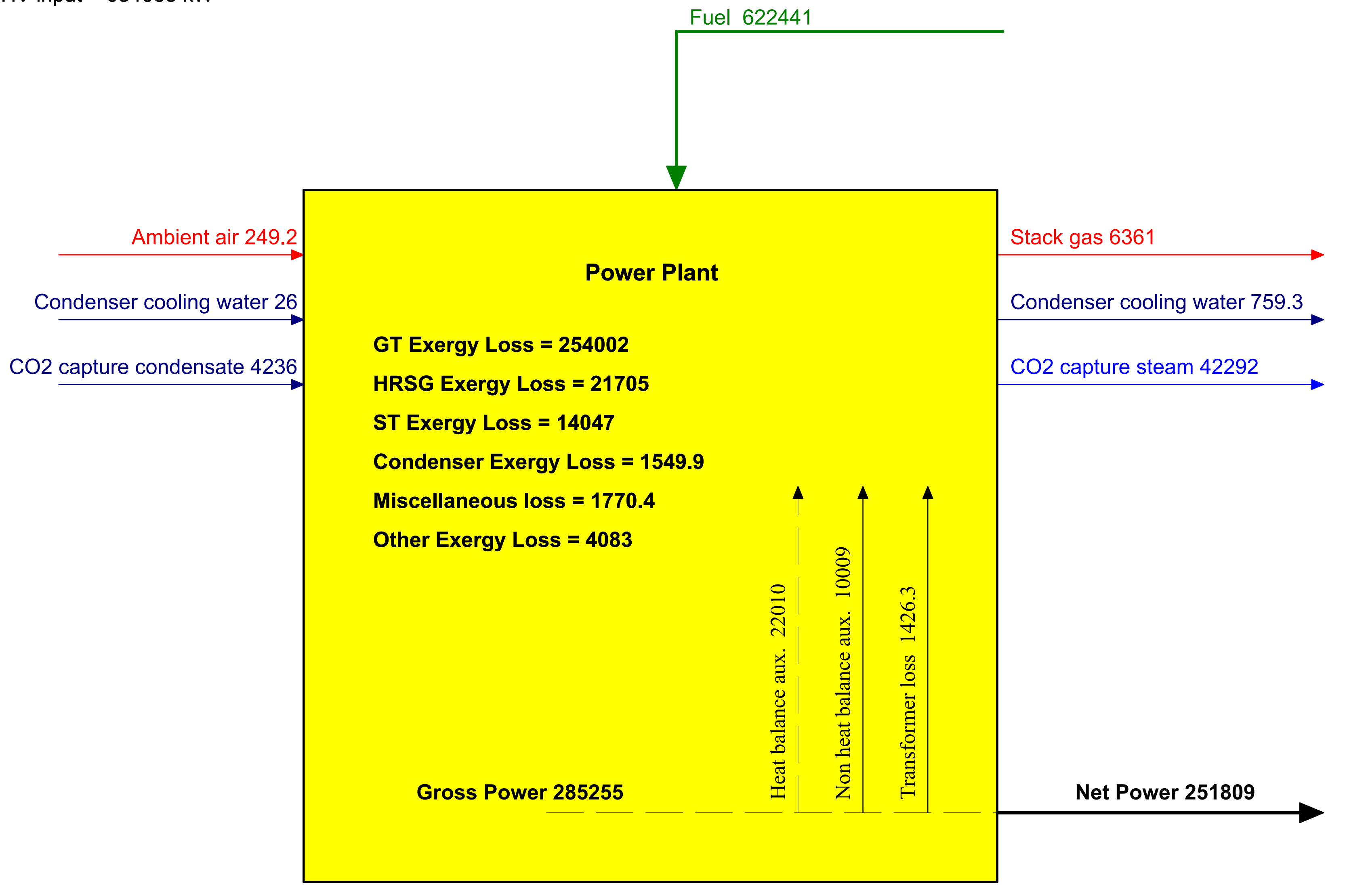
Fuel chemical LHV input = 616511 kW
Fuel chemical HHV input = 684088 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Fuel exergy input = 622441 kW
Fuel chemical LHV input = 616511 kW
Fuel chemical HHV input = 684088 kW

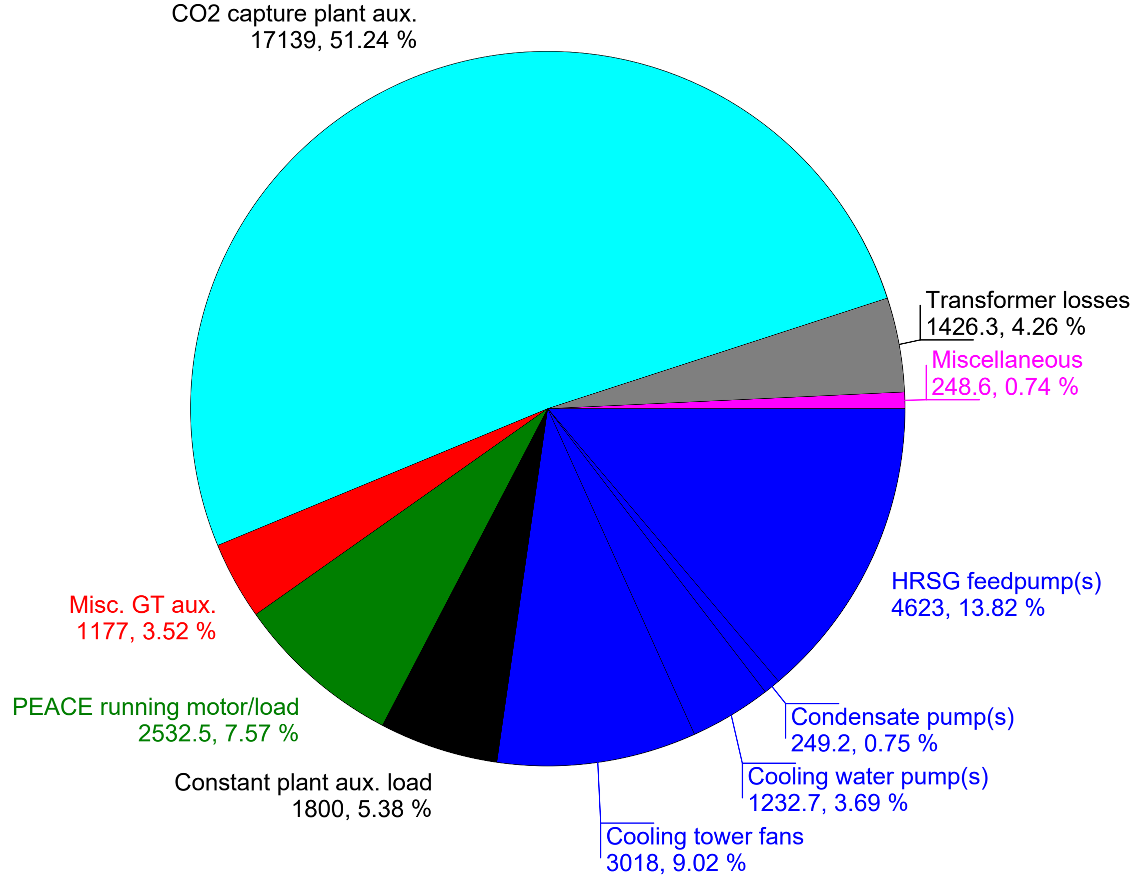
Power Plant Exergy Flow Schematic [kW]



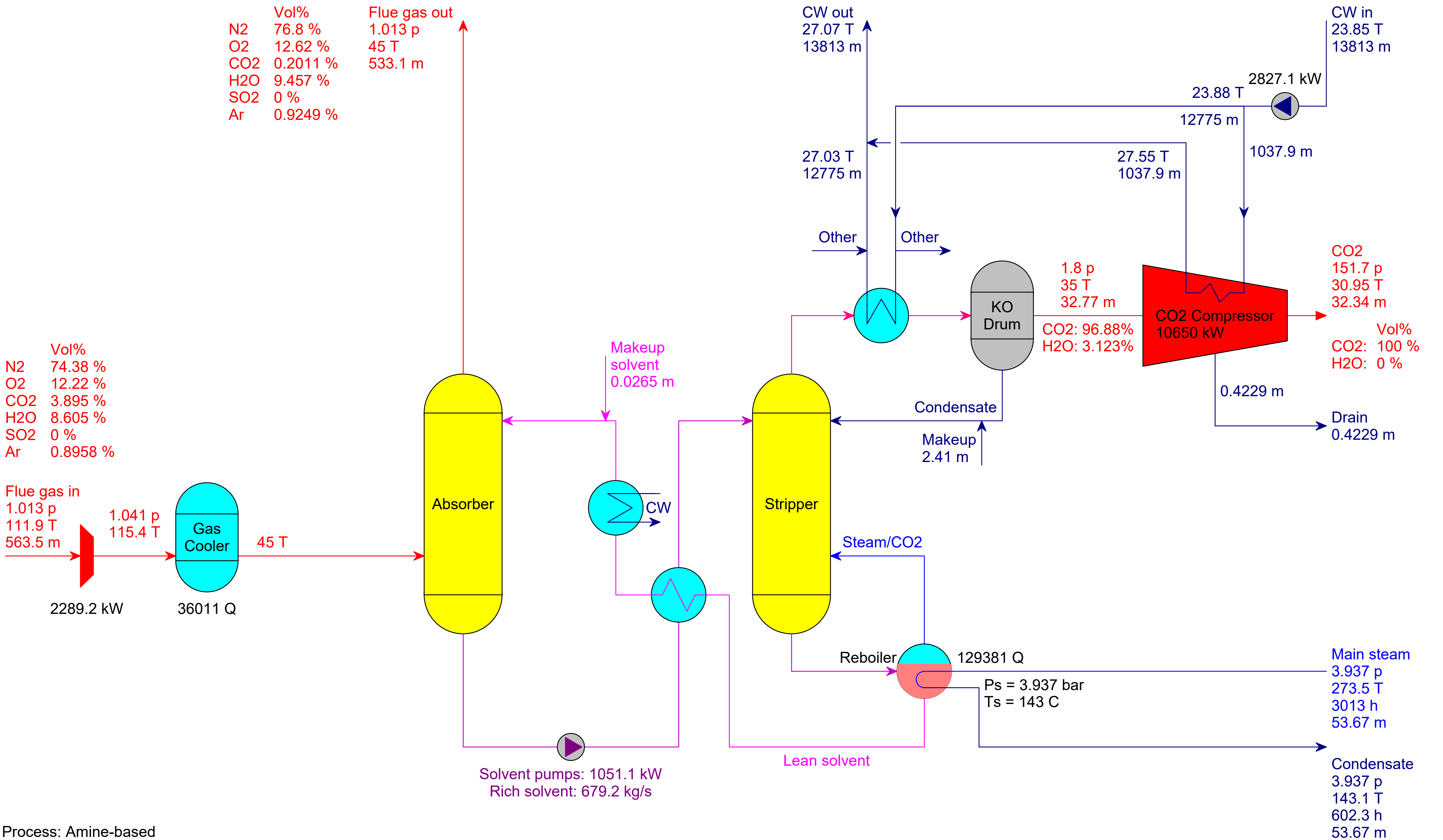
Reference: 1.013 bar, 25 C, water as vapor.

Auxiliaries & Losses [kW]

Total auxiliaries & transformer losses = 33446 kW



CO2 Capture Plant Flow Diagram

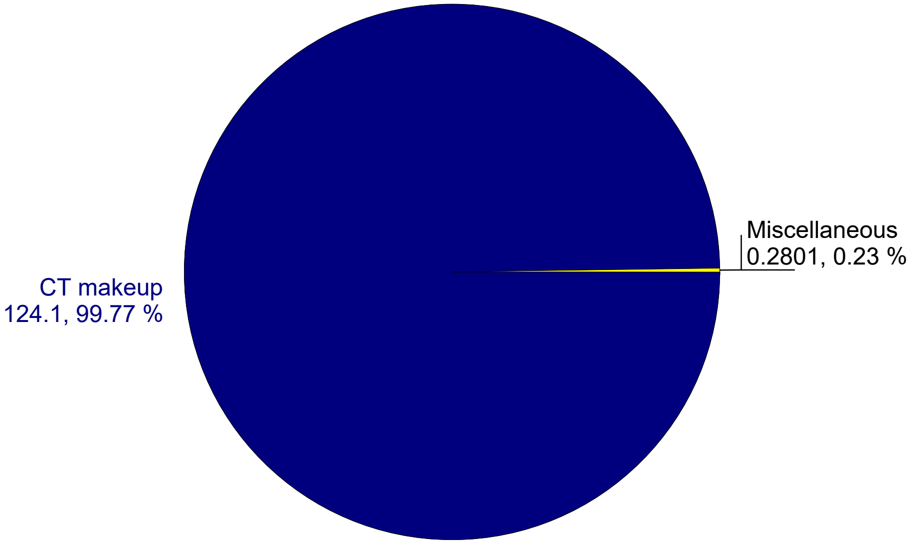


Process: Amine-based
CO2 capture: 32.34 kg/s, 2794.6 tonne/day
CO2 capture efficiency: 95 %
Heat input: 129381 kW, 129.4 MW, 4000 kJ/kg CO2
Total electrical power consumption: 17139 kW
Solvent consumption: 2.289 tonne/day

p[bar] T[C] h[kJ/kg] m[kg/s] Q[kW]

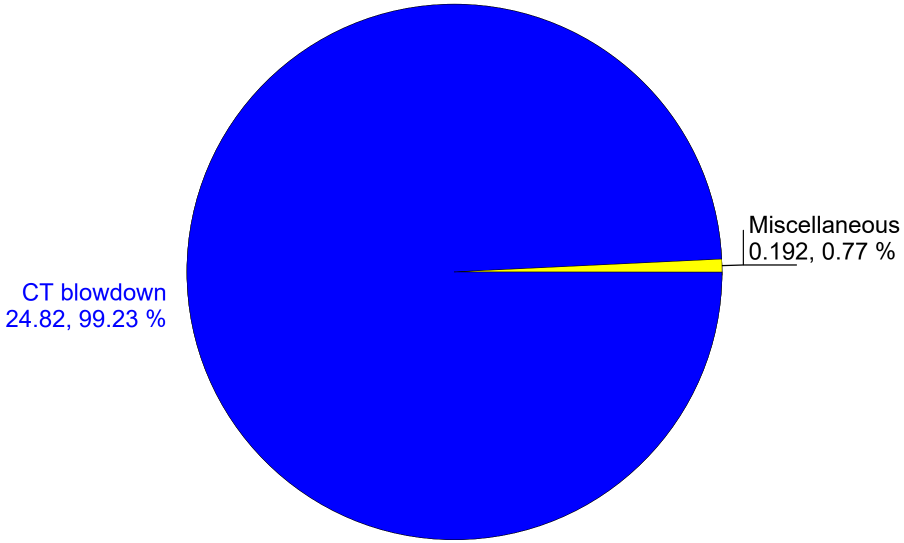
Plant Water Consumption [kg/s]

Plant water consumption = 124.4 kg/s

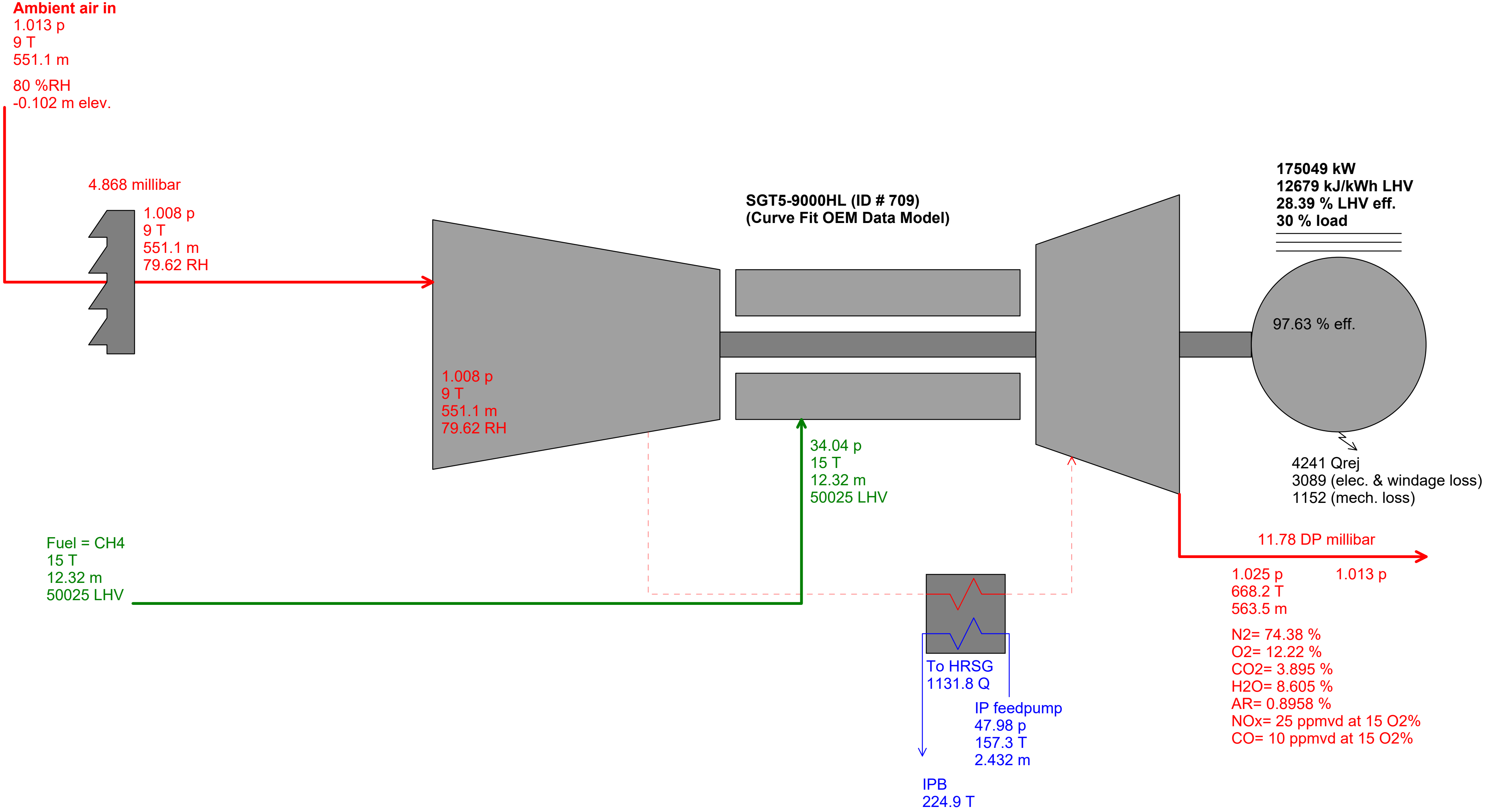


Plant Water Discharge [kg/s]

Plant water discharge = 25.01 kg/s

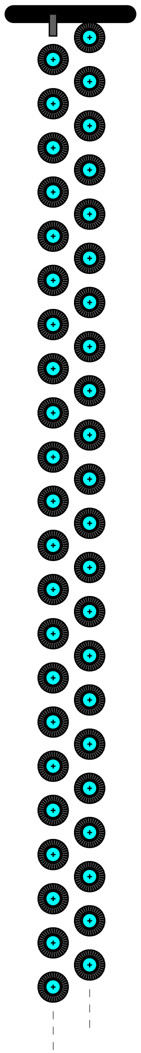


GT generator power = 175049 kW
GT Heat Rate @ gen term = 12679 kJ/kWh
GT efficiency @ gen term = 25.589% HHV = 28.394% LHV
GT @ 30 % rating



p[bar], T[C], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

HPS3 Hardware Design



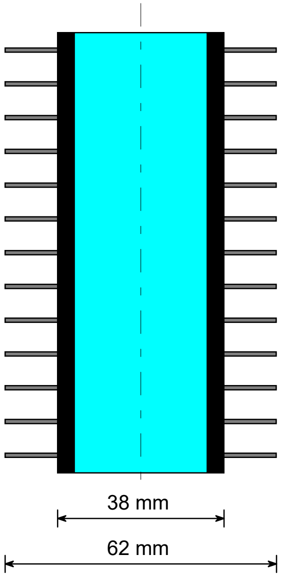
HPS3
2 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

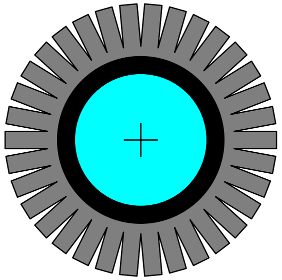
Gas Out
646.7 T
563.5 m

Gas In
667.2 T
563.5 m

Steam In
131.1 p
536.2 T
3434 h
77.97 m

Steam Out
131 p
604.3 T
3611 h
77.97 m



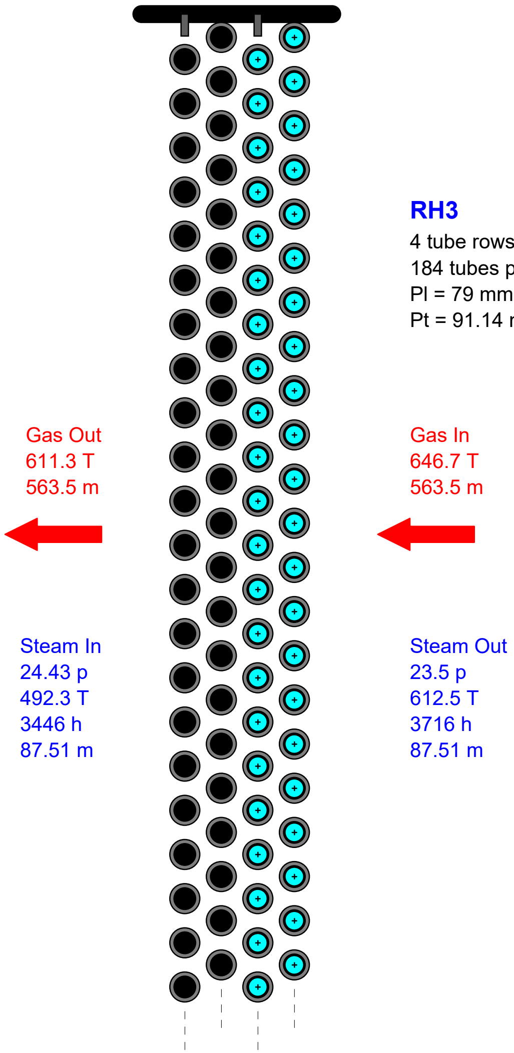


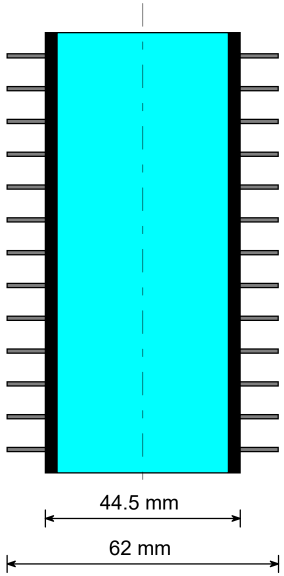
Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP304
Tube material	TP347HFG
Tube outer diameter	38 mm
Tube wall thickness	3.81 mm
Fin height	12 mm
Fin spacing	6.723 mm
Fin thickness	1 mm
Number of fins per meter	129.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4645 m^2
Maximum gas velocity	8.069 m/s
Gas pressure drop	0.2021 millibar
Steam side velocity	8.045 m/s
Steam side pressure drop	0.0683 bar
Heat transfer from gas	13862 kW
Heat transfer to steam	13793 kW

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS3
Date: 06/15/20	
Drawing No:	

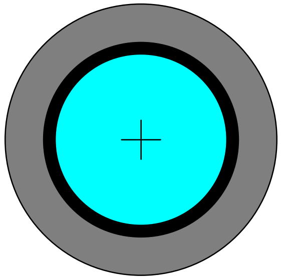
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

RH3 Hardware Design





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	TP347HFG
Tube outer diameter	44.5 mm
Tube wall thickness	2.667 mm
Fin height	8.75 mm
Fin spacing	6.507 mm
Fin thickness	1 mm
Number of fins per meter	133.2
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	8064 m^2
Maximum gas velocity	8.838 m/s
Gas pressure drop	0.3973 millibar
Steam side velocity	30.94 m/s
Steam side pressure drop	0.9249 bar
Heat transfer from gas	23757 kW
Heat transfer to steam	23639 kW



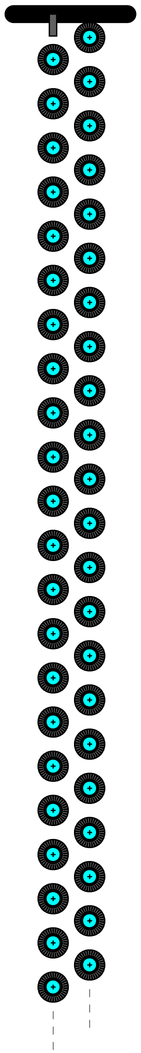
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH3
Date: 06/15/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

HPS1 Hardware Design



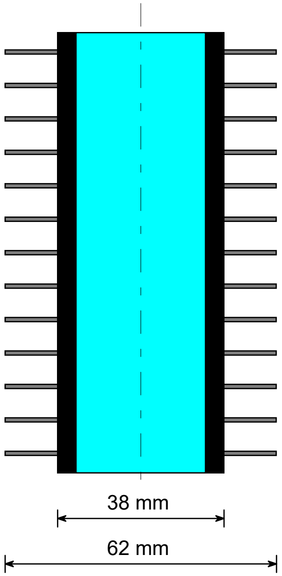
HPS1
2 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

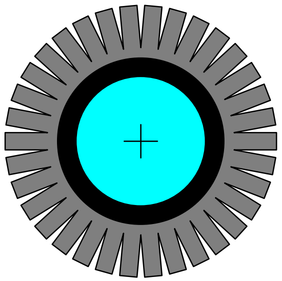
Gas Out
597.4 T
563.5 m

Gas In
611.3 T
563.5 m

Steam In
131.1 p
524.3 T
3402 h
75.54 m

Steam Out
131.1 p
570.5 T
3524 h
75.54 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T91
Tube outer diameter	38 mm
Tube wall thickness	4.191 mm
Fin height	12 mm
Fin spacing	6.65 mm
Fin thickness	1 mm
Number of fins per meter	130.7
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4680 m^2
Maximum gas velocity	7.618 m/s
Gas pressure drop	0.1906 millibar
Steam side velocity	7.892 m/s
Steam side pressure drop	0.0695 bar
Heat transfer from gas	9244 kW
Heat transfer to steam	9198 kW

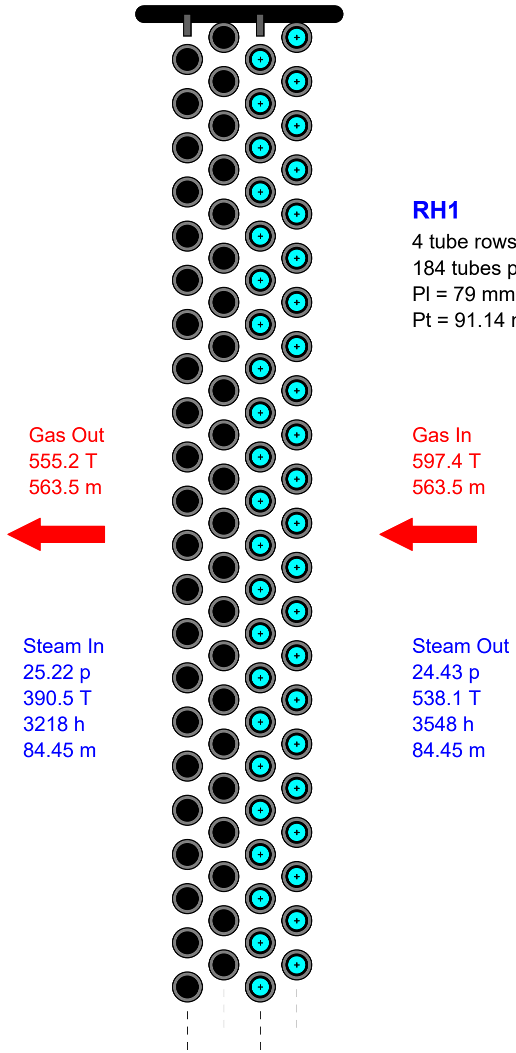
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

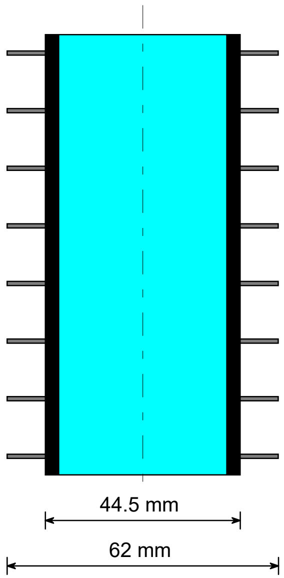
0 50 mm

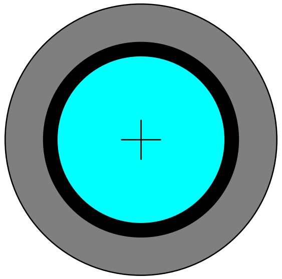
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS1
Date: 06/15/20	
Drawing No:	

RH1 Hardware Design



RH1
4 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T22
Tube outer diameter	44.5 mm
Tube wall thickness	3.048 mm
Fin height	8.75 mm
Fin spacing	12.19 mm
Fin thickness	1 mm
Number of fins per meter	75.8
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	5493 m^2
Maximum gas velocity	8.138 m/s
Gas pressure drop	0.2868 millibar
Steam side velocity	26.53 m/s
Steam side pressure drop	0.7942 bar
Heat transfer from gas	27998 kW
Heat transfer to steam	27858 kW

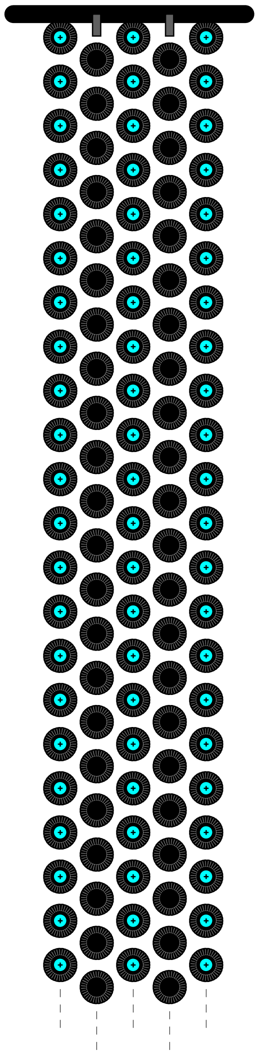
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH1
Date: 06/15/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

HPS0 (OTB) Hardware Design



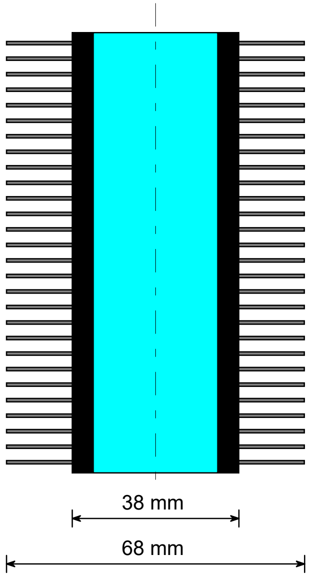
Gas Out
467.8 T
563.5 m

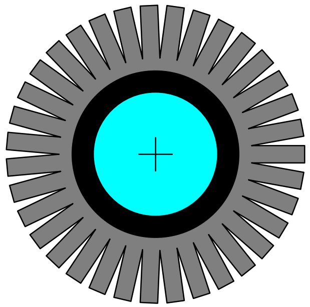
Steam In
136 p
334.4 T
2648.4 h
75.54 m

HPS0 (OTB)
4.777 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
555.2 T
563.5 m

Steam Out
131.1 p
524.3 T
3402 h
75.54 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4.777
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	26214 m^2
Maximum gas velocity	7.342 m/s
Gas pressure drop	0.7197 millibar
Steam side velocity	13.01 m/s
Steam side pressure drop	4.808 bar
Heat transfer from gas	57199 kW
Heat transfer to steam	56915 kW

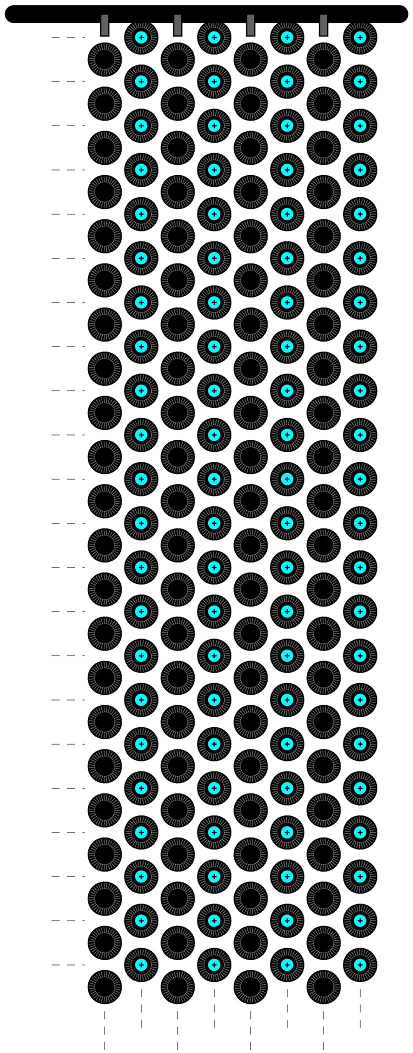
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS0 (OTB)
Date: 06/15/20	
Drawing No:	

HPB1 (OTB) Hardware Design



Gas Out
340.1 T
563.5 m

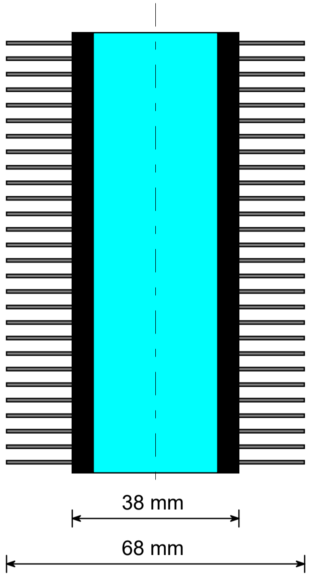
Water In
141.5 p
337.5 T
1576.9 h
75.54 m

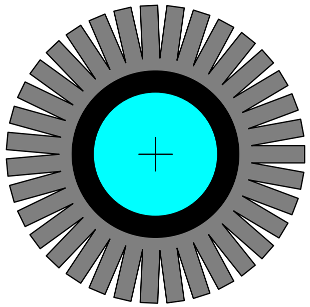
HPB1 (OTB)

11.4 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
467.8 T
563.5 m

Steam Out
136 p
334.4 T
2648.4 h
75.54 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	11.4
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	62568 m^2
Maximum gas velocity	6.335 m/s
Gas pressure drop	1.44 millibar
Water side velocity	1.036 m/s
Water side pressure drop	5.565 bar
Heat transfer from gas	81346 kW
Heat transfer to steam/water	80941 kW

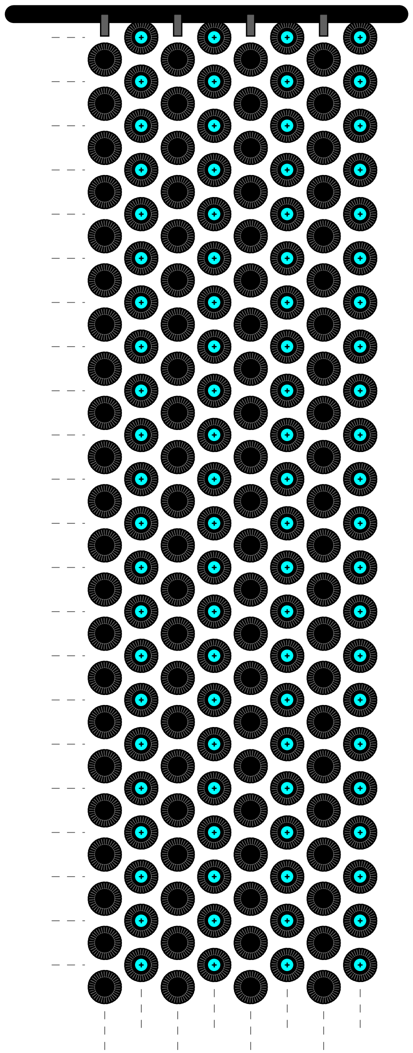
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPB1 (OTB)
Date: 06/15/20	
Drawing No:	

HPE3 (OTB) Hardware Design



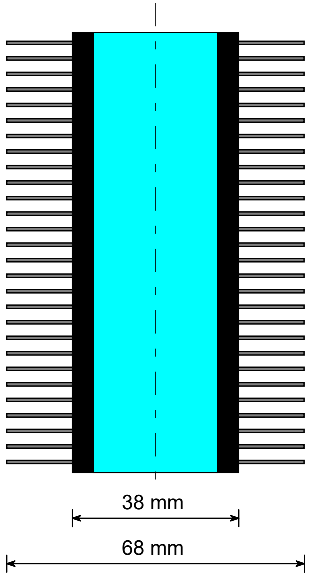
Gas Out
302.8 T
563.5 m

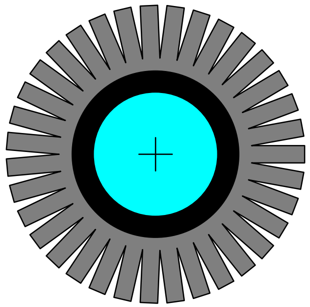
Water In
143.1 p
287.2 T
1269.9 h
75.54 m

HPE3 (OTB)
17.82 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
340.1 T
563.5 m

Water Out
141.5 p
337.5 T
1576.9 h
75.54 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	17.82
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	97782 m^2
Maximum gas velocity	5.564 m/s
Gas pressure drop	1.961 millibar
Water side velocity	0.9276 m/s
Water side pressure drop	1.555 bar
Heat transfer from gas	23300 kW
Heat transfer to water	23184 kW

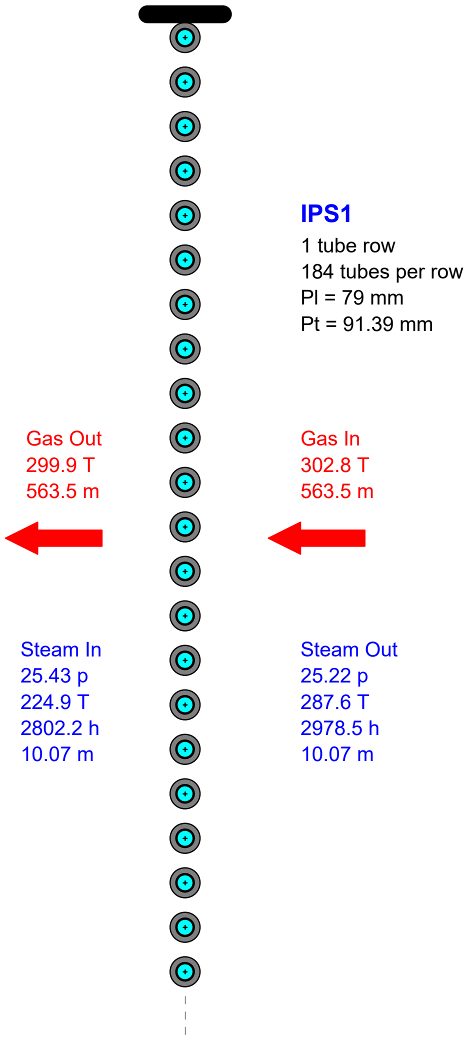
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE3 (OTB)
Date: 06/15/20	
Drawing No:	

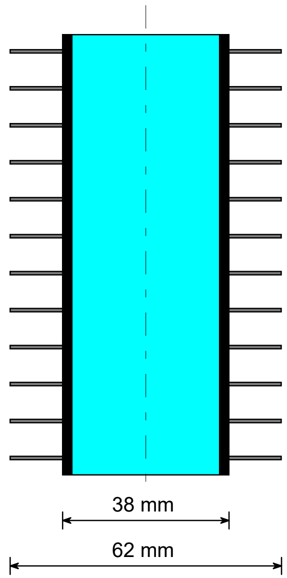
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

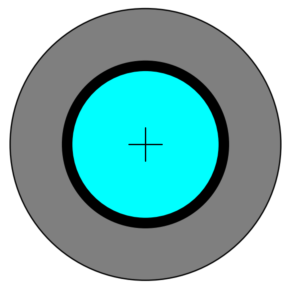
0 150 mm

0 50 mm

IPS1 Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	7.626 mm
Fin thickness	0.8 mm
Number of fins per meter	118.7
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.39 mm
# of tube rows (longitudinal)	1
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2154.4 m^2
Maximum gas velocity	4.879 m/s
Gas pressure drop	0.0521 millibar
Steam side velocity	5.331 m/s
Steam side pressure drop	0.2084 bar
Heat transfer from gas	1783.5 kW
Heat transfer to steam	1774.6 kW

Flow out of drawing

Flow into drawing

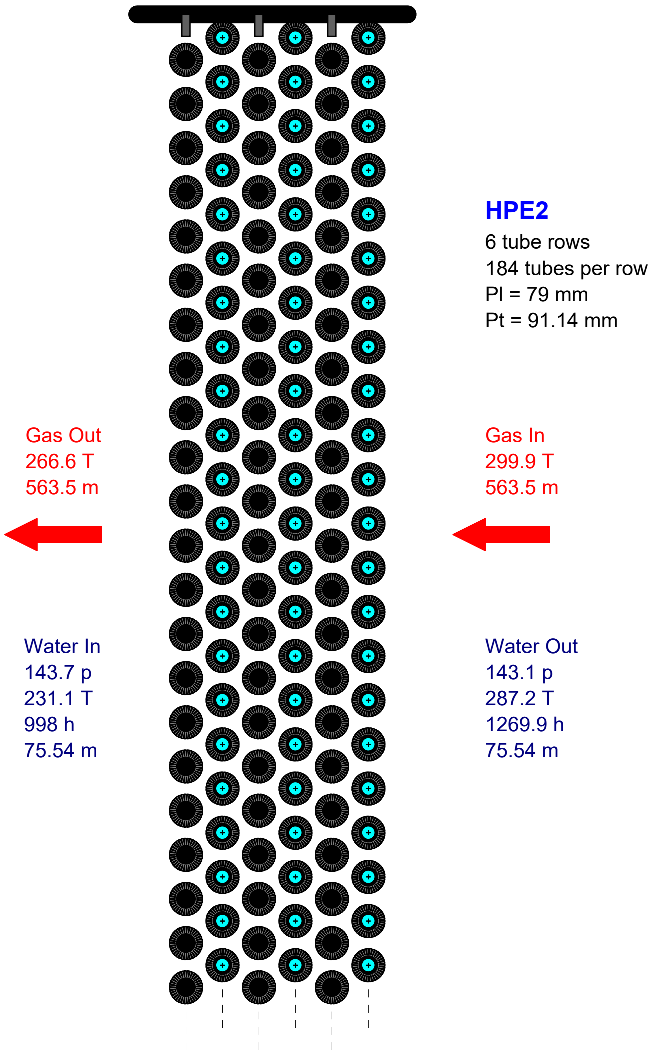
p[bar] T[C] m[kg/s] h[kJ/kg]

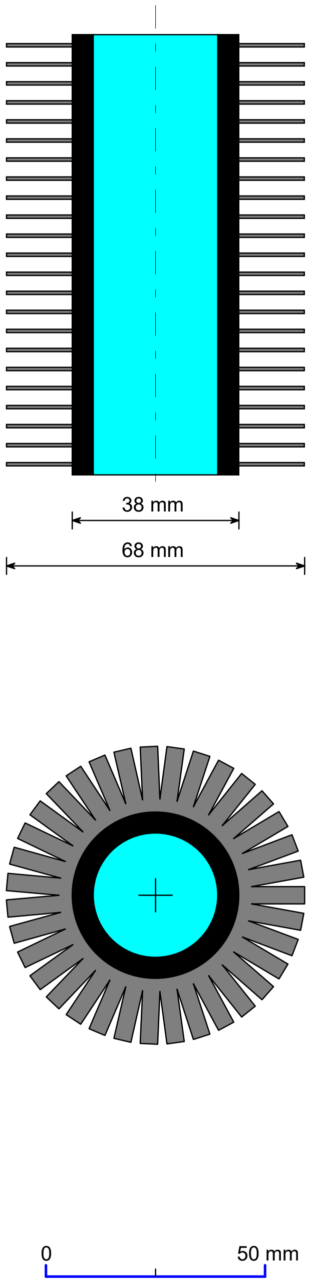
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPS1
Date: 06/15/20	
Drawing No:	

HPE2 Hardware Design



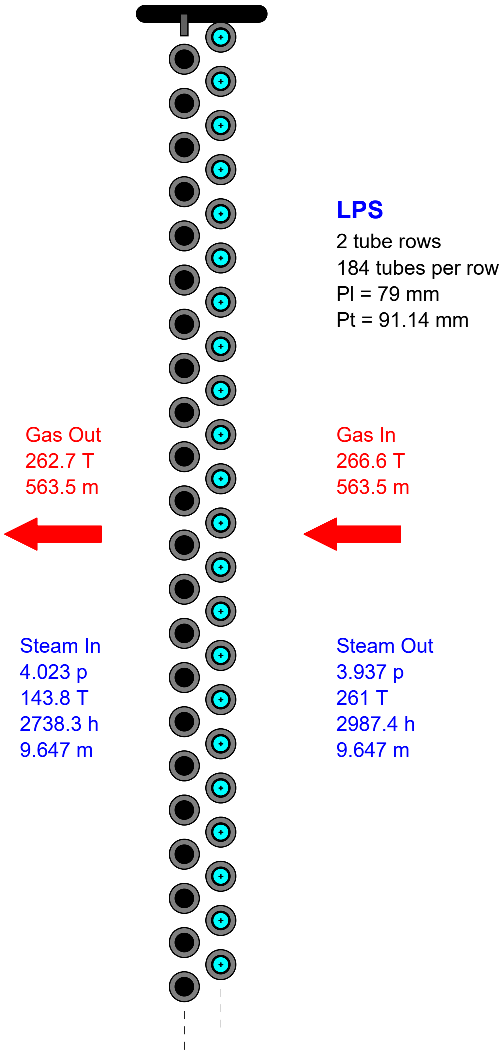


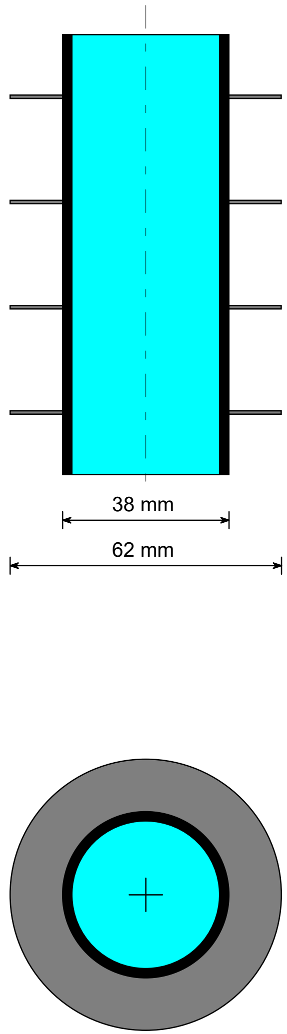
Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	3.555 mm
Fin thickness	0.8 mm
Number of fins per meter	229.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	27374 m^2
Maximum gas velocity	5.071 m/s
Gas pressure drop	0.5085 millibar
Water side velocity	0.8105 m/s
Water side pressure drop	0.5998 bar
Heat transfer from gas	20644 kW
Heat transfer to water	20541 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE2
Date: 06/15/20	
Drawing No:	

LPS Hardware Design





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	23.26 mm
Fin thickness	0.8 mm
Number of fins per meter	41.56
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2091.2 m^2
Maximum gas velocity	4.46 m/s
Gas pressure drop	0.0645 millibar
Steam side velocity	31.58 m/s
Steam side pressure drop	0.0861 bar
Heat transfer from gas	2414.5 kW
Heat transfer to steam	2402.4 kW

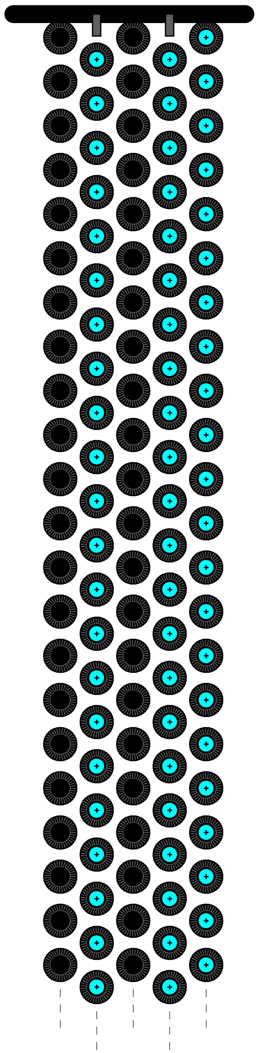
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0   150 mm

0   50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPS
Date: 06/15/20	
Drawing No:	

IPB Hardware Design



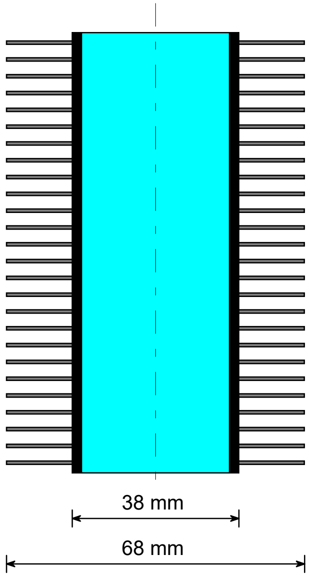
IPB
5 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

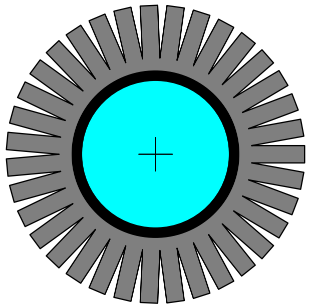
Gas Out
233.5 T
563.5 m

Gas In
262.7 T
563.5 m

Water In
25.43 p
218.8 T
938.2 h
9.551 m

Steam Out
25.43 p
224.9 T
2802.2 h
9.551 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.045 mm
Fin thickness	0.8 mm
Number of fins per meter	260
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	5
# of rows per pass	1.251
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	25540 m^2
Maximum gas velocity	4.824 m/s
Gas pressure drop	0.4321 millibar
Water side velocity	0.9994 m/s
Water side pressure drop	0 bar
Heat transfer from gas	17895 kW
Heat transfer to steam/water	17806 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

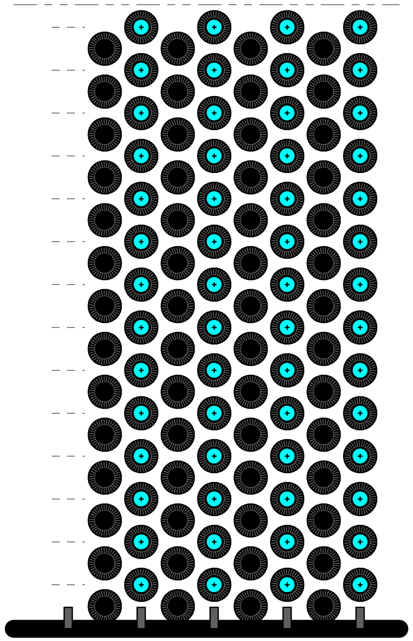
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPB
Date: 06/15/20	
Drawing No:	

IPE2 Hardware Design

Parallel HX

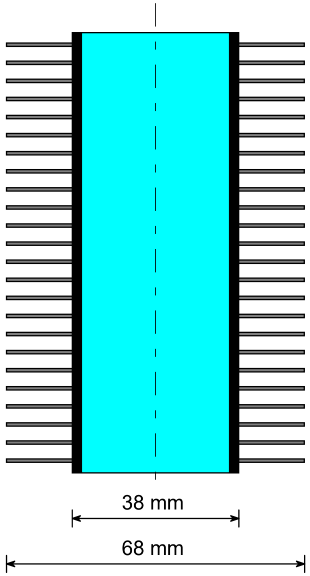


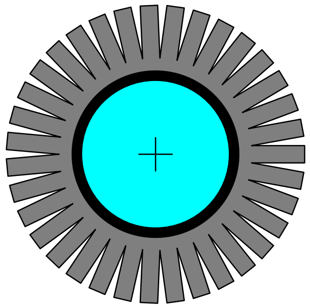
IPE2 (Parallel)

14 tube rows
14 tubes per row
Pl = 79 mm
Pt = 88.19 mm

Gas Out	Gas In
183.8 T	233.5 T
43.92 m	43.92 m

Water In	Water Out
26.36 p	25.43 p
143.3 T	218.8 T
604.9 h	938.2 h
9.647 m	9.647 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.339 mm
Fin thickness	0.8 mm
Number of fins per meter	241.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	88.19 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	14
Tube length	20.4 m
Gas path transverse width	1.279 m
Gas path frontal area	26.09 m^2
HX total outside surface area	5089 m^2
Maximum gas velocity	4.733 m/s
Gas pressure drop	1.198 millibar
Water side velocity	0.8666 m/s
Water side pressure drop	0.9346 bar
Heat transfer from gas	3231 kW
Heat transfer to water	3215 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

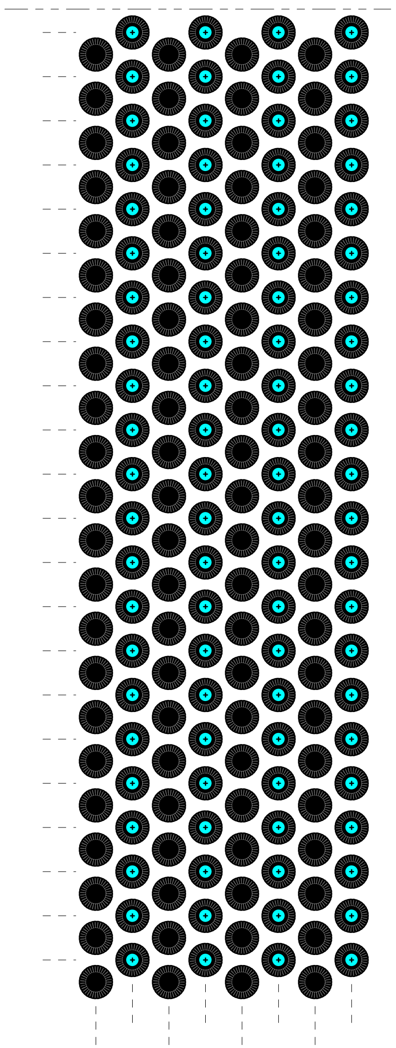
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPE2 (Parallel)
Date: 06/15/20	
Drawing No:	

HPE0 Hardware Design

Parallel HX



HPE0 (Parallel)

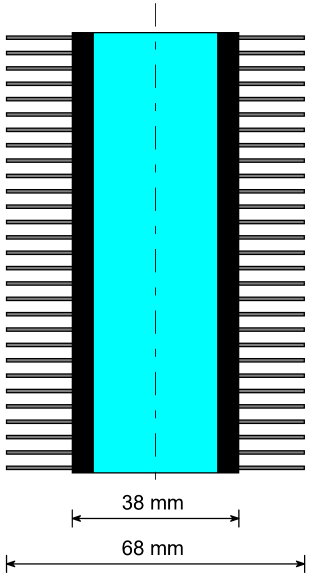
14 tube rows
170 tubes per row
Pl = 79 mm
Pt = 91.12 mm

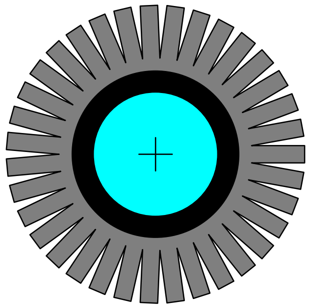
Gas Out
183.8 T
519.5 m

Gas In
233.5 T
519.5 m

Water In
145.2 p
150.2 T
641.8 h
75.54 m

Water Out
143.7 p
231.1 T
998 h
75.54 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.699 mm
Fin thickness	0.8 mm
Number of fins per meter	285.8
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.12 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	170
Tube length	20.4 m
Gas path transverse width	15.54 m
Gas path frontal area	316.9 m^2
HX total outside surface area	72030 m^2
Maximum gas velocity	4.519 m/s
Gas pressure drop	1.198 millibar
Water side velocity	0.7903 m/s
Water side pressure drop	1.528 bar
Heat transfer from gas	27040 kW
Heat transfer to water	26906 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

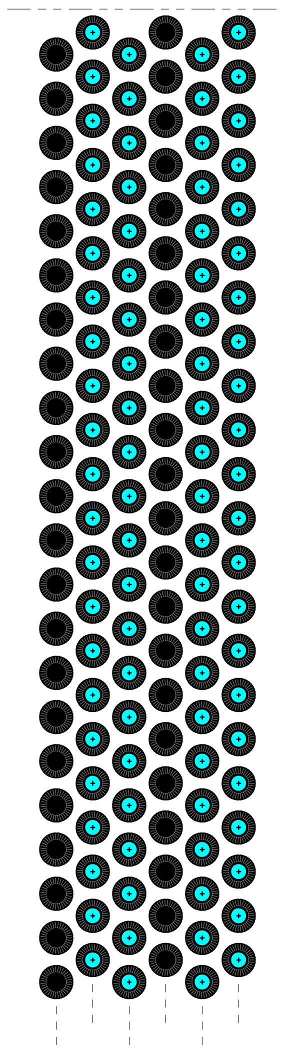
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE0 (Parallel)
Date: 06/15/20	
Drawing No:	

LPB Hardware Design

Parallel HX



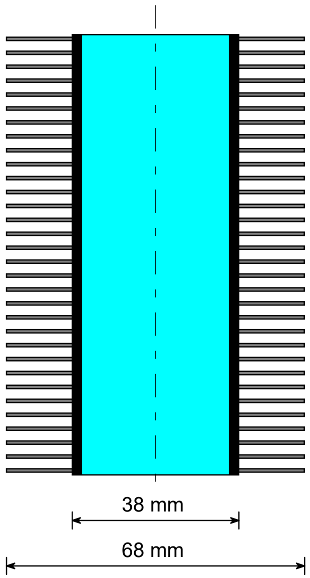
LPB
6 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

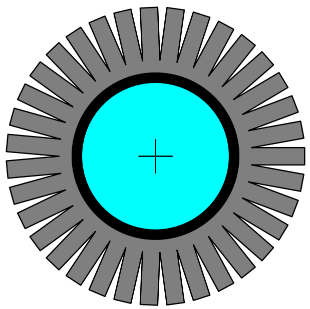
Gas Out
149.4 T
563.5 m

Gas In
183.8 T
563.5 m

Water In
4.023 p
140.8 T
592.4 h
9.647 m

Steam Out
4.023 p
143.8 T
2738.3 h
9.647 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	2.359 mm
Fin thickness	0.8 mm
Number of fins per meter	316.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1.501
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	36720 m^2
Maximum gas velocity	4.191 m/s
Gas pressure drop	0.5018 millibar
Water side velocity	0.7603 m/s
Water side pressure drop	0 bar
Heat transfer from gas	20807 kW
Heat transfer to steam/water	20704 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

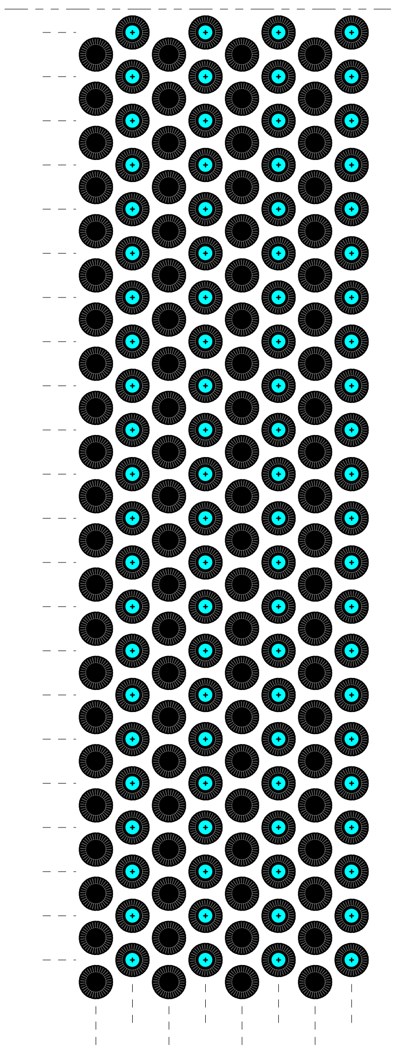
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPB
Date: 06/15/20	
Drawing No:	

LTE Hardware Design

Parallel HX



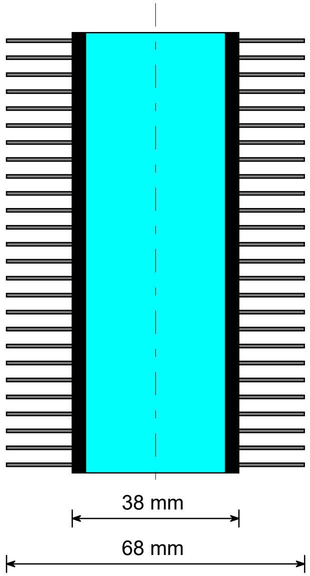
LTE
10 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

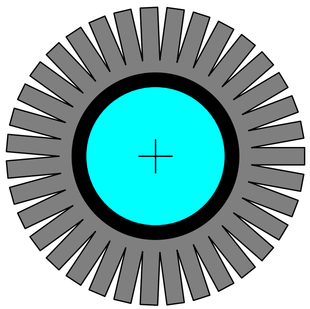
Gas Out
111.9 T
563.5 m

Gas In
149.4 T
563.5 m

Water In
3.753 p
89.77 T
376.6 h
103.8 m

Water Out
3.687 p
140.7 T
592.2 h
103.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	3.048 mm
Fin height	15 mm
Fin spacing	3.077 mm
Fin thickness	0.8 mm
Number of fins per meter	257.9
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	10
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	50703 m^2
Maximum gas velocity	3.733 m/s
Gas pressure drop	0.6271 millibar
Water side velocity	0.7455 m/s
Water side pressure drop	0.0659 bar
Heat transfer from gas	22501 kW
Heat transfer to water	22389 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

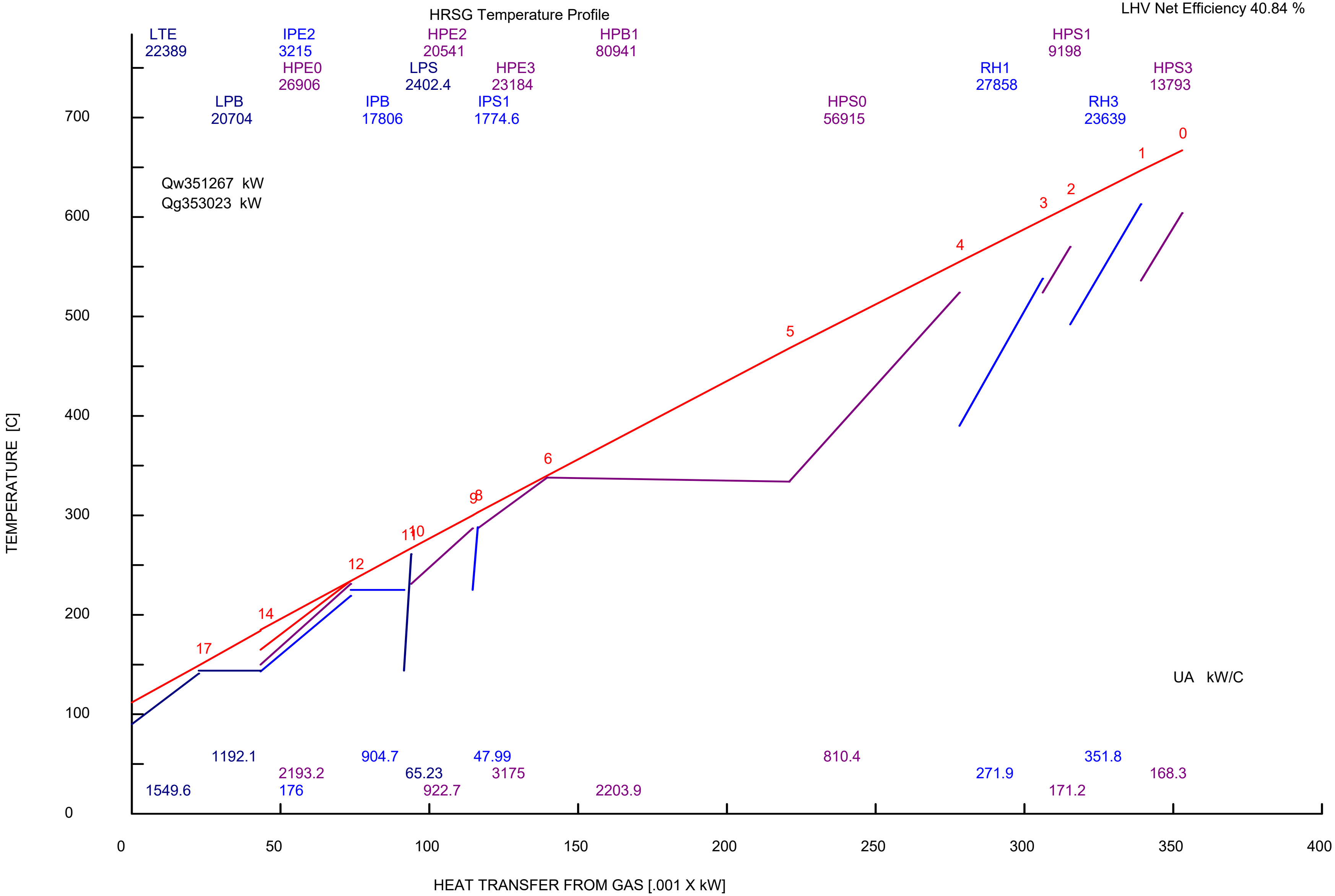
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LTE
Date: 06/15/20	
Drawing No:	

GT MASTER 29.0 AECOM

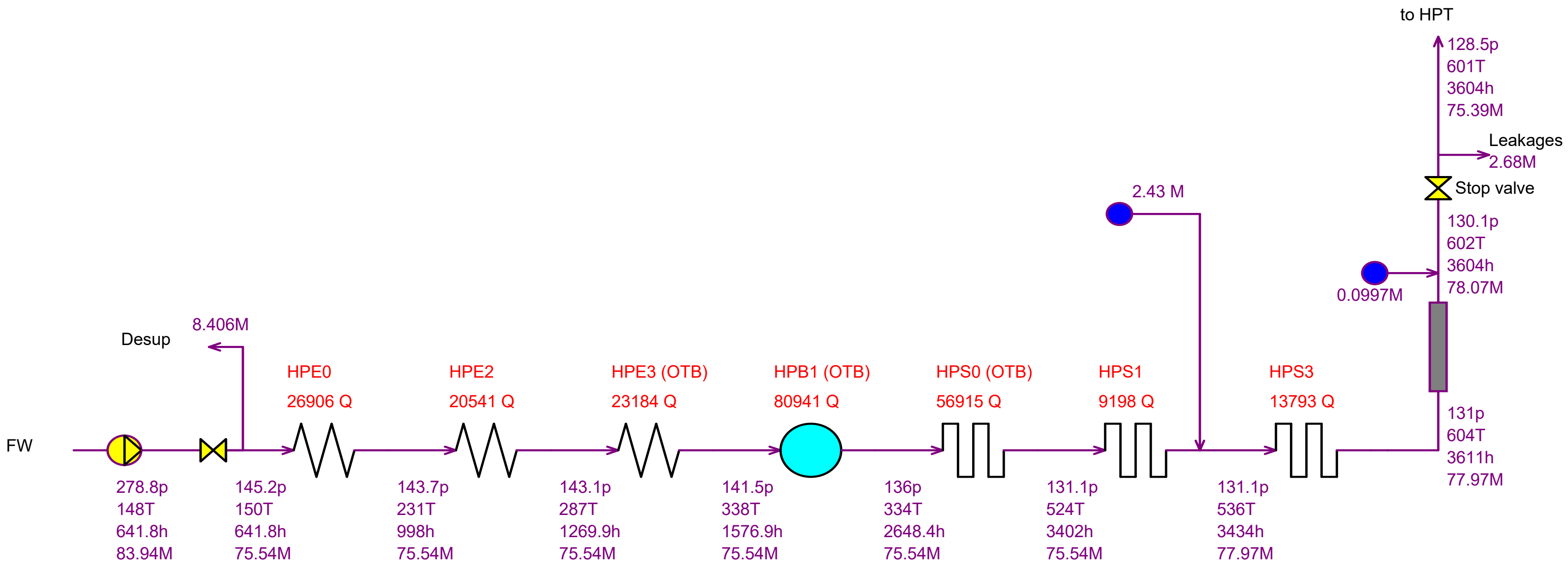
Net Power 251809 kW
LHV Net Heat Rate 8814 kJ/kWh
LHV Net Efficiency 40.84 %



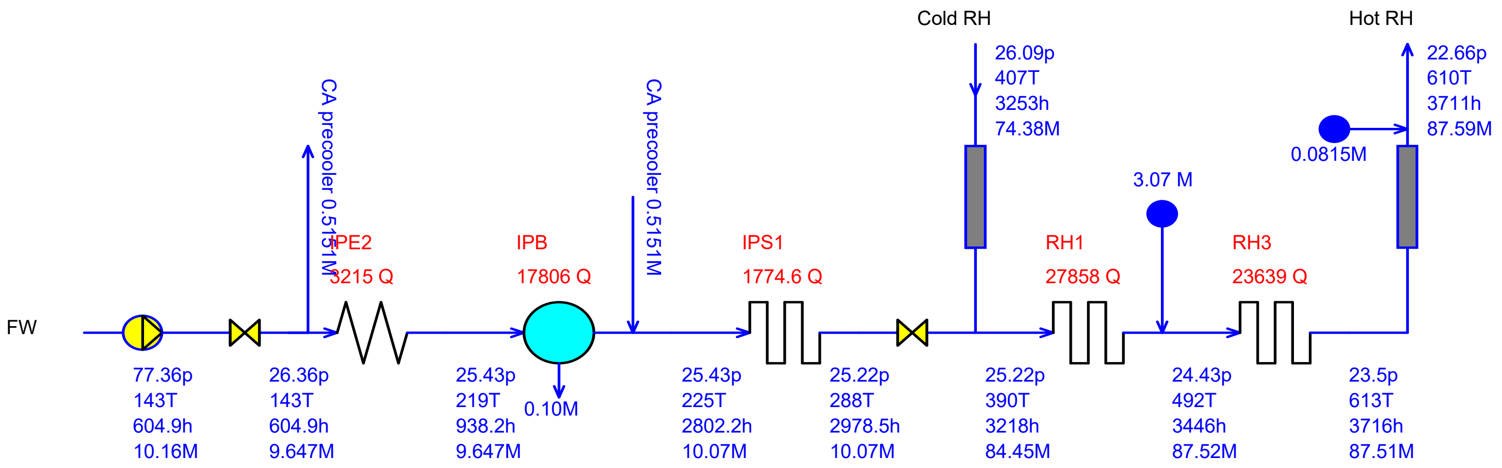
1220 06-11-2020 19:56:02 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

HP Water Path



IP & Reheat Water Path

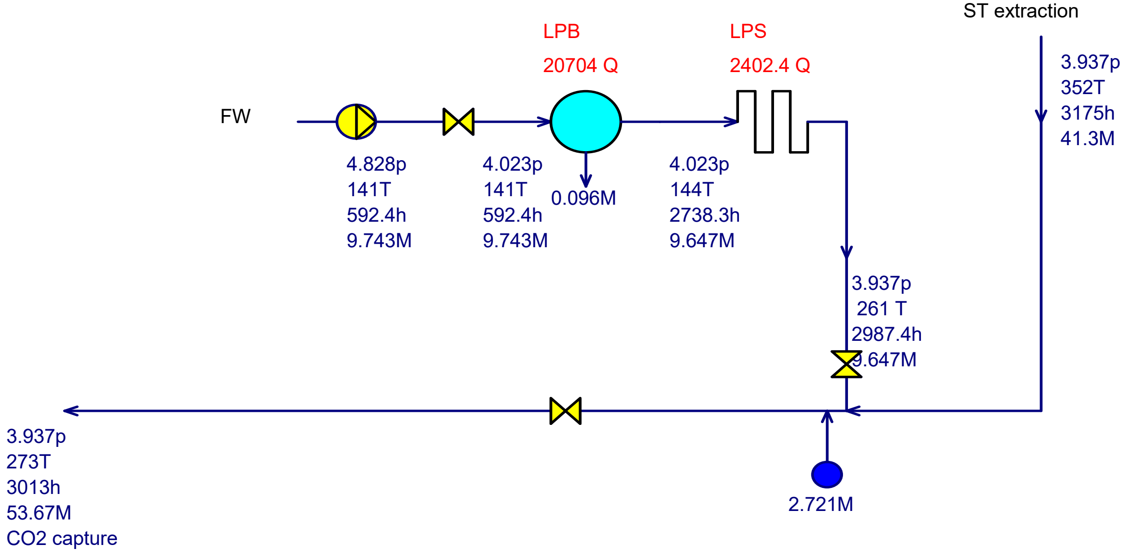


p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

1220 06-11-2020 19:56:02 file=

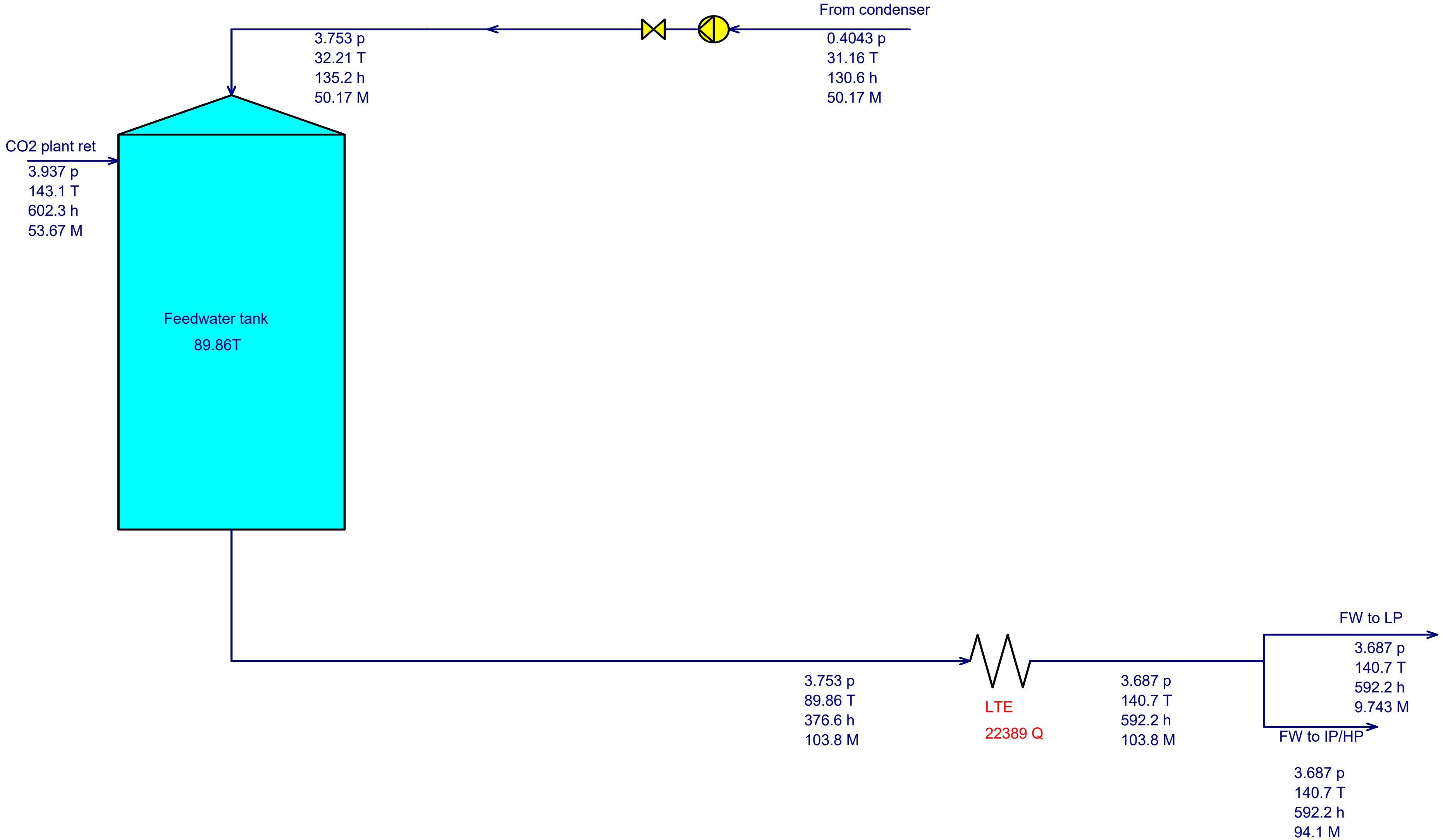
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

LP Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

Feedwater Path

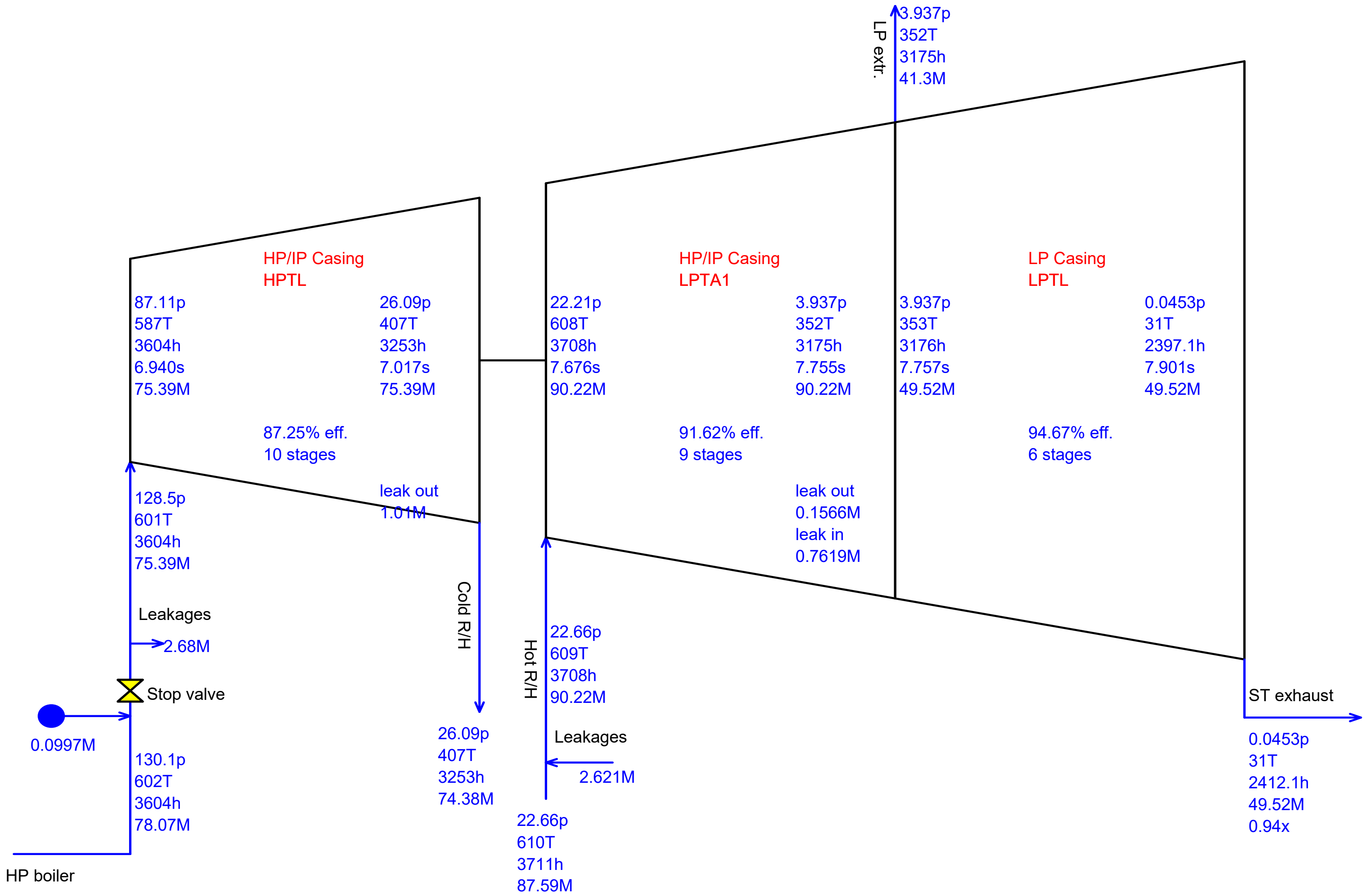


p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

1220 06-11-2020 19:56:02 file= Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

ST Expansion Power 112376 kW
ST Generator Output 110206 kW

Steam Turbine Group Data

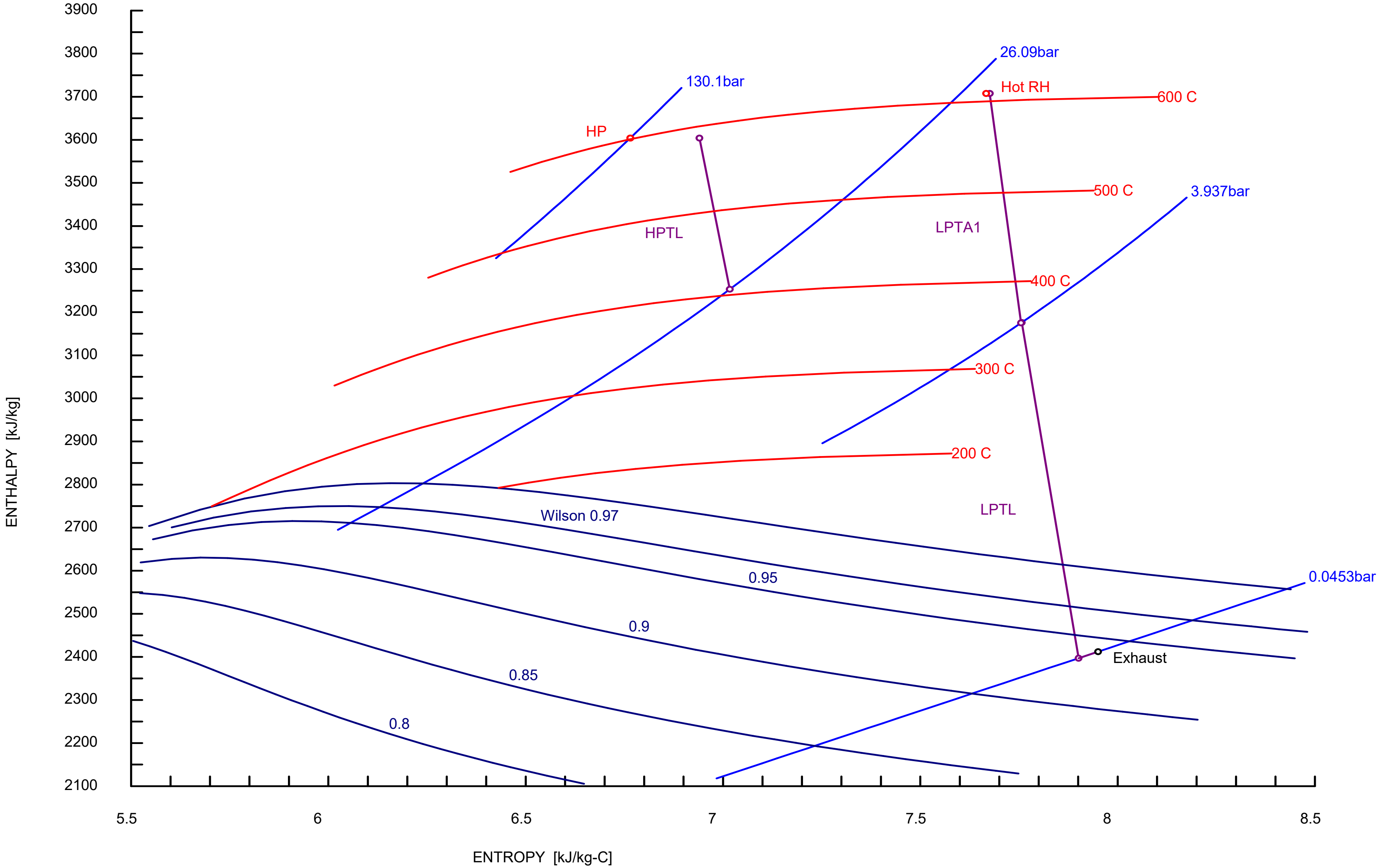


ST Model Adjustments: Disabled
p[bar], T[C], h[kJ/kg], s[kJ/kg-C], M[kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 19:56:02 file=

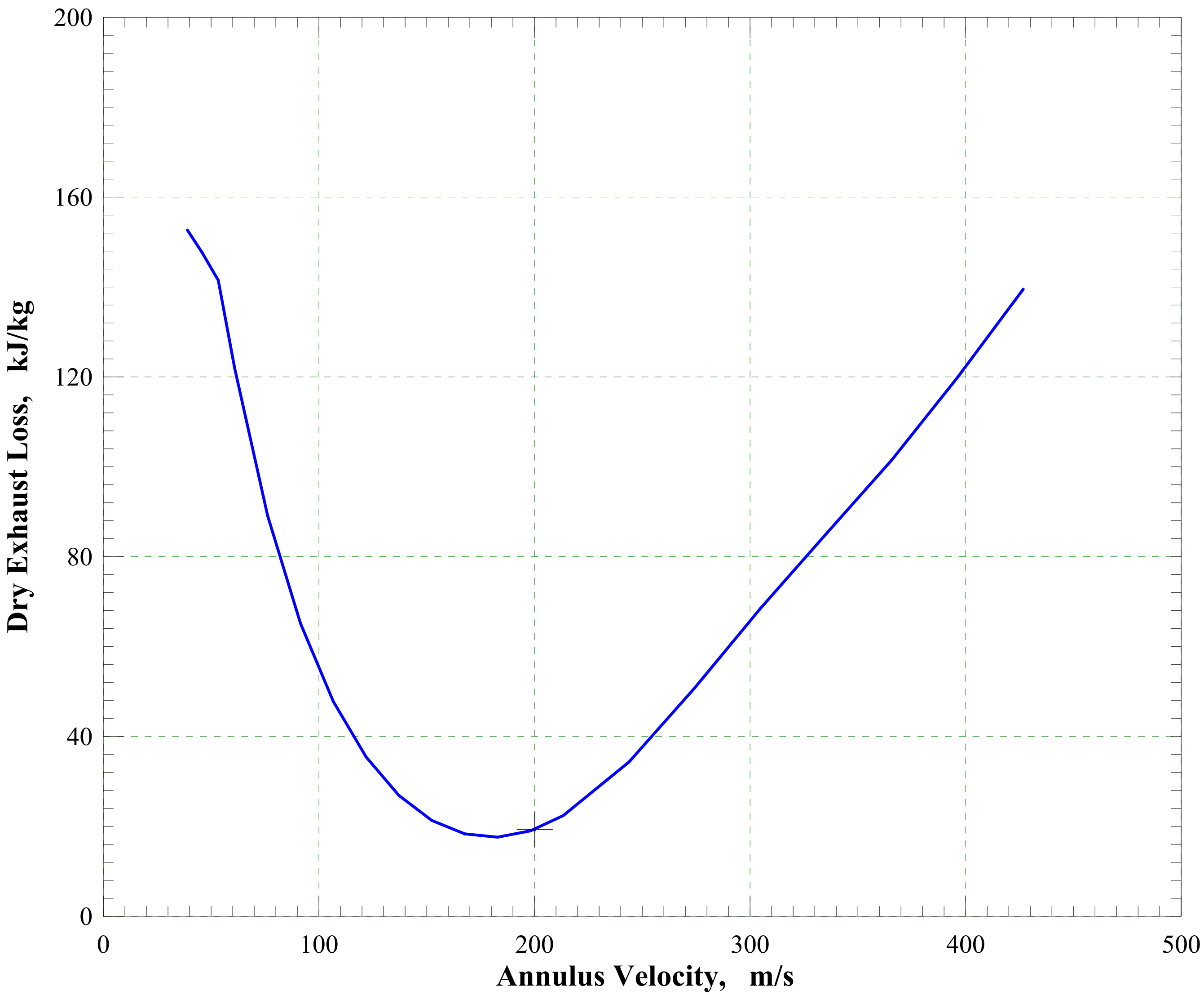
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

ST Expansion Power 112376 kW
ST Generator Output 110206 kW

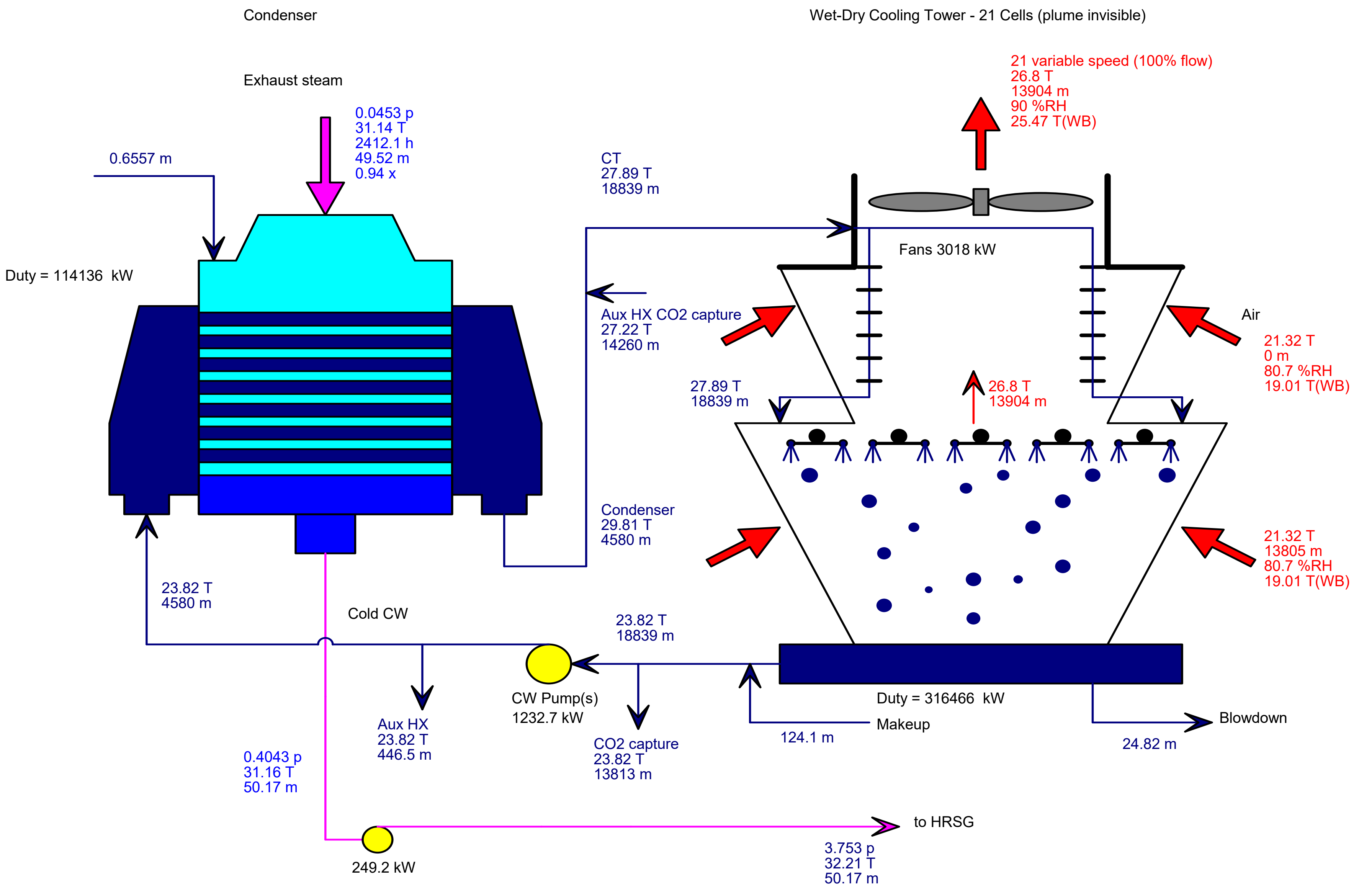
Steam Turbine Expansion Path



Steam Turbine Exhaust Loss



Cooling System

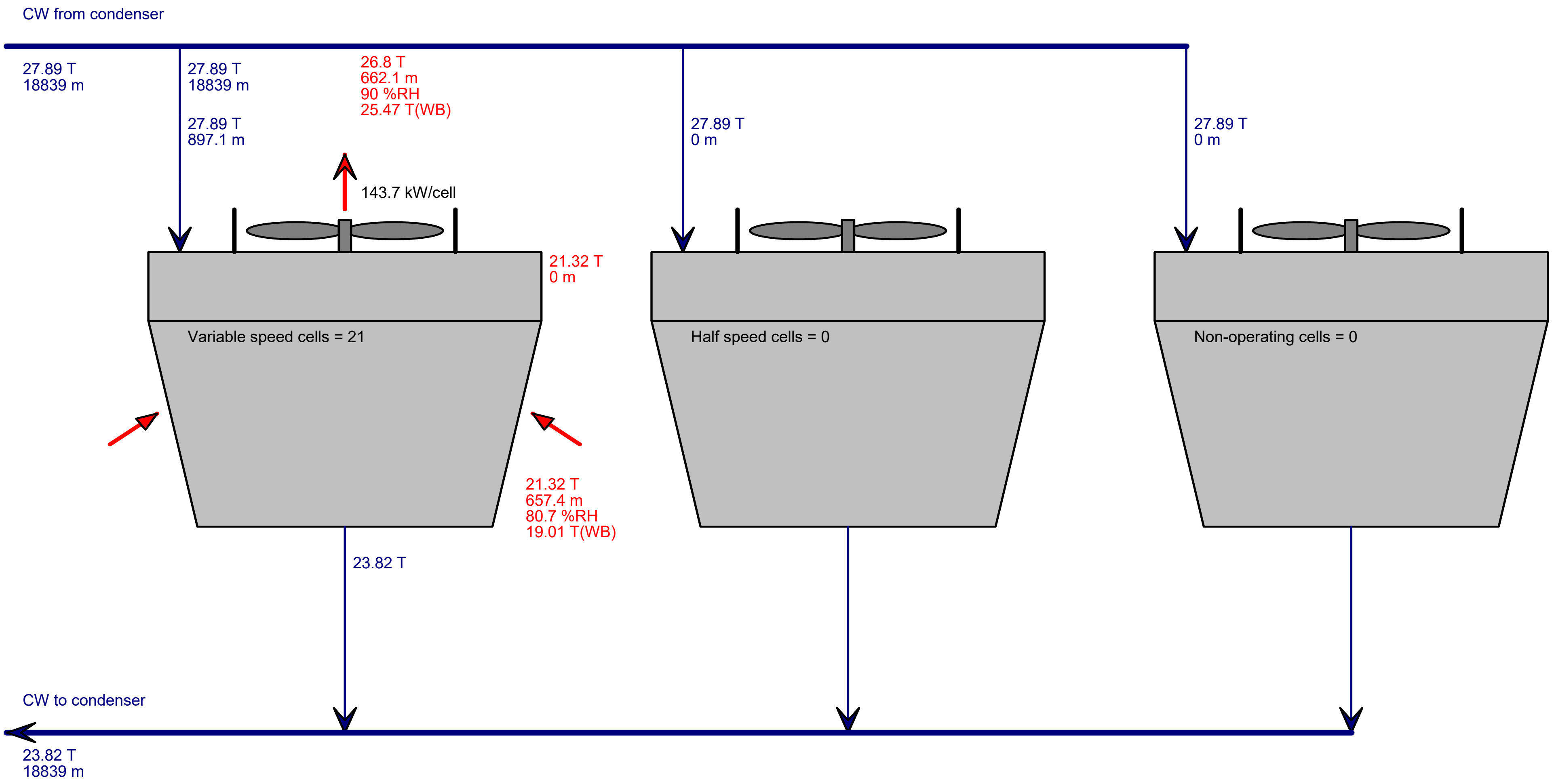


p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

1220 06-11-2020 19:56:02 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Cooling Tower Cells - 21 existing cells

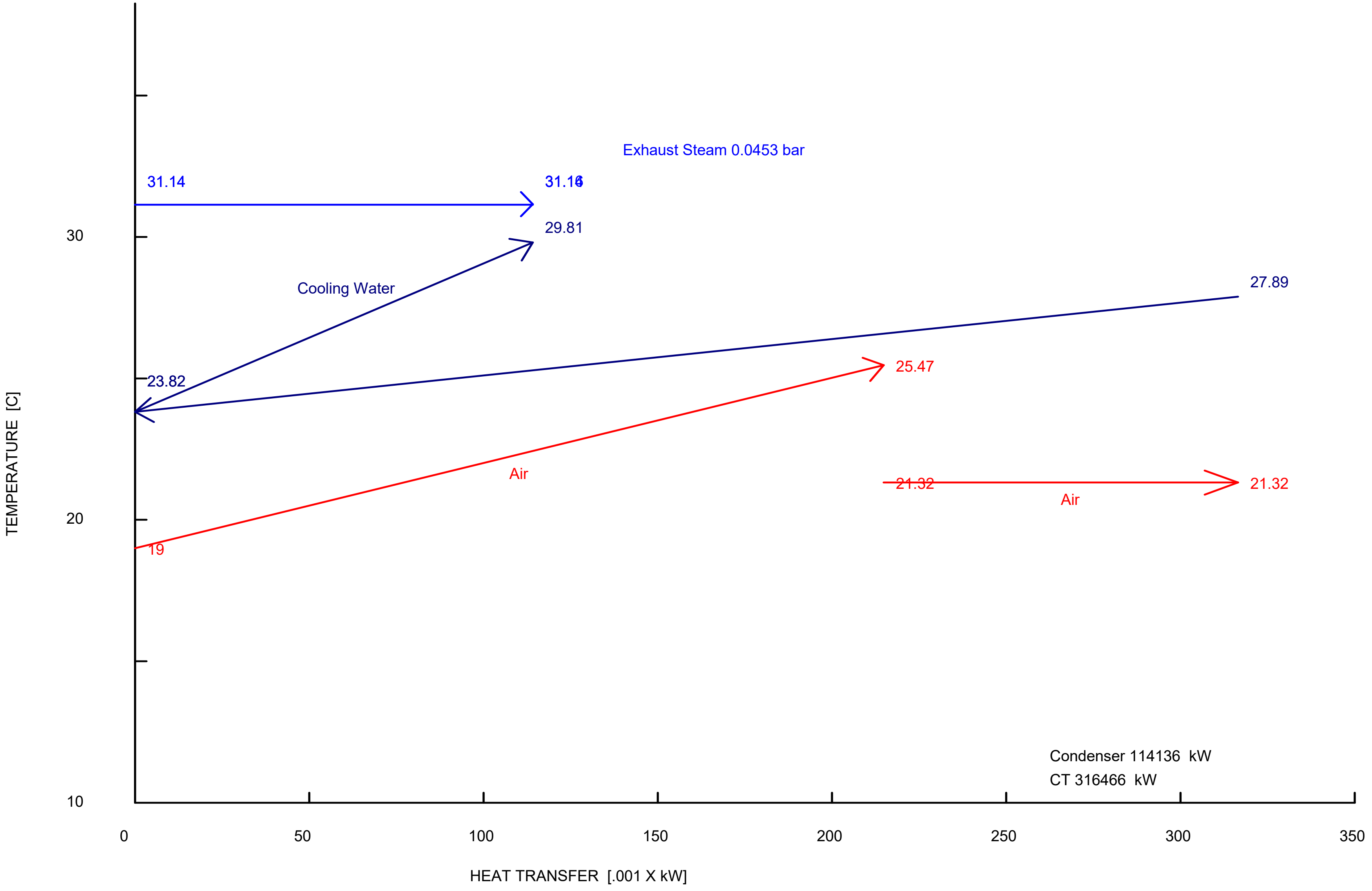


p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

1220 06-11-2020 19:56:02 file=

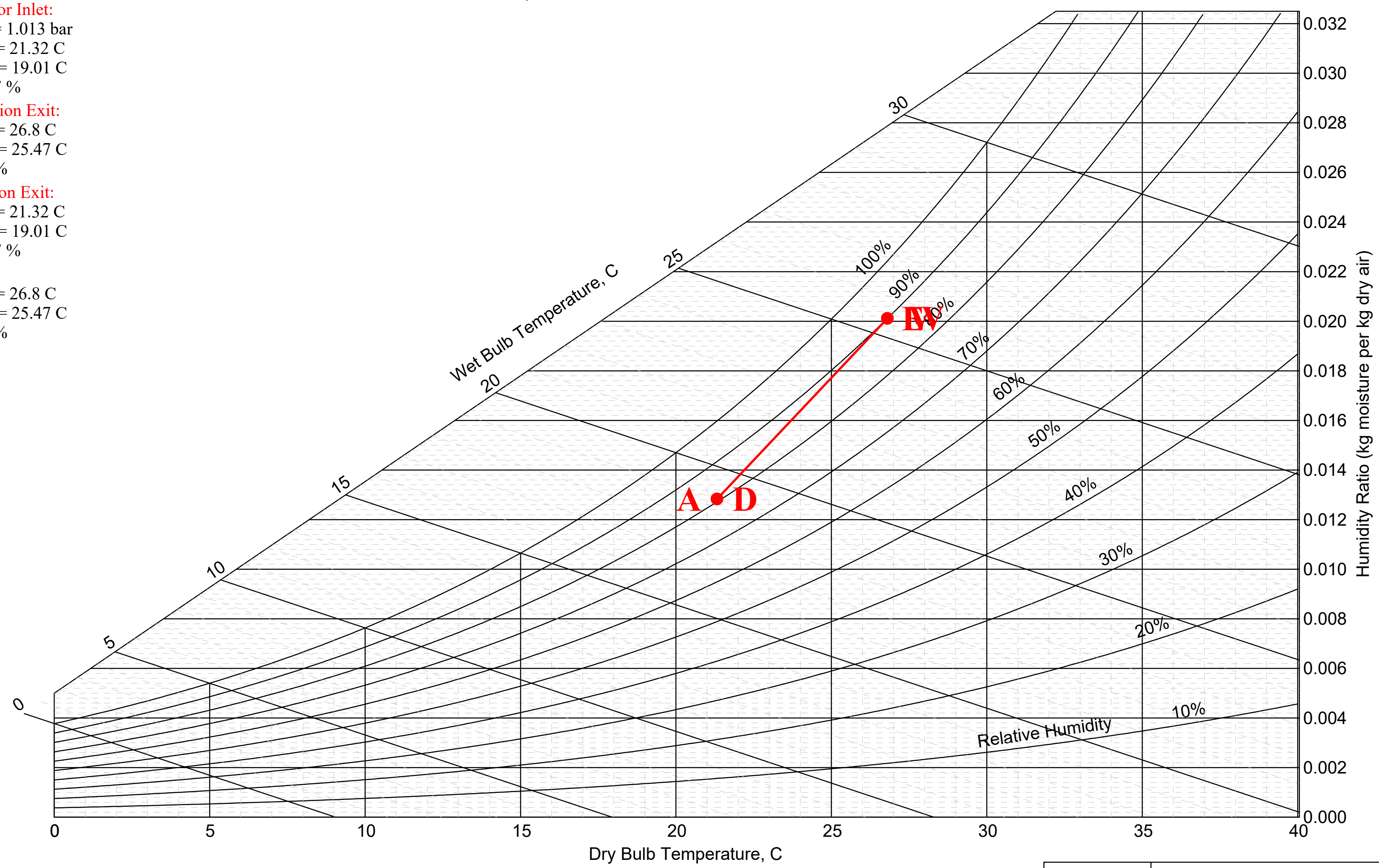
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Water Cooled Condenser and Wet-Dry Cooling Tower T-Q Diagram



AIR STATES:
A) Ambient or Inlet:
Pressure = 1.013 bar
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %
W) Wet Section Exit:
Dry bulb = 26.8 C
Wet bulb = 25.47 C
RH = 90 %
D) Dry Section Exit:
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %
E) Air Exit:
Dry bulb = 26.8 C
Wet bulb = 25.47 C
RH = 90 %

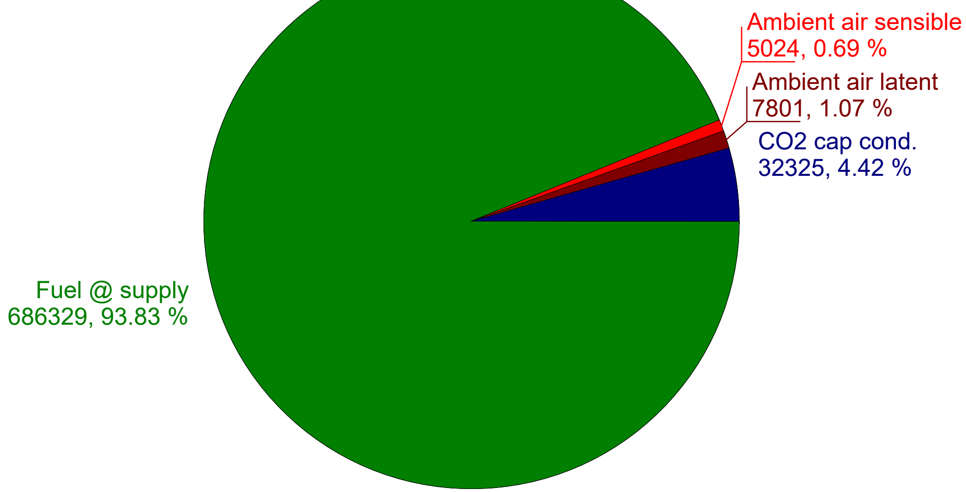
Psychrometric Chart



Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Cooling Tower
Date: 06/15/20	
Drawing No:	

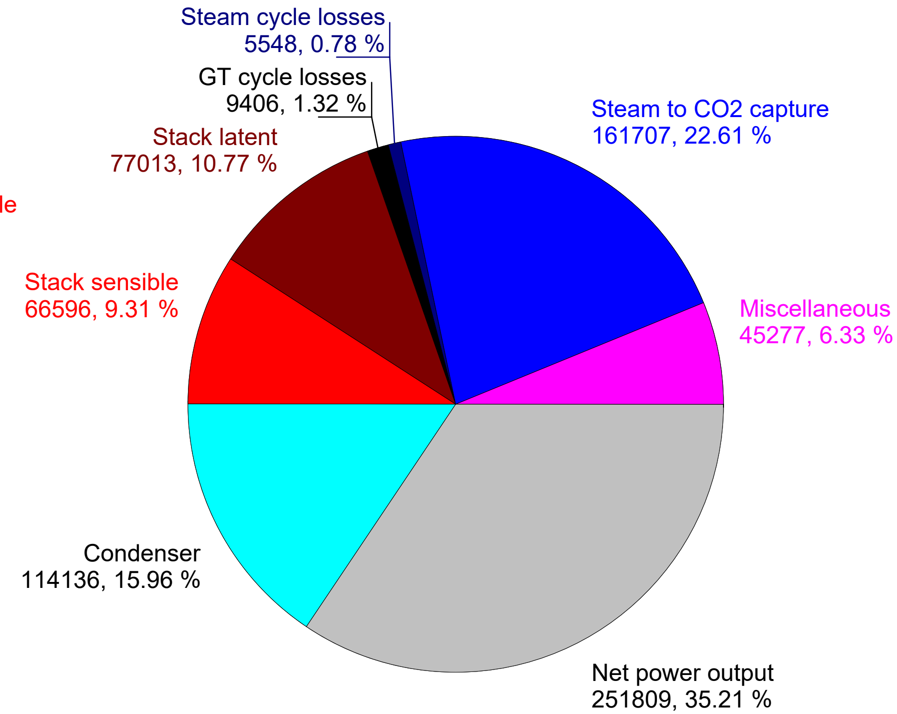
Plant Energy In [kW]

Plant energy in = 731493 kW
Plant fuel chemical LHV input = 616511 kW, HHV = 684088 kW
Plant net LHV elec. eff. = 40.84 % (100% * 251809 / 616511), Net HHV elec. eff. = 36.81 %



Plant Energy Out [kW]

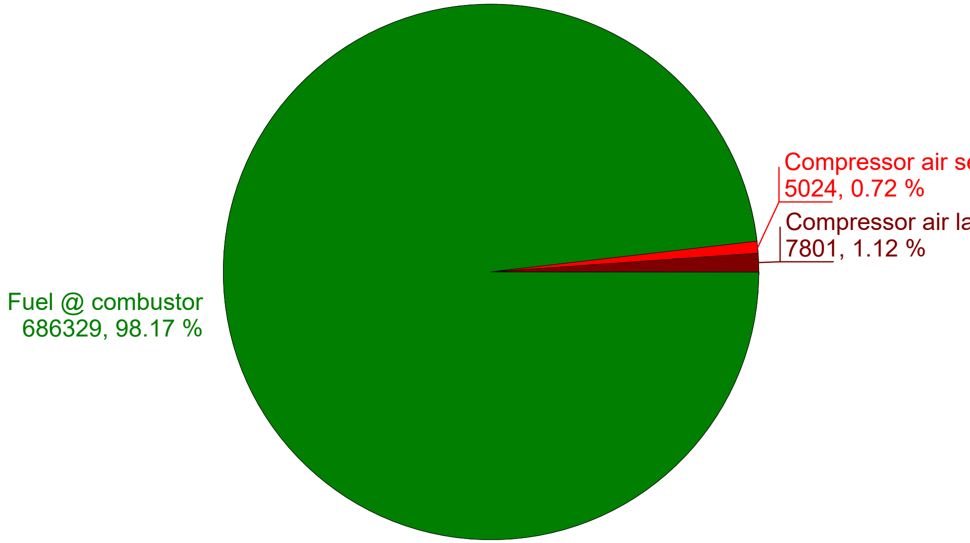
Plant energy out = 715230 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

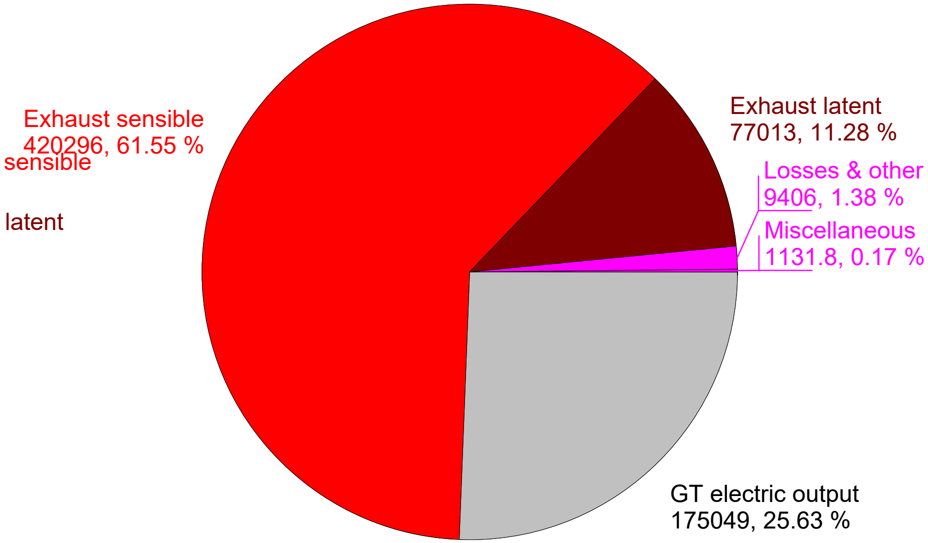
GT Cycle Energy In [kW]

GT cycle energy in = 699153 kW
GT fuel chemical LHV input = 616510 kW, HHV = 684088 kW



GT Cycle Energy Out [kW]

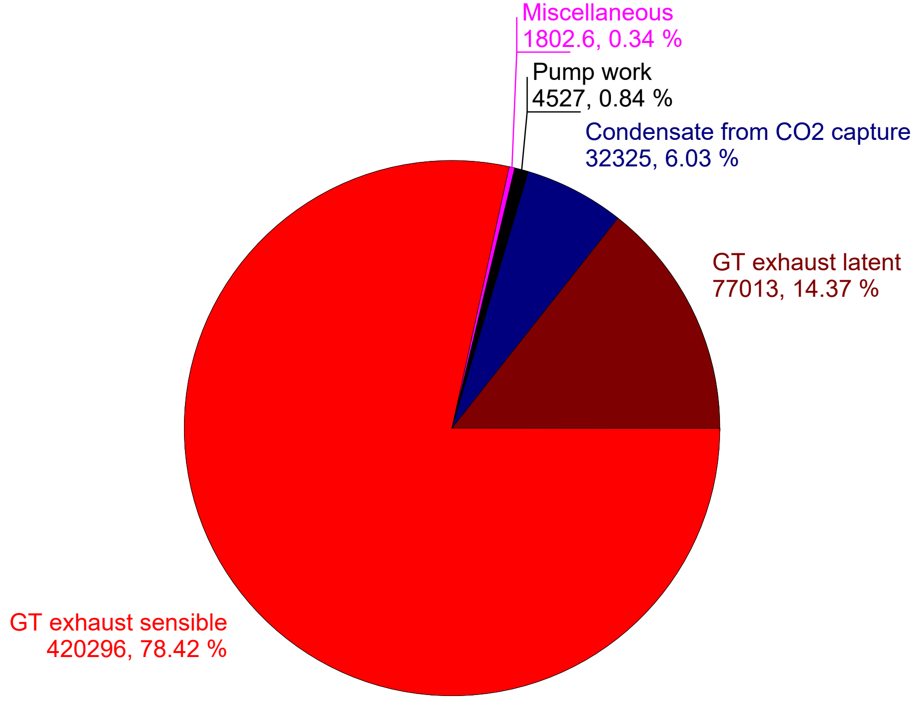
GT cycle energy out = 682897 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

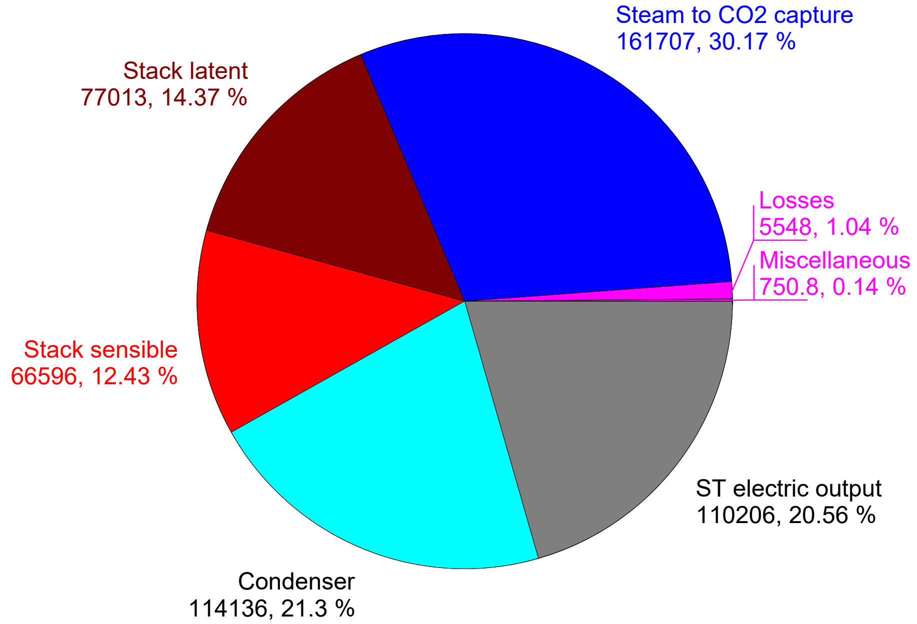
Steam Cycle Energy In [kW]

Steam cycle energy in = 535965 kW



Steam Cycle Energy Out [kW]

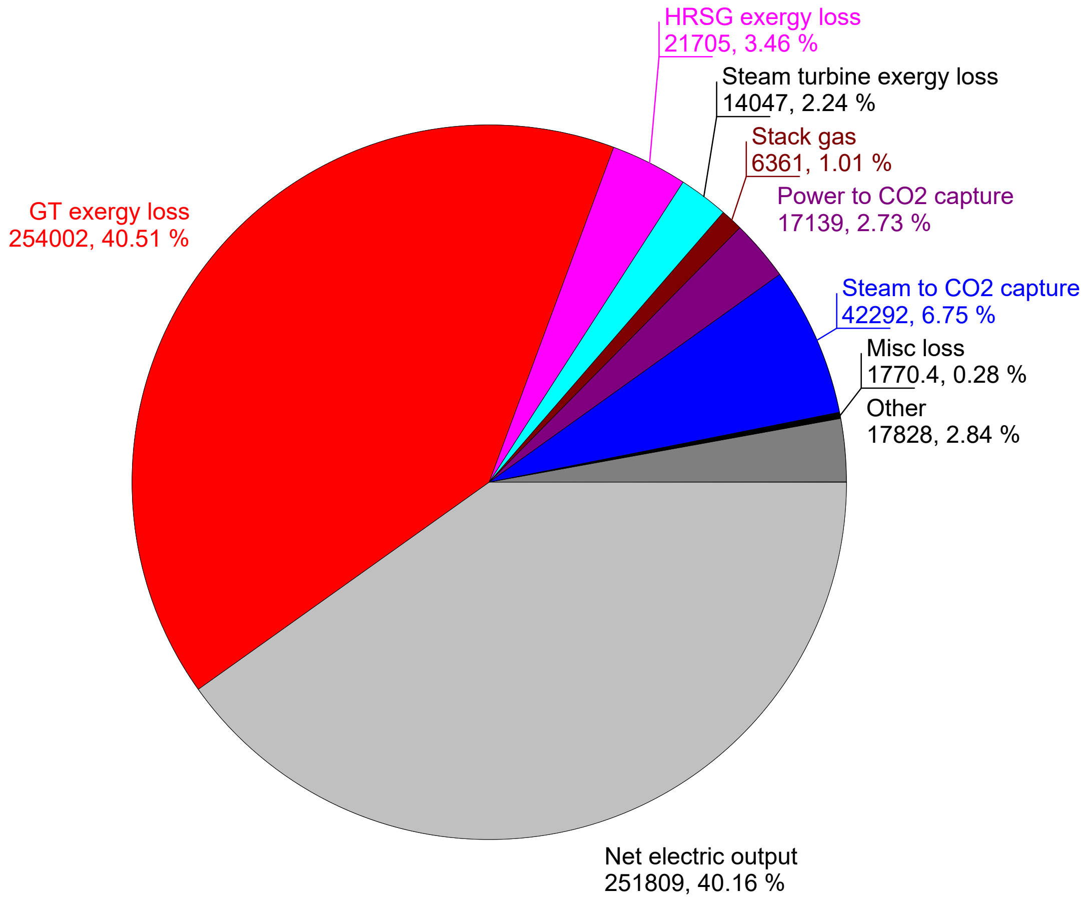
Steam cycle energy out = 535958 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Plant Exergy Analysis [kW]

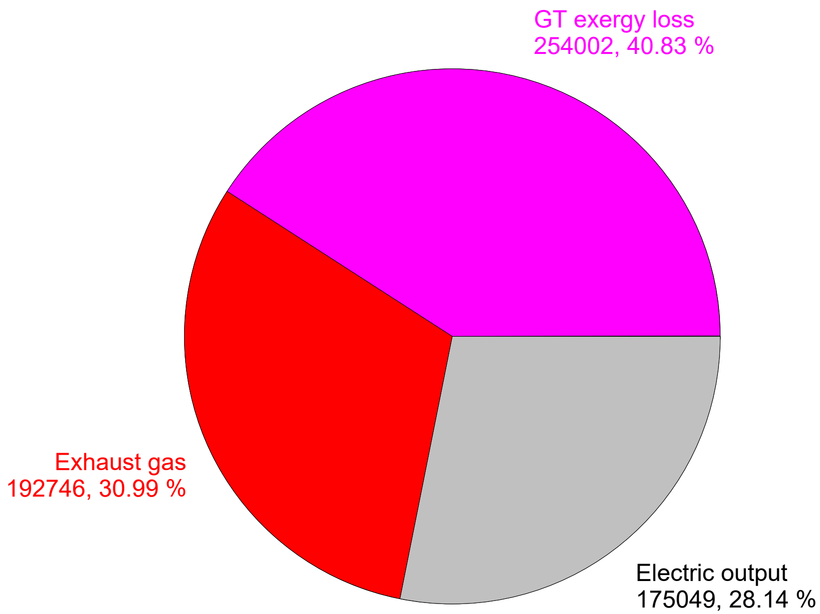
Plant exergy input = 626952 kW
Fuel exergy input = 622441 kW
Plant fuel chemical LHV input = 616511 kW, HHV = 684088 kW



Reference: 1.013 bar, 25 C, water as vapor.

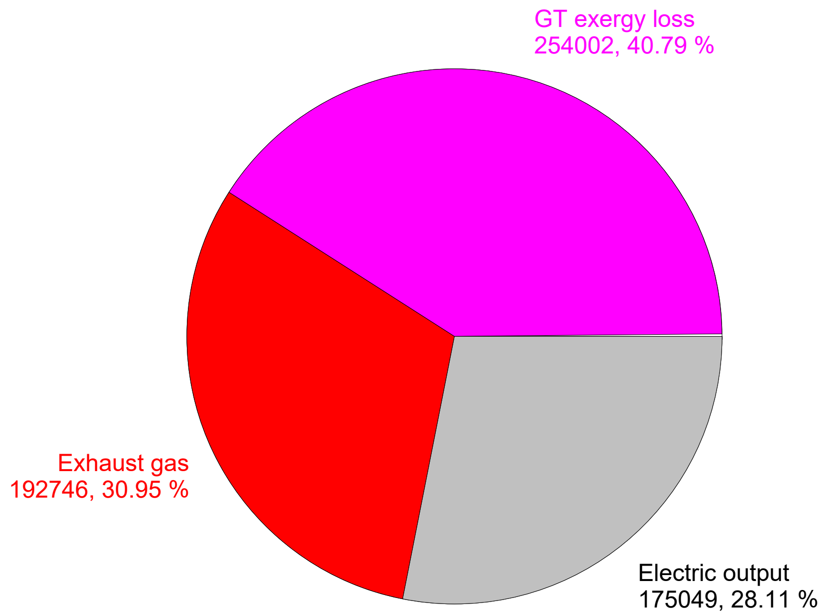
GT Exergy Analysis [kW]

GT exergy in = 622037 kW



GT & Peripheral Exergy Analysis [kW]

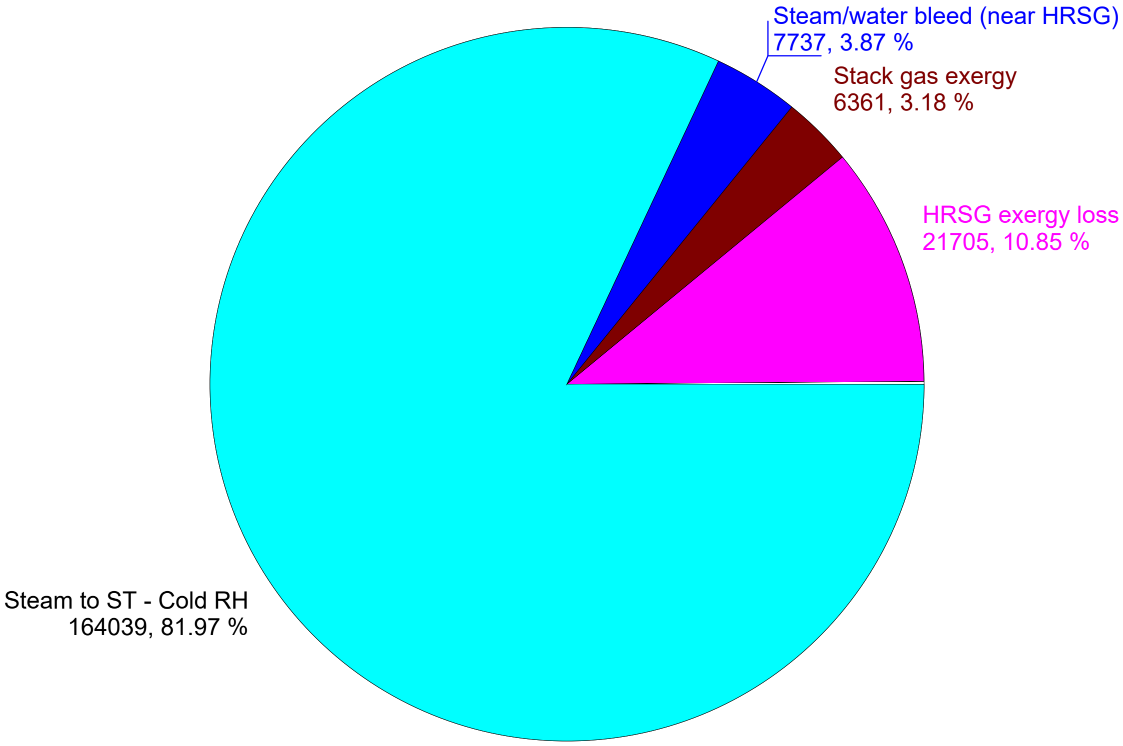
GT & peripheral exergy in = 622690 kW



Reference: 1.013 bar, 25 C, water as vapor.

HRSG Exergy Analysis [kW]

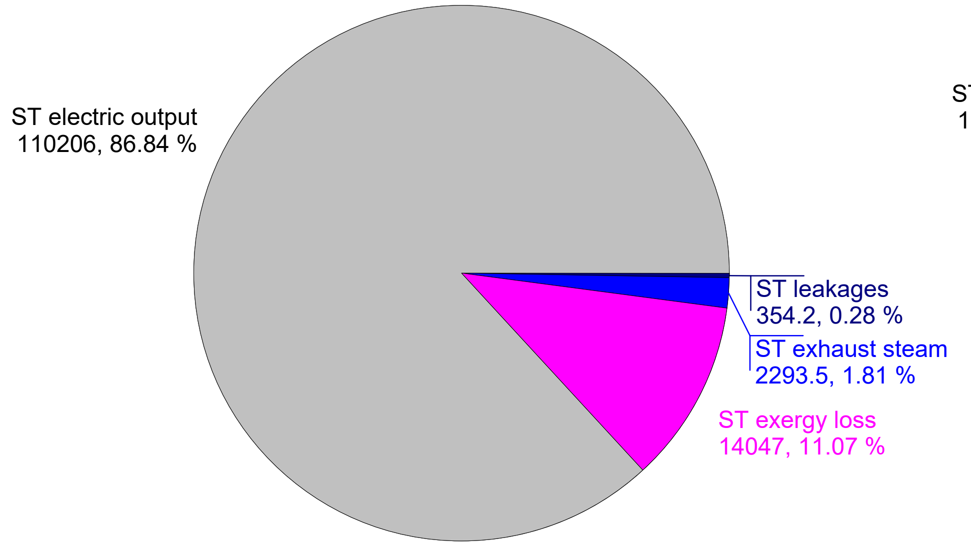
HRSG exergy in = 200118 kW



Reference: 1.013 bar, 25 C, water as vapor.

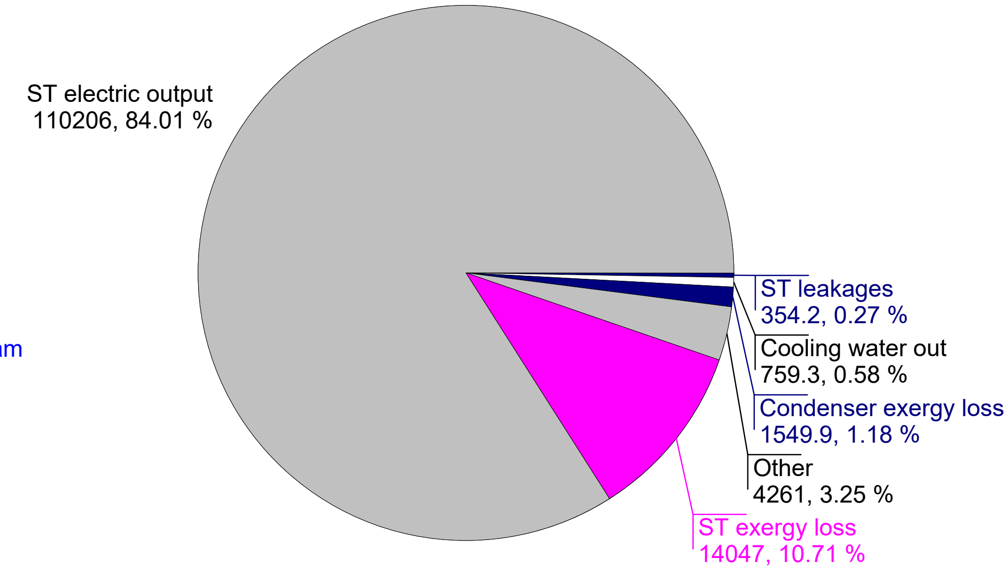
ST Exergy Analysis [kW]

ST exergy in = 126900 kW



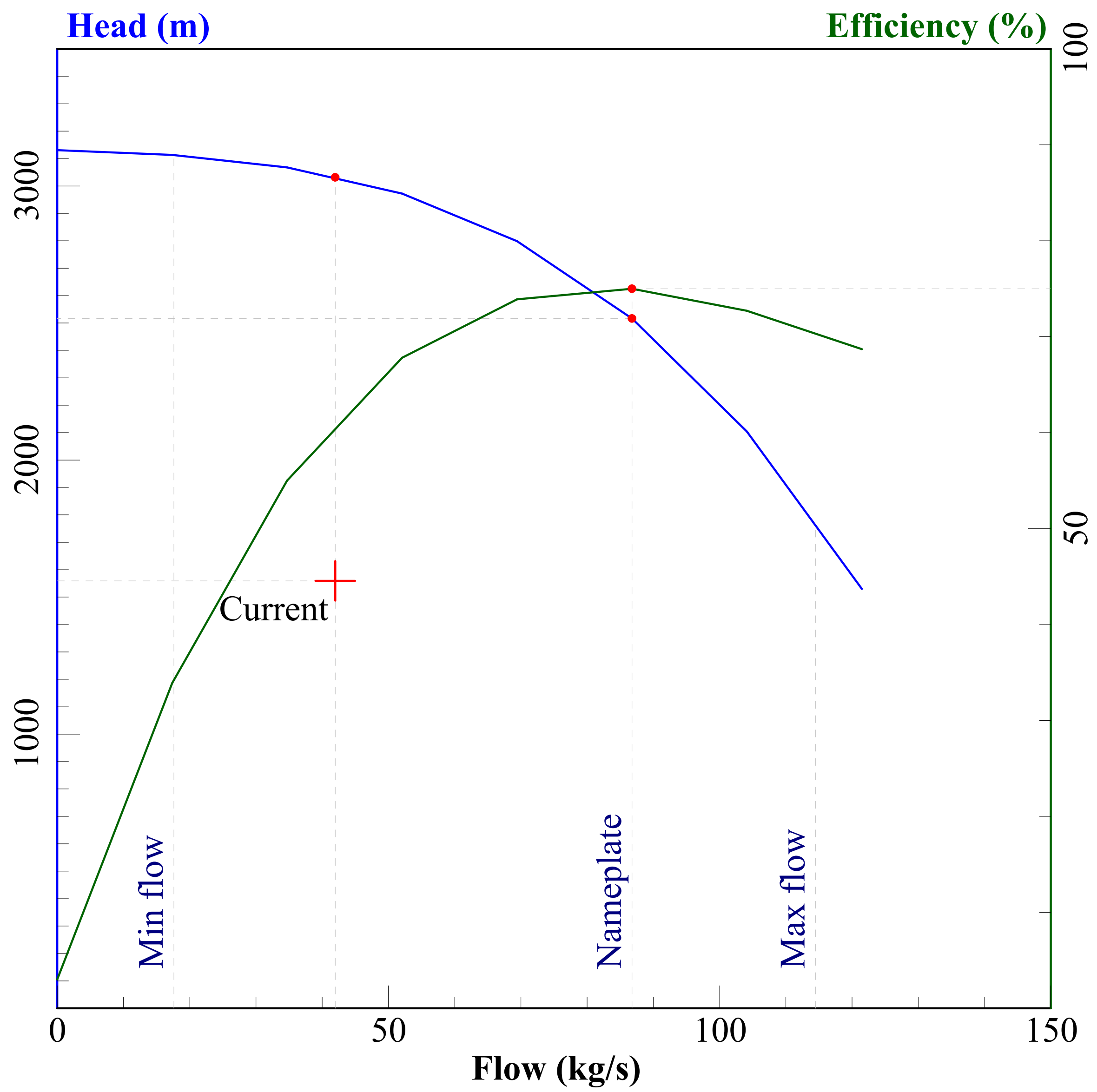
ST & Condenser Exergy Analysis [kW]

ST & condenser exergy in = 131177 kW



Reference: 1.013 bar, 25 C, water as vapor.

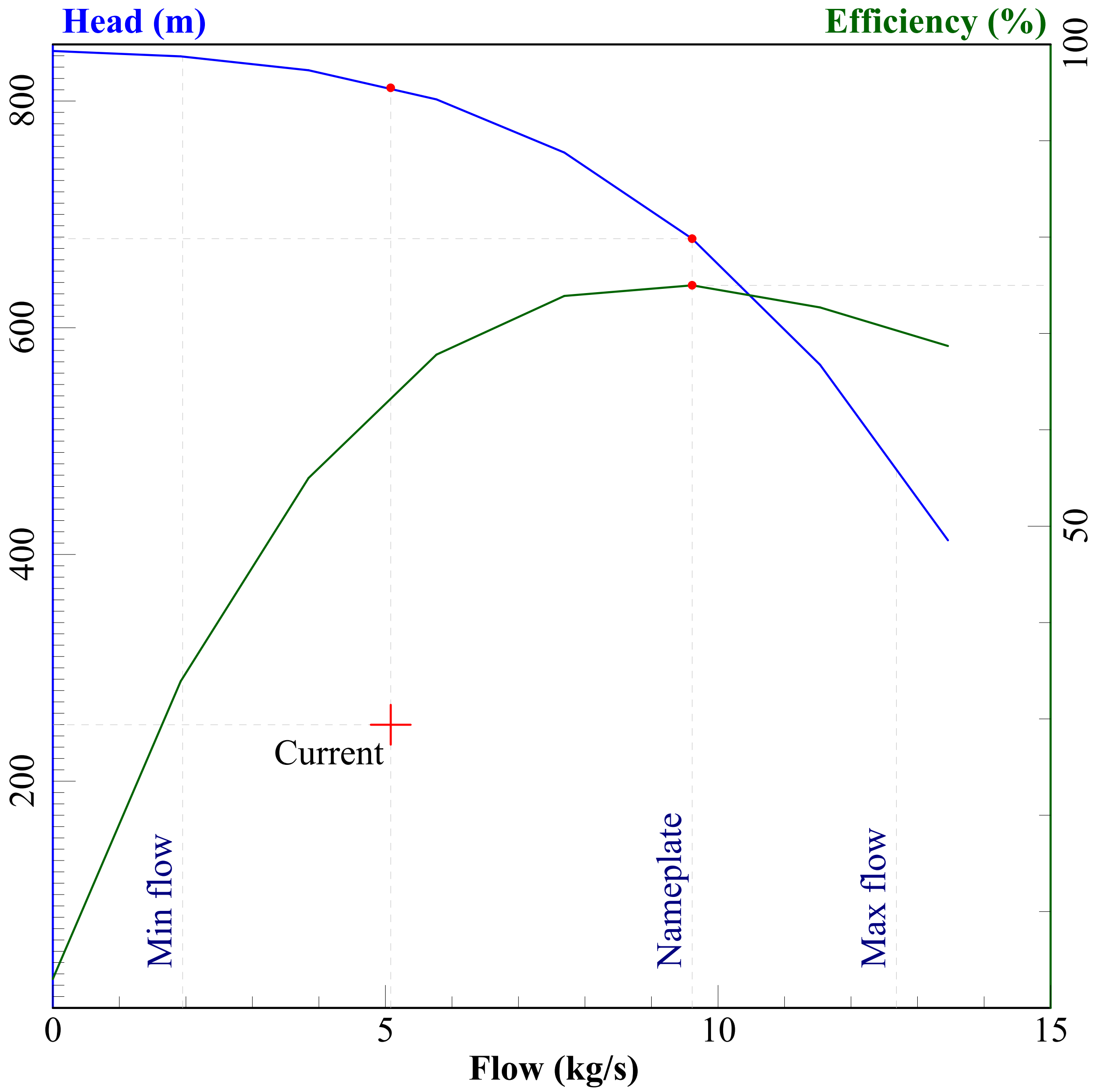
HP Feedwater Pump (P1)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	86.77 kg/s
Nameplate head	2516.5 m
Nameplate flow (nominal)	5678 lpm
Nameplate head (nominal)	2560.3 m
Nameplate RPM	3000
Current pump flow	41.97 kg/s
Current head	3031 m
Current head after valve	1559.2 m
Current RPM	3000
Minimum continuous flow	17.61 kg/s
Maximum continuous flow	114.5 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HP Feedwater Pump (P1)
Date: 06/15/20	
Drawing No:	

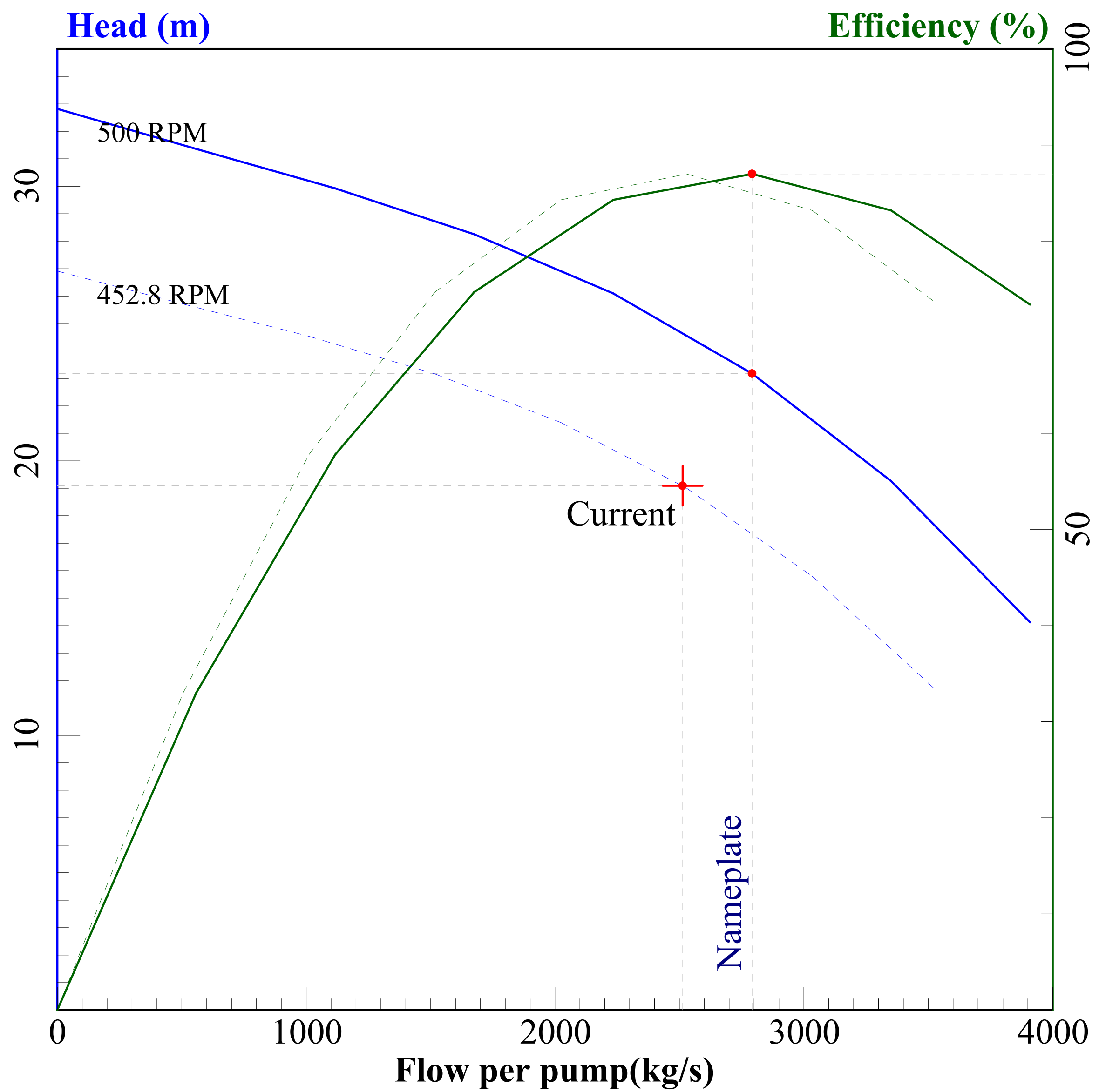
IP Feedwater Pump (P2)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	9.612 kg/s
Nameplate head	678.6 m
Nameplate flow (nominal)	662.4 lpm
Nameplate head (nominal)	701 m
Nameplate RPM	3000
Current pump flow	5.081 kg/s
Current head	811.7 m
Current head after valve	249.8 m
Current RPM	3000
Minimum continuous flow	1.951 kg/s
Maximum continuous flow	12.68 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IP Feedwater Pump (P2)
Date: 06/15/20	
Drawing No:	

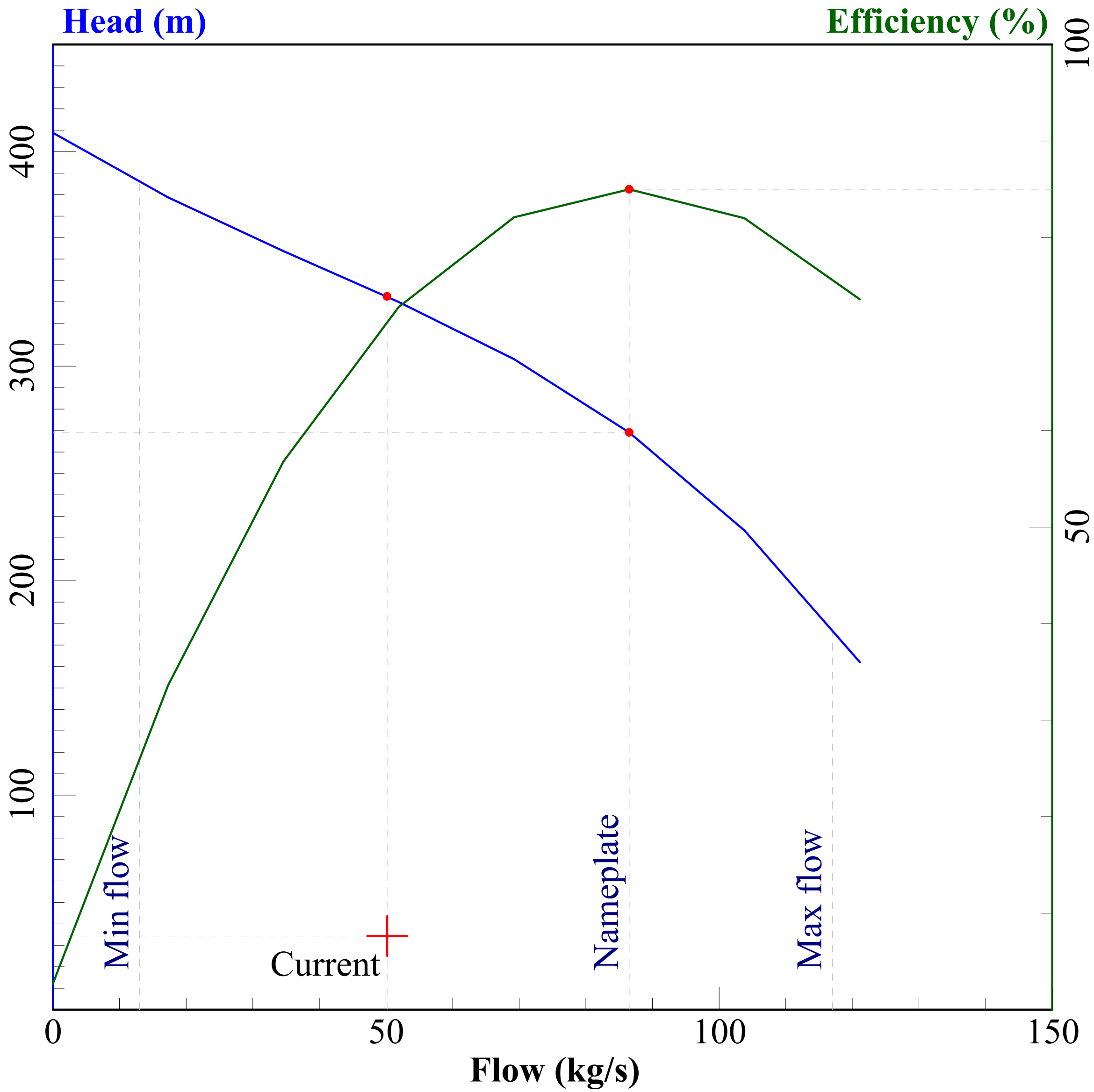
Condenser C.W. Pump (P4)



No. per Condenser	2
No. operating per Condenser	2
Nameplate flow	2792.3 kg/s
Nameplate head	23.18 m
Nameplate flow (nominal)	170344 lpm
Nameplate head (nominal)	24.38 m
Nameplate RPM	500
Current pump flow	2513 kg/s
Current head	19.09 m
Current head after valve	19.09 m
Current RPM	452.8

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condenser C.W. Pump (P4)
Date: 06/15/20	
Drawing No:	

Condensate Forwarding Pump (P6)



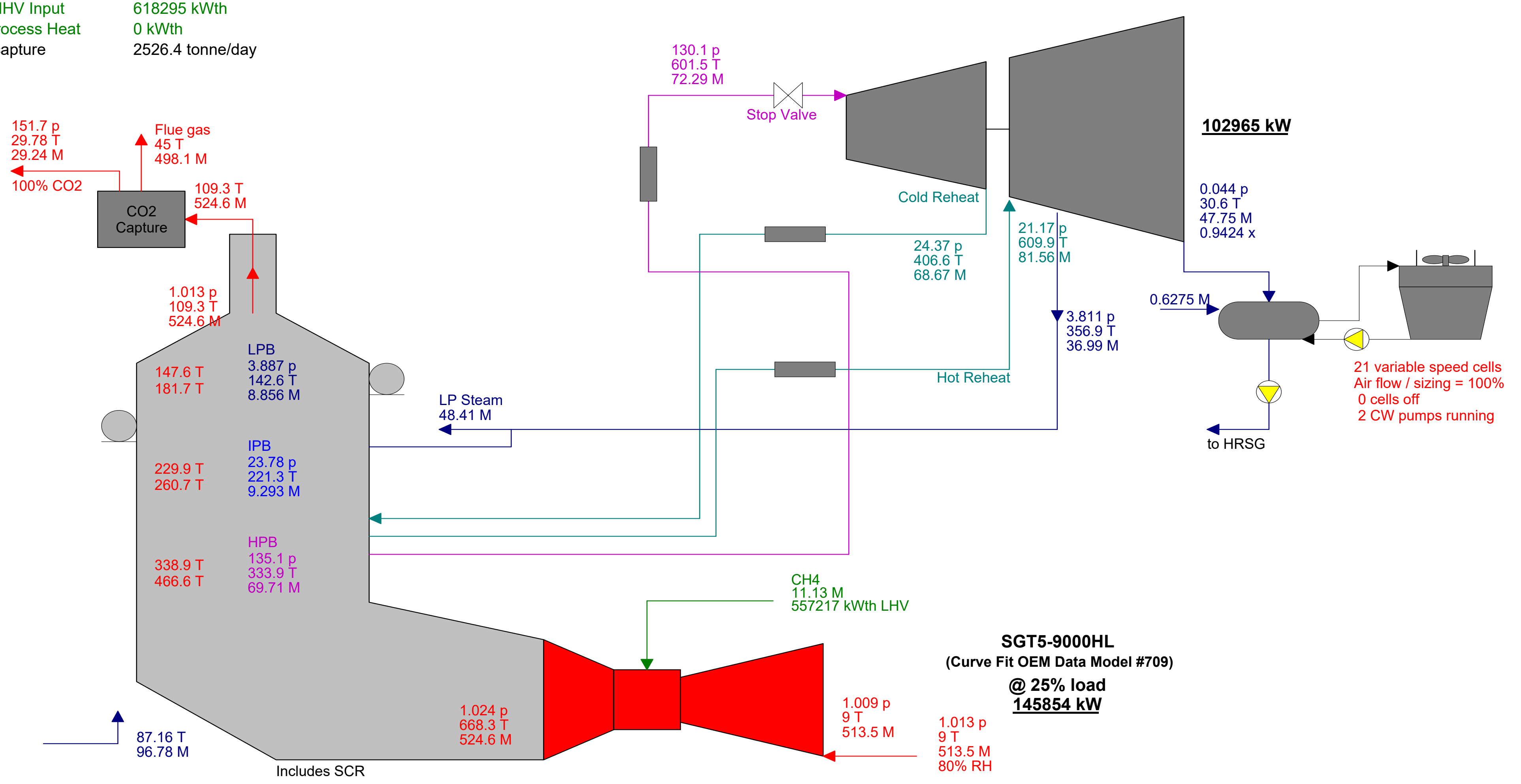
No. per Condenser	2
No. operating per Condenser	1
Nameplate flow	86.51 kg/s
Nameplate head	269.2 m
Nameplate flow (nominal)	5300 lpm
Nameplate head (nominal)	274.3 m
Nameplate RPM	1500
Current pump flow	50.17 kg/s
Current head	332.5 m
Current head after valve	34.31 m
Current RPM	1500
Minimum continuous flow	13 kg/s
Maximum continuous flow	117 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condensate Forwarding Pump (P6)
Date: 06/15/20	
Drawing No:	

GT MASTER 29.0 AECOM

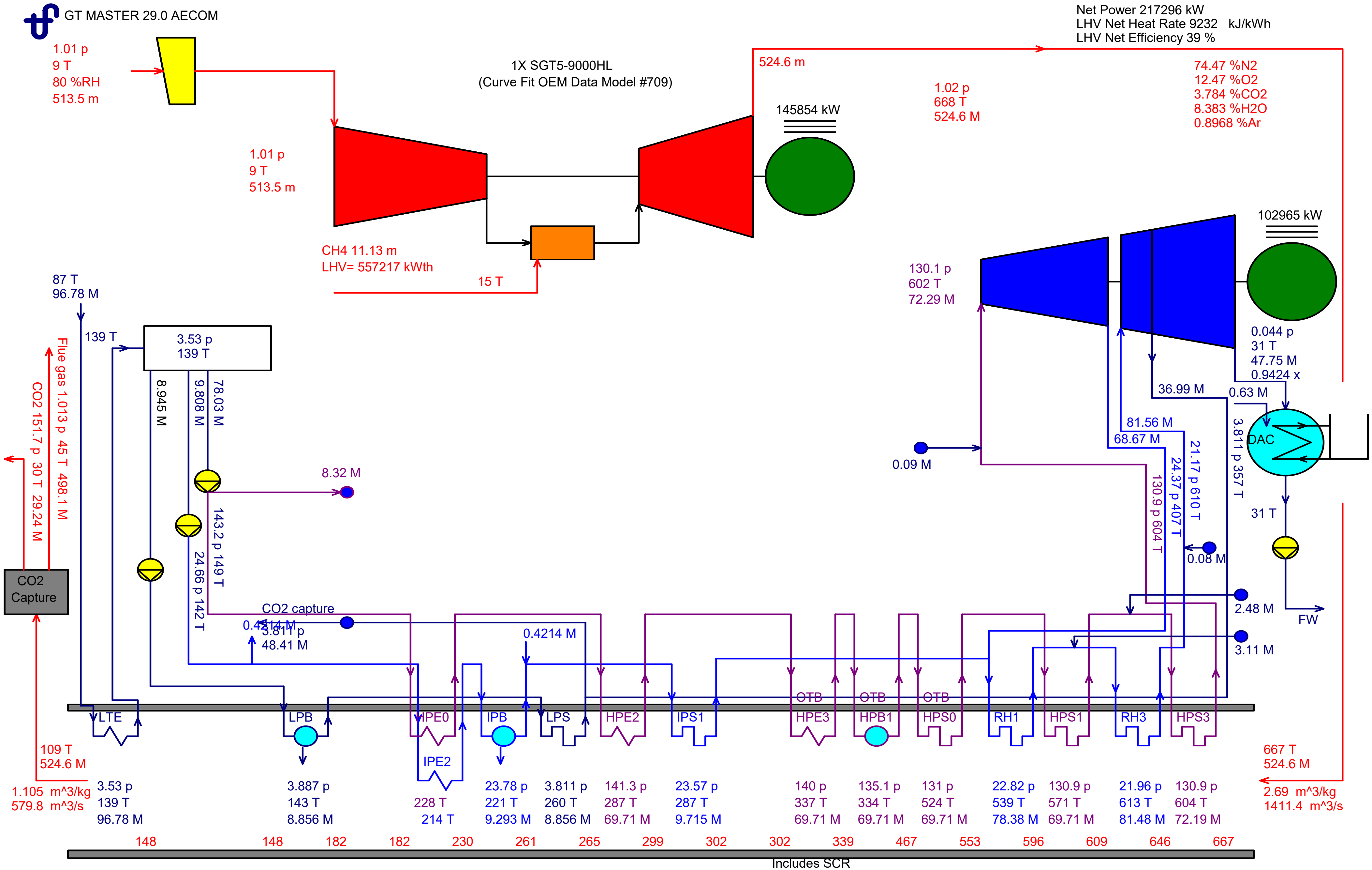
Gross Power	248819 kW
Net Power	217296 kW
Aux. & Losses	31523 kW
LHV Gross Heat Rate	8062 kJ/kWh
LHV Net Heat Rate	9232 kJ/kWh
LHV Gross Electric Eff.	44.65 %
LHV Net Electric Eff.	39 %
Fuel LHV Input	557217 kWth
Fuel HHV Input	618295 kWth
Net Process Heat	0 kWth
CO2 capture	2526.4 tonne/day

Ambient
1.013 P
9 T
80% RH
7.353 Twb



p [bar] T [C] M [kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 20:06:49 file=

GT MASTER 29.0 AECOM
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM



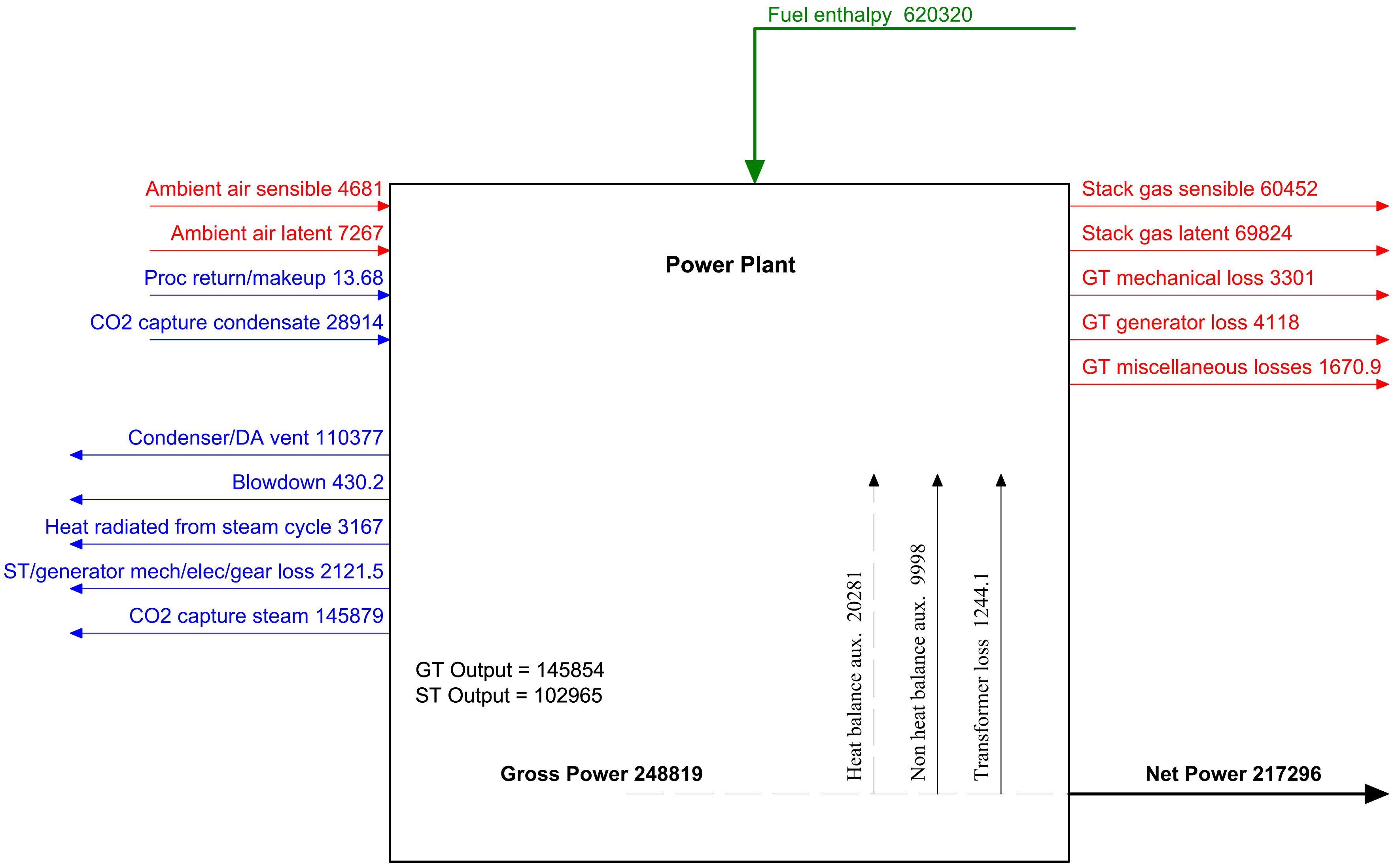
p[bar], T[C], M[kg/s], Steam Properties: IAPWS-IF97

1220 06-11-2020 20:06:49 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Fuel chemical LHV input = 557216 kW
Fuel chemical HHV input = 618295 kW

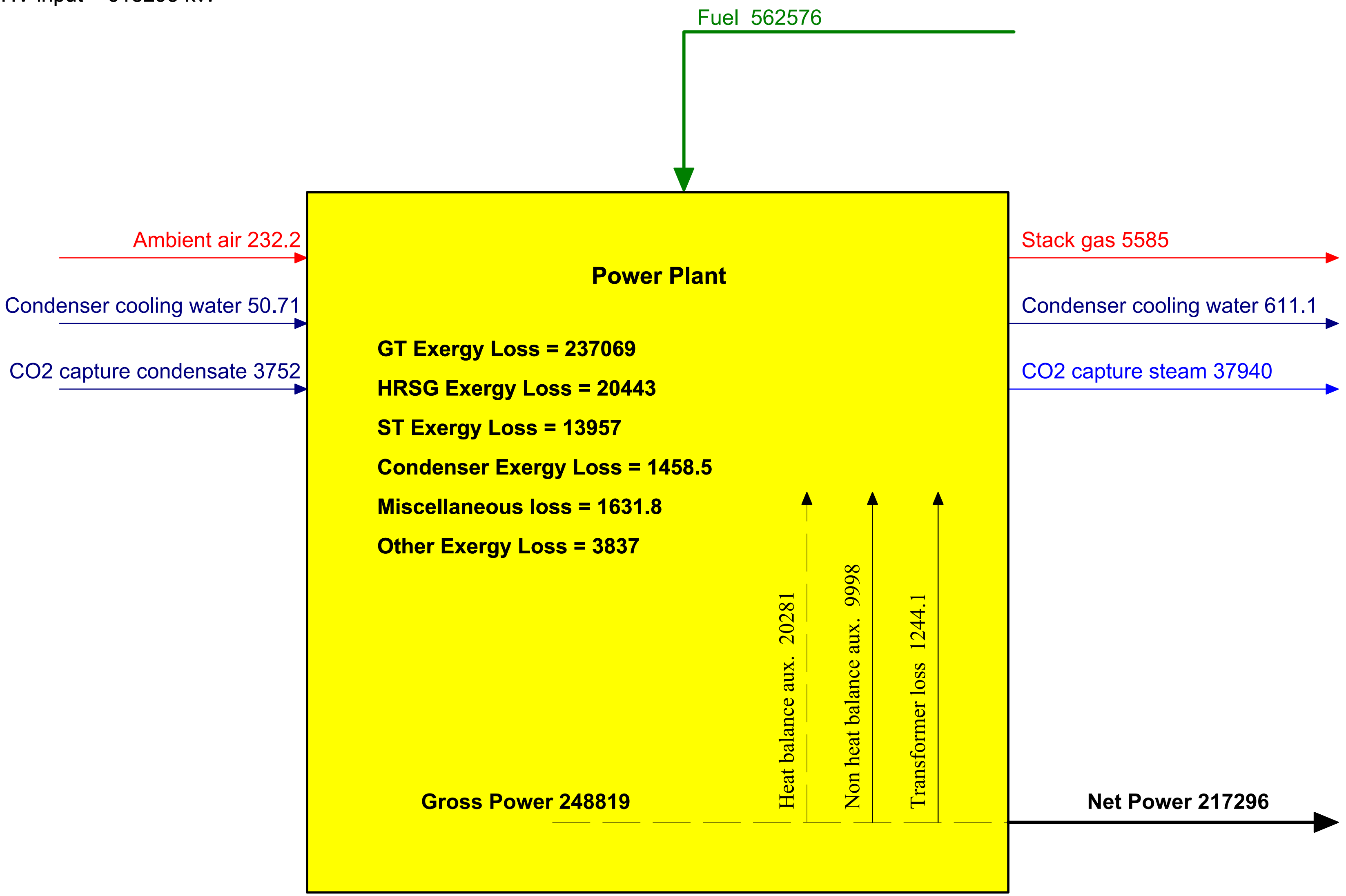
Power Plant Energy Flow Schematic [kW]



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Fuel exergy input = 562576 kW
Fuel chemical LHV input = 557216 kW
Fuel chemical HHV input = 618295 kW

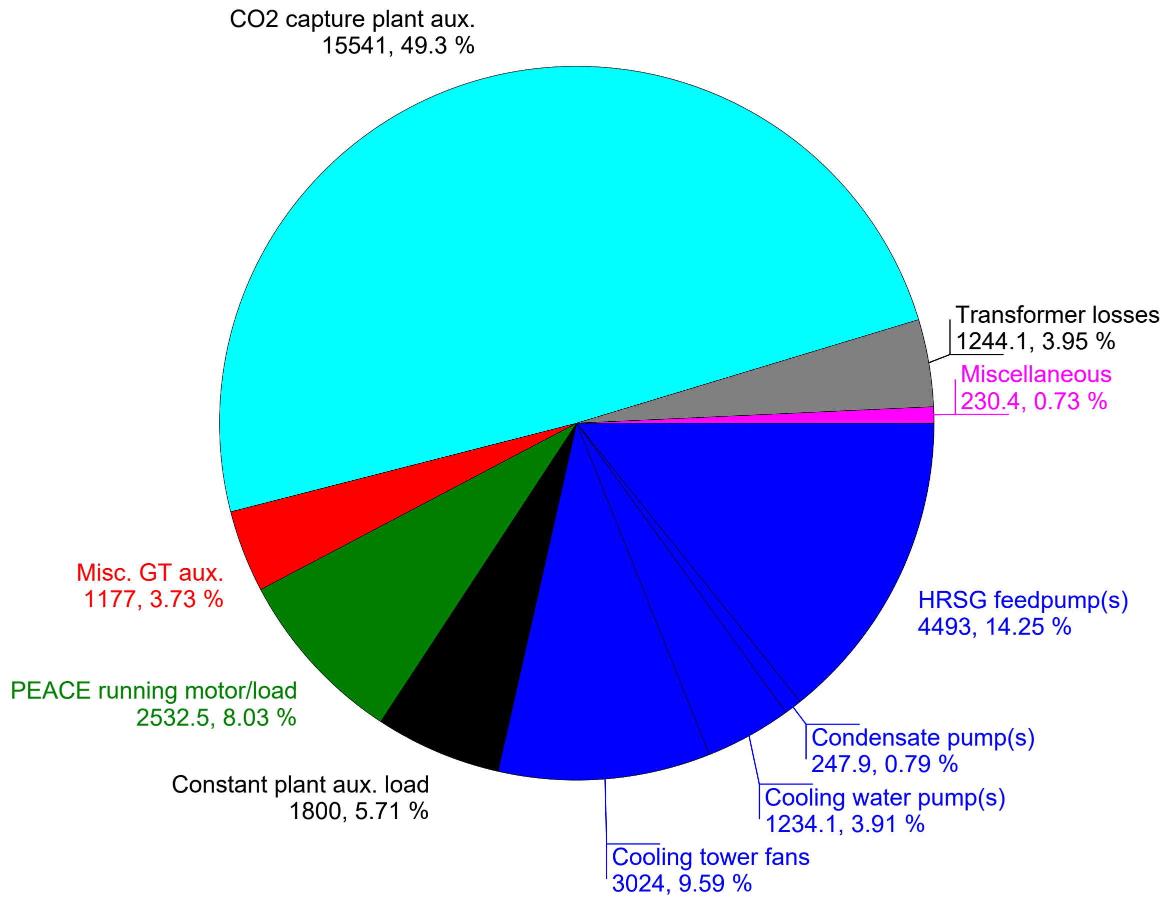
Power Plant Exergy Flow Schematic [kW]



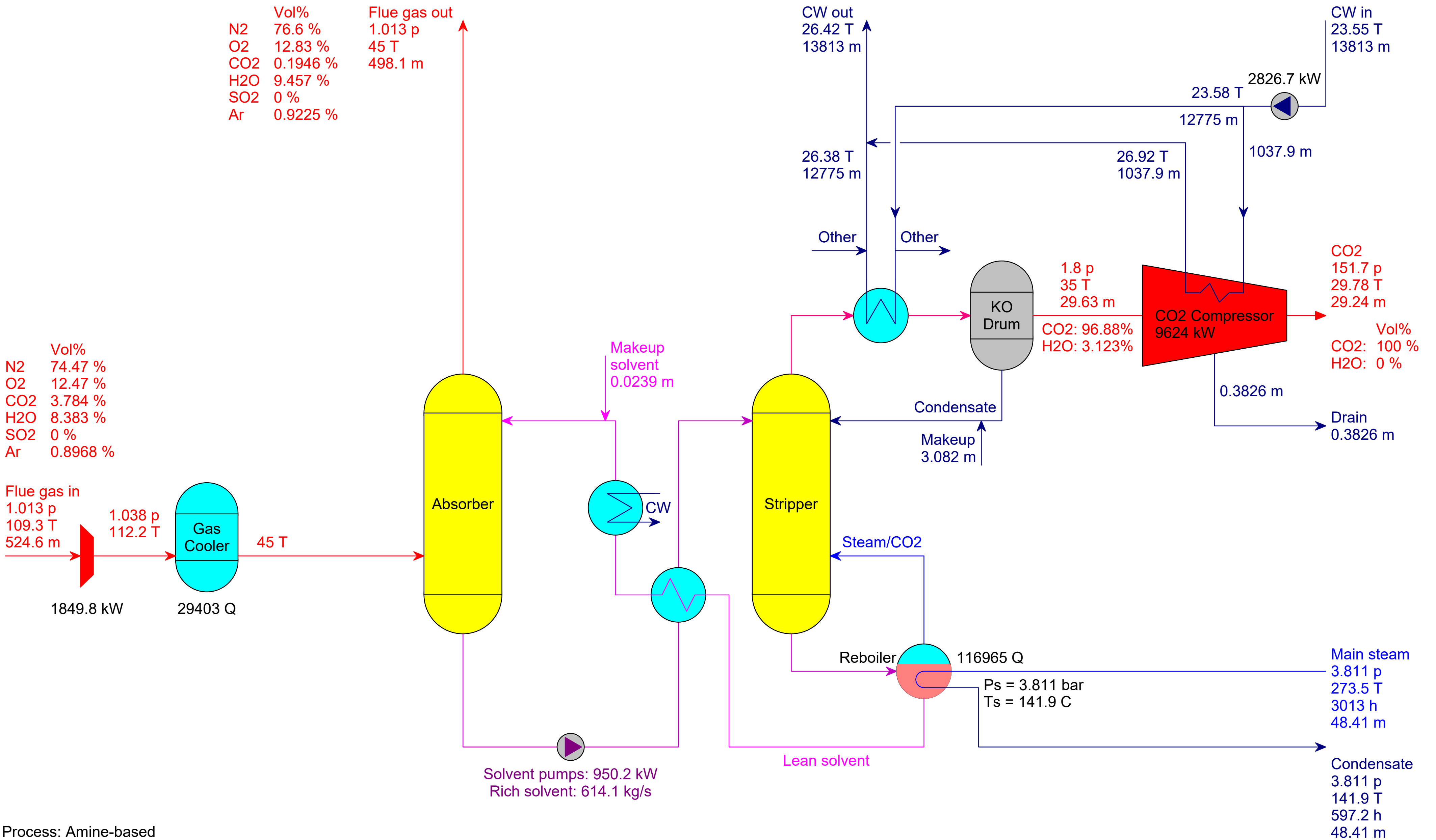
Reference: 1.013 bar, 25 C, water as vapor.

Auxiliaries & Losses [kW]

Total auxiliaries & transformer losses = 31523 kW



CO2 Capture Plant Flow Diagram

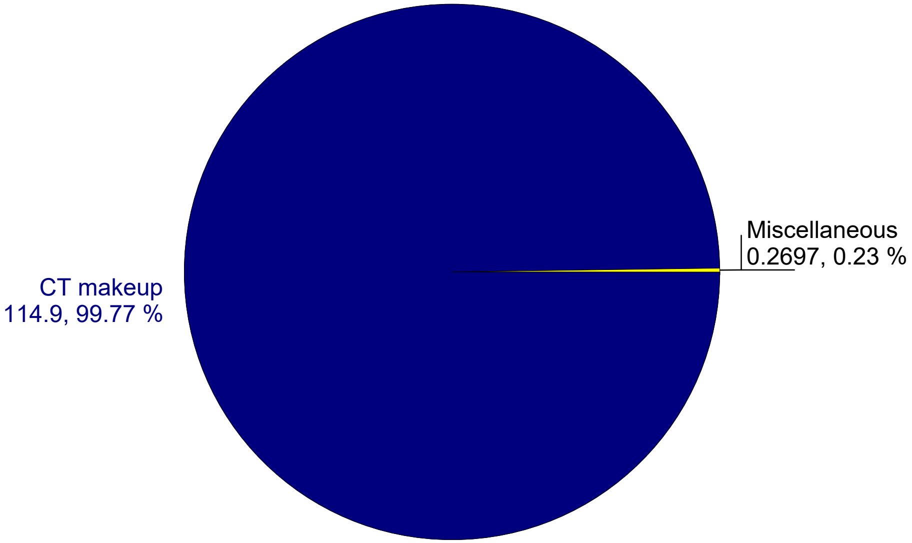


Process: Amine-based
CO2 capture: 29.24 kg/s, 2526.4 tonne/day
CO2 capture efficiency: 95 %
Heat input: 116965 kW, 117 MW, 4000 kJ/kg CO2
Total electrical power consumption: 15541 kW
Solvent consumption: 2.069 tonne/day

p[bar] T[C] h[kJ/kg] m[kg/s] Q[kW]

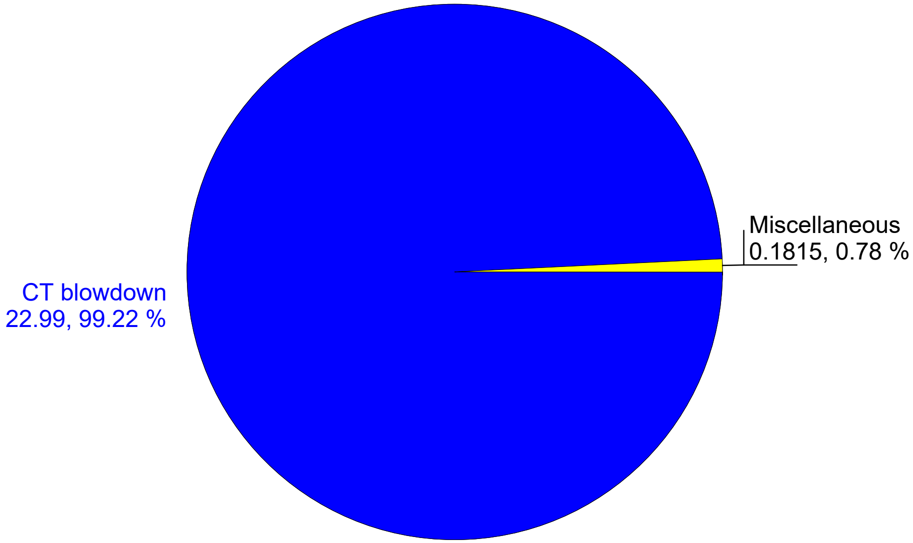
Plant Water Consumption [kg/s]

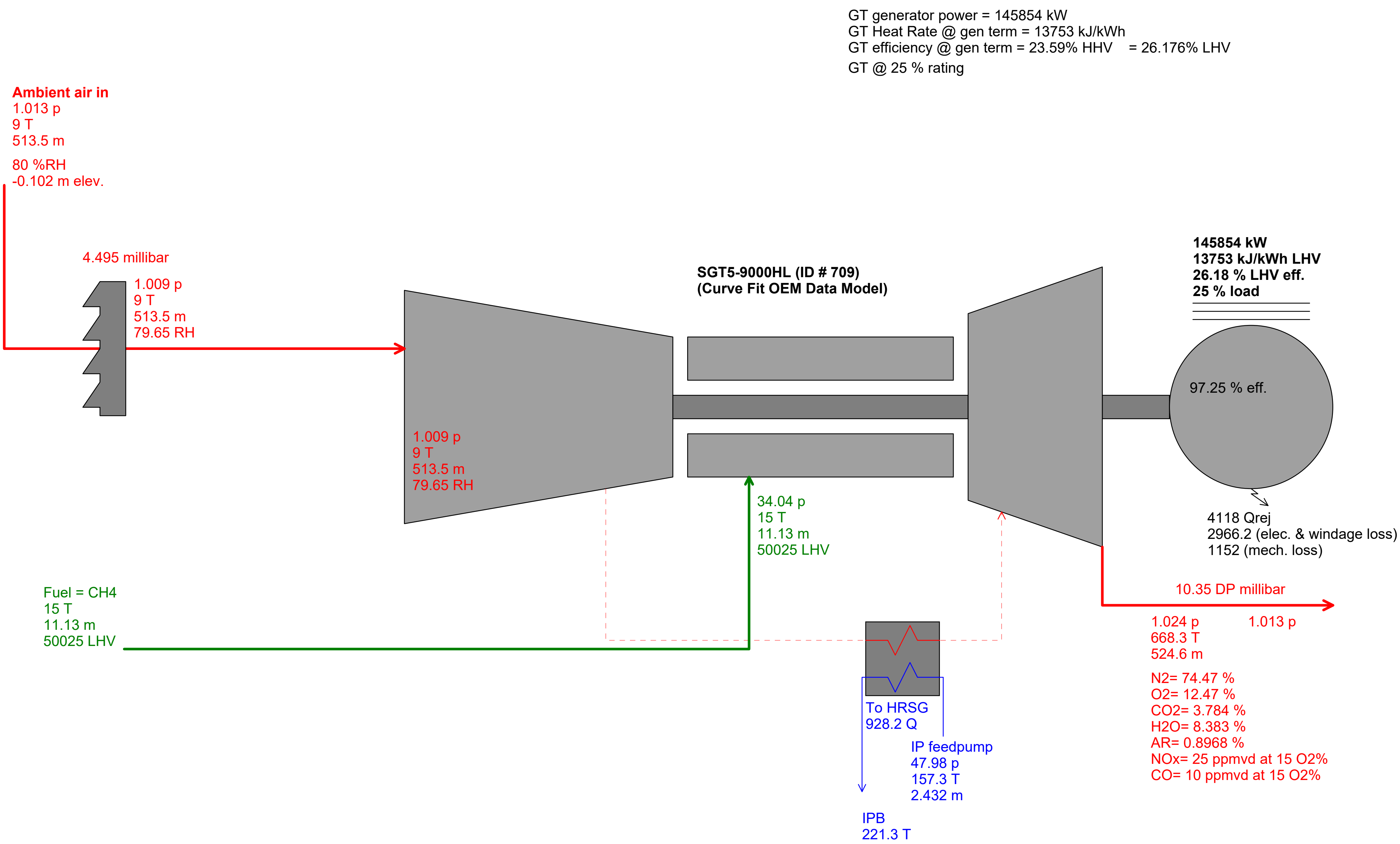
Plant water consumption = 115.2 kg/s



Plant Water Discharge [kg/s]

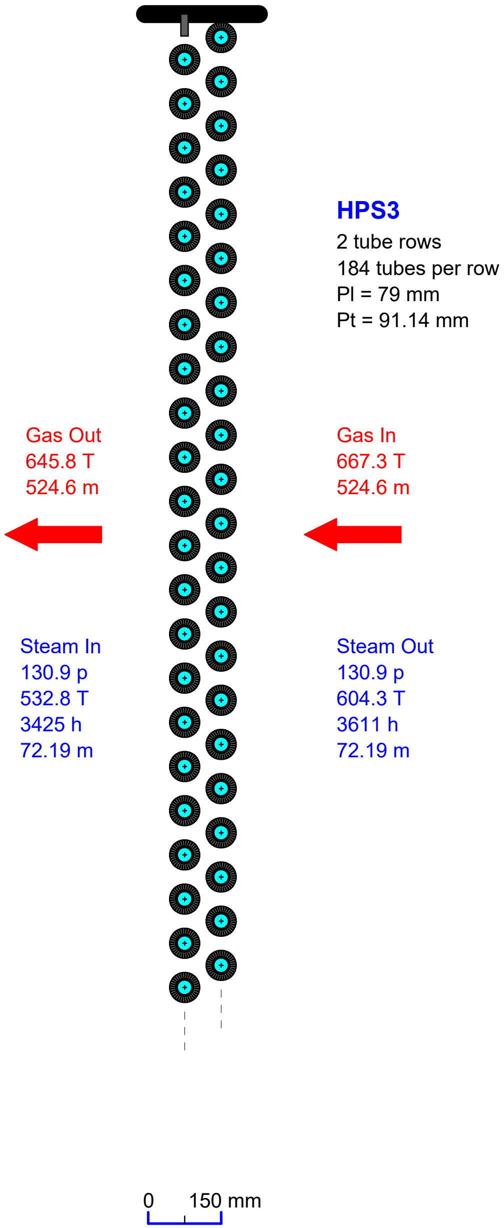
Plant water discharge = 23.17 kg/s

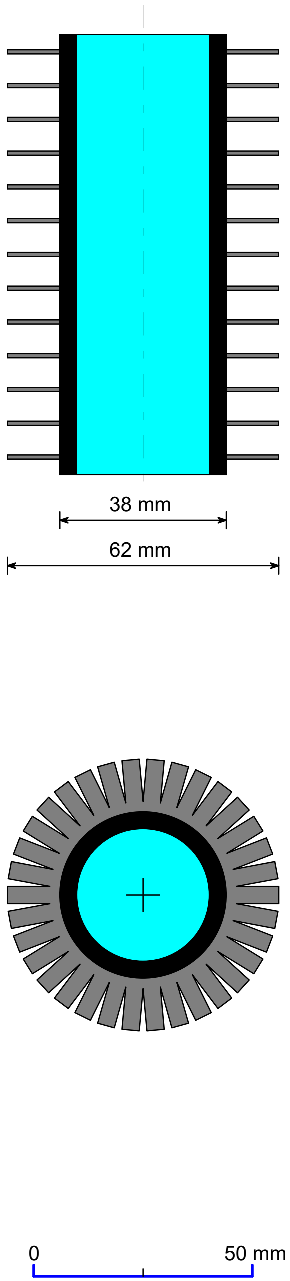




p[bar], T[C], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

HPS3 Hardware Design



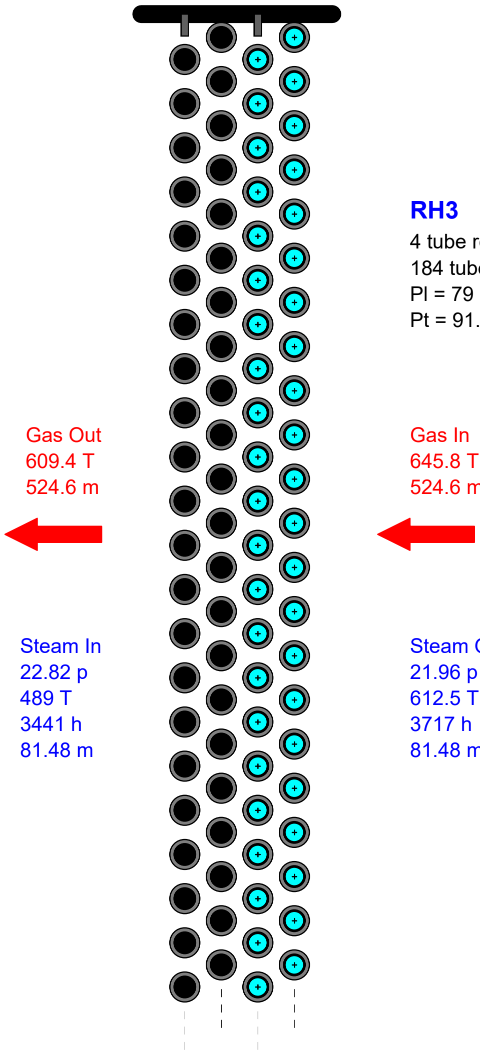


Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP304
Tube material	TP347HFG
Tube outer diameter	38 mm
Tube wall thickness	3.81 mm
Fin height	12 mm
Fin spacing	6.723 mm
Fin thickness	1 mm
Number of fins per meter	129.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4645 m^2
Maximum gas velocity	7.506 m/s
Gas pressure drop	0.1793 millibar
Steam side velocity	7.437 m/s
Steam side pressure drop	0.0592 bar
Heat transfer from gas	13474 kW
Heat transfer to steam	13407 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS3
Date: 06/11/20	
Drawing No:	

RH3 Hardware Design



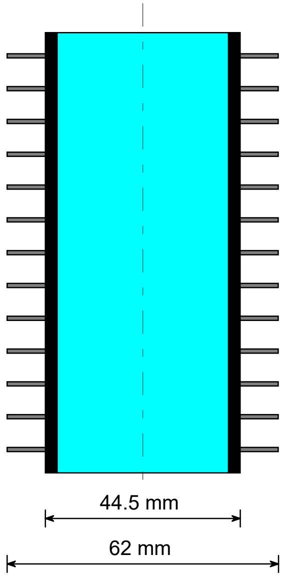
RH3
4 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

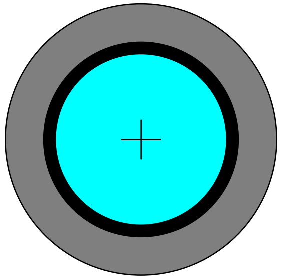
Gas Out
609.4 T
524.6 m

Gas In
645.8 T
524.6 m

Steam In
22.82 p
489 T
3441 h
81.48 m

Steam Out
21.96 p
612.5 T
3717 h
81.48 m





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	TP347HFG
Tube outer diameter	44.5 mm
Tube wall thickness	2.667 mm
Fin height	8.75 mm
Fin spacing	6.507 mm
Fin thickness	1 mm
Number of fins per meter	133.2
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	8064 m^2
Maximum gas velocity	8.212 m/s
Gas pressure drop	0.3519 millibar
Steam side velocity	30.8 m/s
Steam side pressure drop	0.8675 bar
Heat transfer from gas	22672 kW
Heat transfer to steam	22560 kW

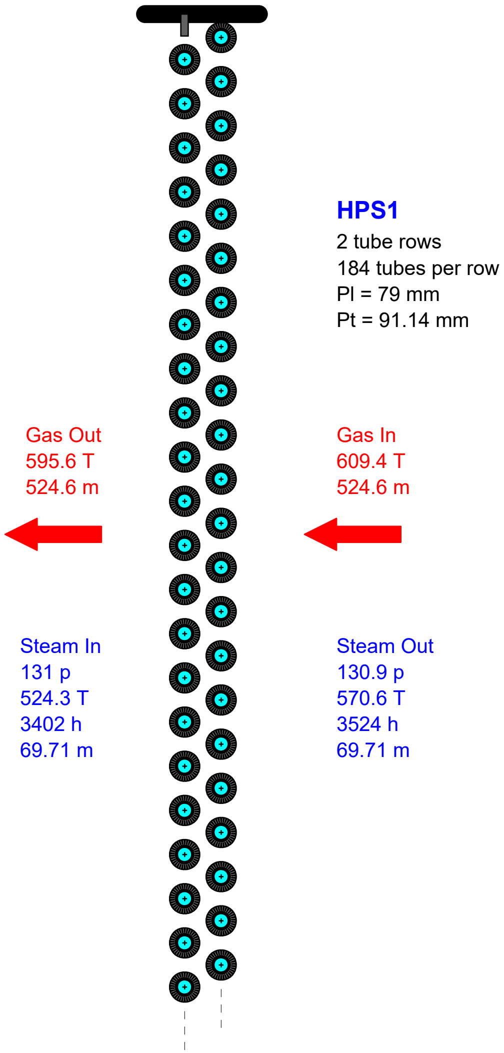
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

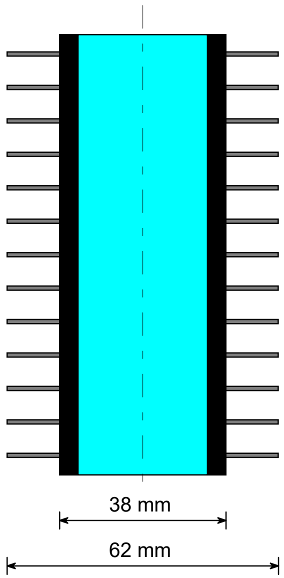
0   150 mm

0   50 mm

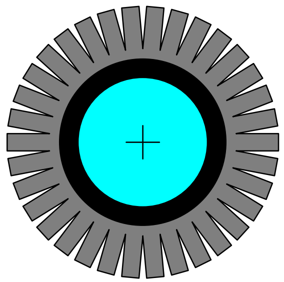
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH3
Date: 06/11/20	
Drawing No:	

HPS1 Hardware Design





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T91
Tube outer diameter	38 mm
Tube wall thickness	4.191 mm
Fin height	12 mm
Fin spacing	6.65 mm
Fin thickness	1 mm
Number of fins per meter	130.7
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	4680 m^2
Maximum gas velocity	7.074 m/s
Gas pressure drop	0.1689 millibar
Steam side velocity	7.294 m/s
Steam side pressure drop	0.0601 bar
Heat transfer from gas	8552 kW
Heat transfer to steam	8509 kW



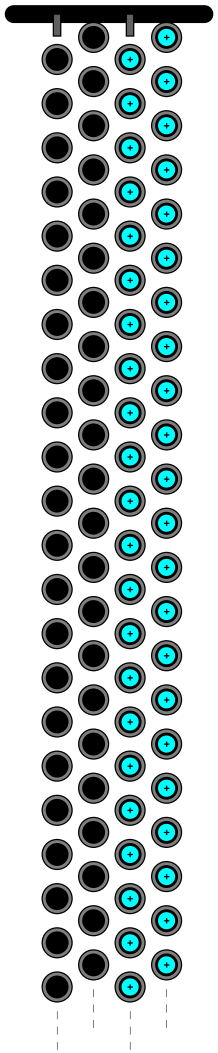
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS1
Date: 06/11/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

RH1 Hardware Design



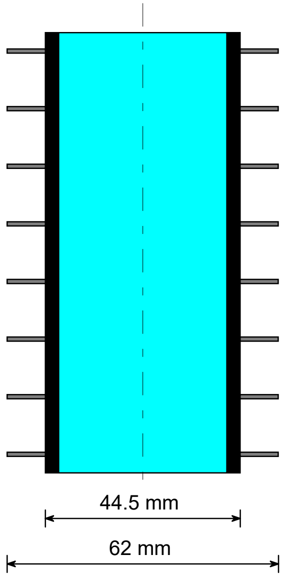
RH1
4 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

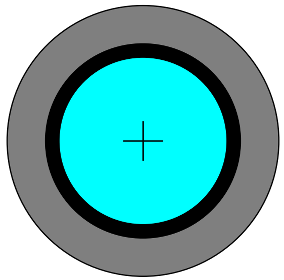
Gas Out
553.2 T
524.6 m

Gas In
595.6 T
524.6 m

Steam In
23.57 p
389.8 T
3220 h
78.38 m

Steam Out
22.82 p
539 T
3552 h
78.38 m





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T22
Tube outer diameter	44.5 mm
Tube wall thickness	3.048 mm
Fin height	8.75 mm
Fin spacing	12.19 mm
Fin thickness	1 mm
Number of fins per meter	75.8
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	5493 m^2
Maximum gas velocity	7.556 m/s
Gas pressure drop	0.2539 millibar
Steam side velocity	26.4 m/s
Steam side pressure drop	0.743 bar
Heat transfer from gas	26156 kW
Heat transfer to steam	26026 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

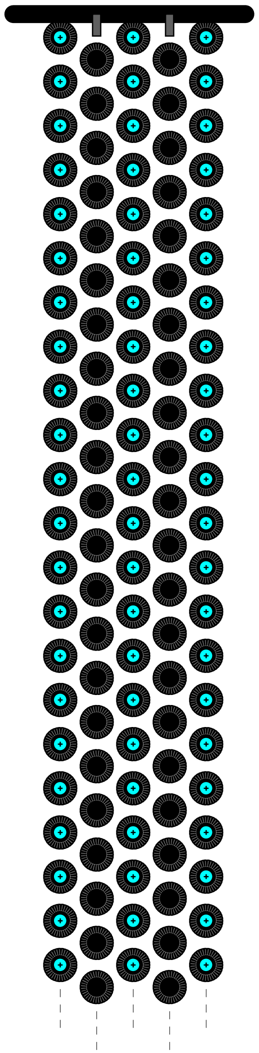
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH1
Date: 06/11/20	
Drawing No:	

Gas Out
466.6 T
524.6 m

Steam In
135.1 p
333.9 T
2650.5 h
69.71 m

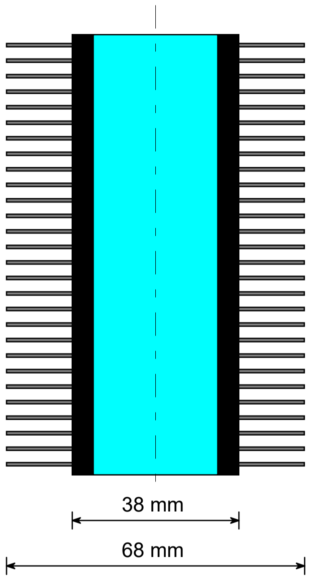


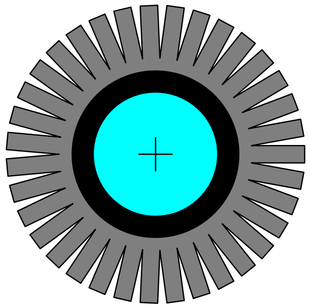
HPS0 (OTB)

4.703 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
553.2 T
524.6 m

Steam Out
131 p
524.3 T
3402 h
69.71 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	4.703
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	25807 m^2
Maximum gas velocity	6.818 m/s
Gas pressure drop	0.6279 millibar
Steam side velocity	12.05 m/s
Steam side pressure drop	4.11 bar
Heat transfer from gas	52655 kW
Heat transfer to steam	52393 kW

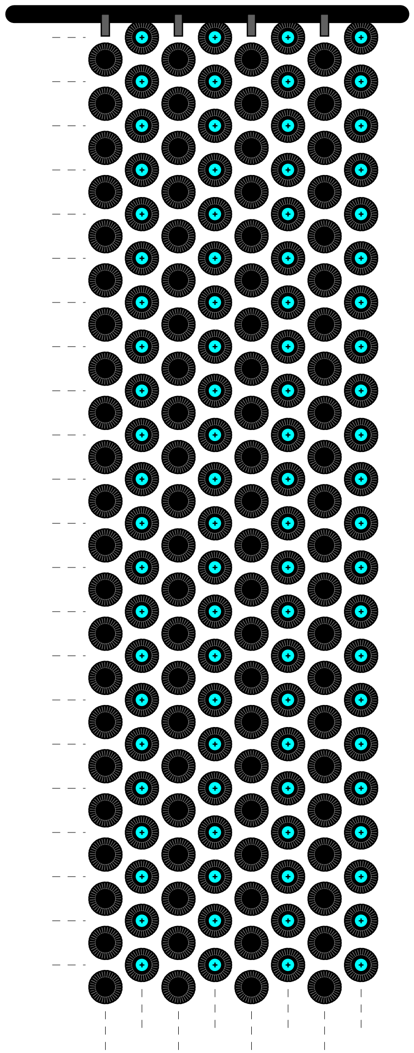
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS0 (OTB)
Date: 06/11/20	
Drawing No:	

HPB1 (OTB) Hardware Design



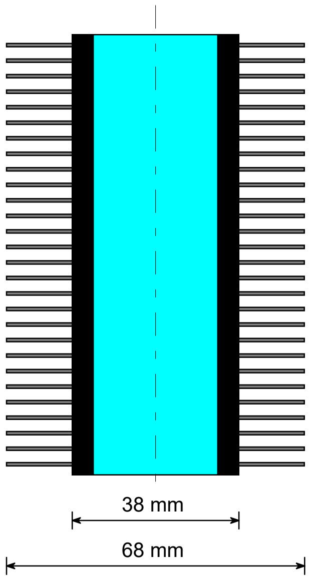
HPB1 (OTB)
11.42 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

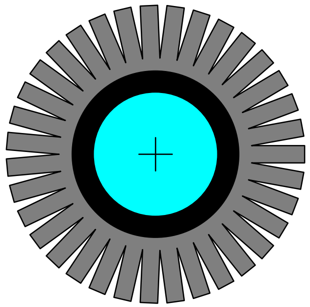
Gas Out
338.9 T
524.6 m

Gas In
466.6 T
524.6 m

Water In
140 p
336.7 T
1570.8 h
69.71 m

Steam Out
135.1 p
333.9 T
2650.5 h
69.71 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	11.42
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	62644 m^2
Maximum gas velocity	5.885 m/s
Gas pressure drop	1.278 millibar
Water side velocity	0.9528 m/s
Water side pressure drop	4.883 bar
Heat transfer from gas	75646 kW
Heat transfer to steam/water	75270 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

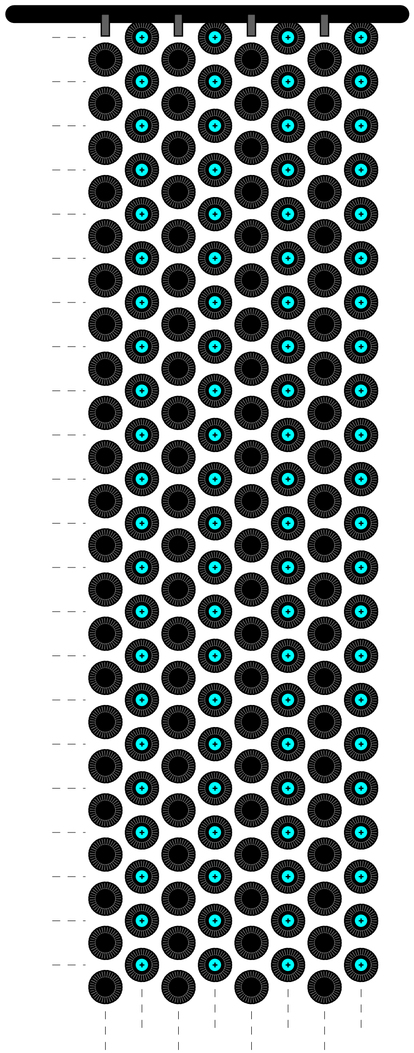
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPB1 (OTB)
Date: 06/11/20	
Drawing No:	

HPE3 (OTB) Hardware Design

Gas Out
302.4 T
524.6 m

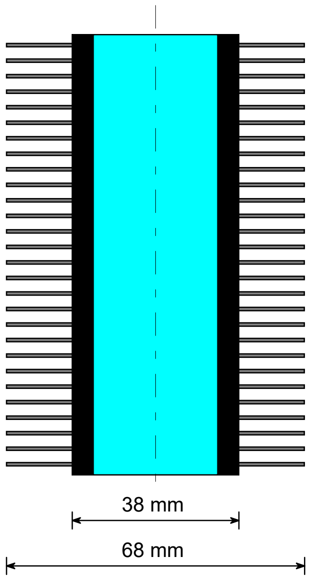
Water In
141.3 p
287 T
1269.1 h
69.71 m

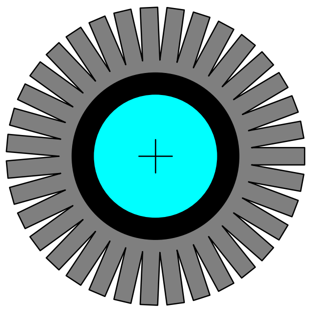


HPE3 (OTB)
17.88 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
338.9 T
524.6 m

Water Out
140 p
336.7 T
1570.8 h
69.71 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.756 mm
Fin thickness	0.8 mm
Number of fins per meter	281.2
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	17.88
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	98113 m^2
Maximum gas velocity	5.17 m/s
Gas pressure drop	1.743 millibar
Water side velocity	0.8551 m/s
Water side pressure drop	1.348 bar
Heat transfer from gas	21139 kW
Heat transfer to water	21034 kW

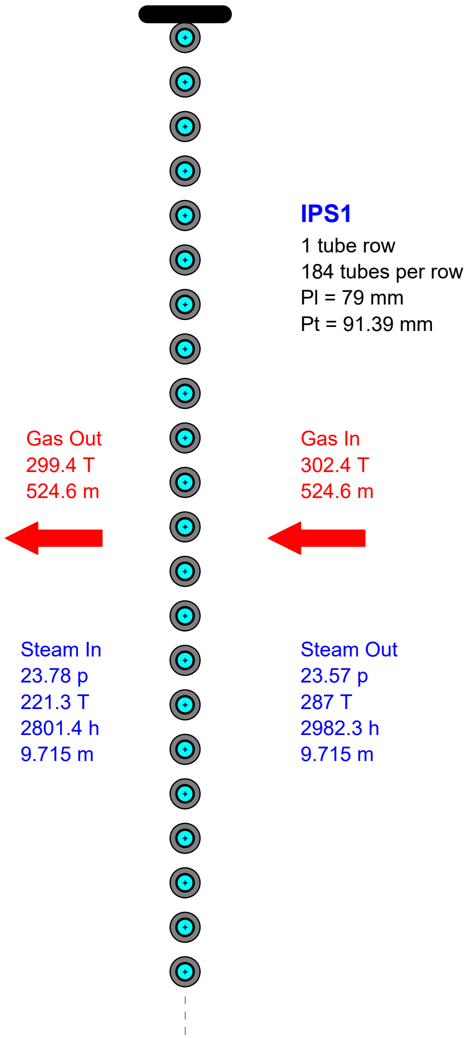
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

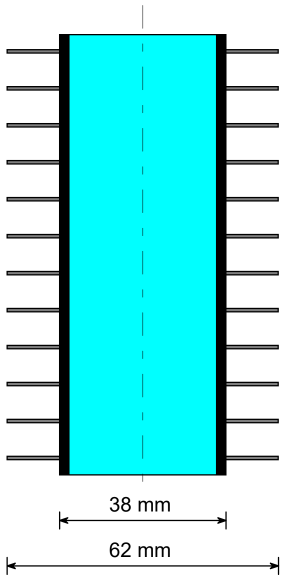
0 150 mm

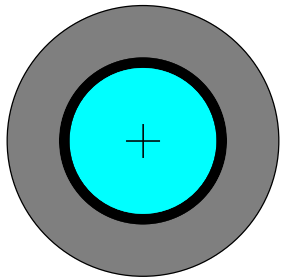
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE3 (OTB)
Date: 06/11/20	
Drawing No:	

IPS1 Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	7.626 mm
Fin thickness	0.8 mm
Number of fins per meter	118.7
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.39 mm
# of tube rows (longitudinal)	1
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2154.4 m^2
Maximum gas velocity	4.537 m/s
Gas pressure drop	0.0462 millibar
Steam side velocity	5.515 m/s
Steam side pressure drop	0.2092 bar
Heat transfer from gas	1766.4 kW
Heat transfer to steam	1757.6 kW

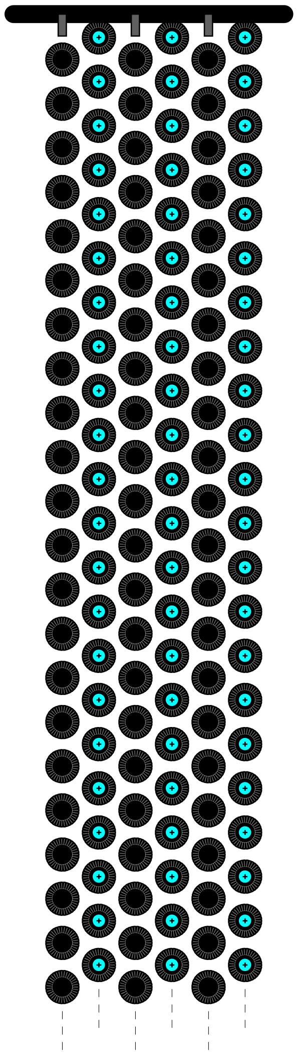
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPS1
Date: 06/11/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

HPE2 Hardware Design



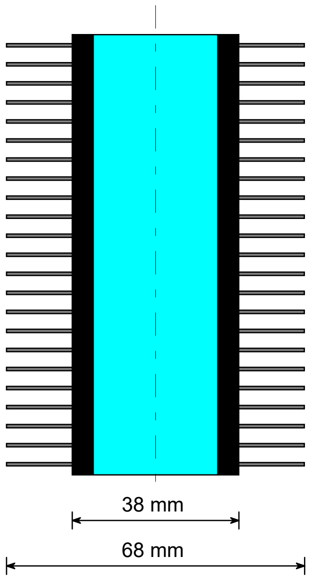
HPE2
6 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

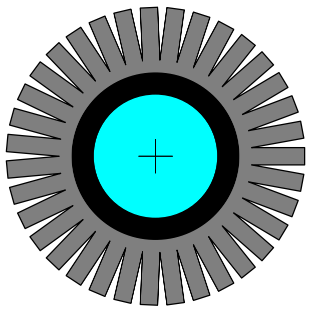
Gas Out
264.5 T
524.6 m

Gas In
299.4 T
524.6 m

Water In
141.9 p
227.9 T
982.9 h
69.71 m

Water Out
141.3 p
287 T
1269.1 h
69.71 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	3.555 mm
Fin thickness	0.8 mm
Number of fins per meter	229.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	27374 m^2
Maximum gas velocity	4.708 m/s
Gas pressure drop	0.4497 millibar
Water side velocity	0.7458 m/s
Water side pressure drop	0.5179 bar
Heat transfer from gas	20052 kW
Heat transfer to water	19952 kW

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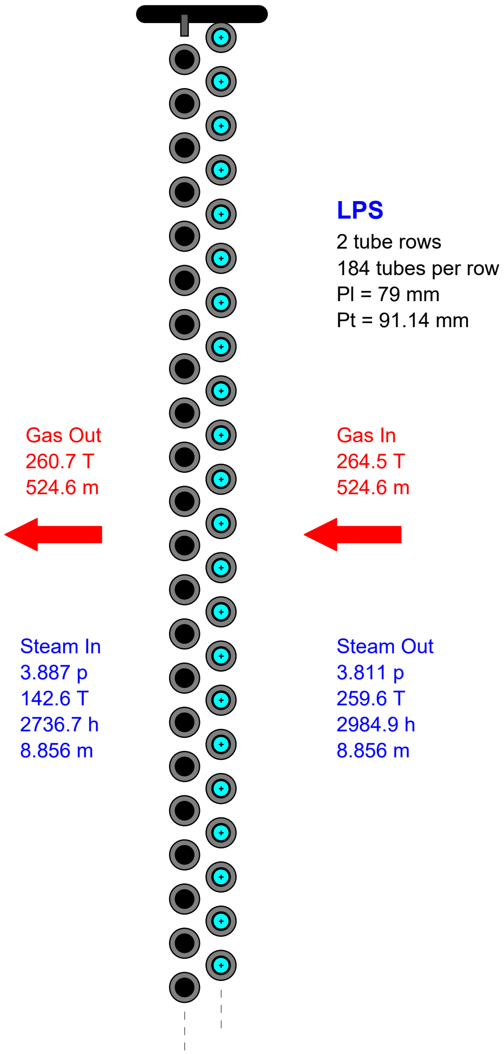
	User: AECOM
	HPE2
Date: 06/11/20	
Drawing No:	

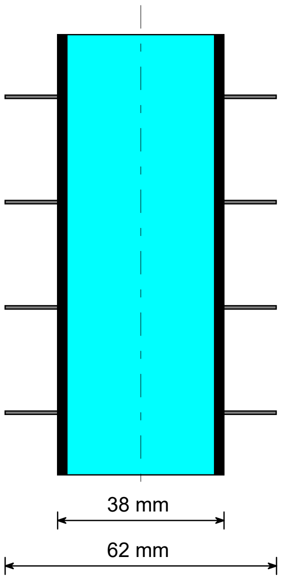
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

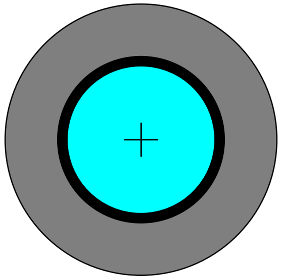
0 150 mm

0 50 mm

LPS Hardware Design







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	23.26 mm
Fin thickness	0.8 mm
Number of fins per meter	41.56
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	2
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	2091.2 m^2
Maximum gas velocity	4.135 m/s
Gas pressure drop	0.057 millibar
Steam side velocity	29.92 m/s
Steam side pressure drop	0.076 bar
Heat transfer from gas	2208.5 kW
Heat transfer to steam	2197.5 kW

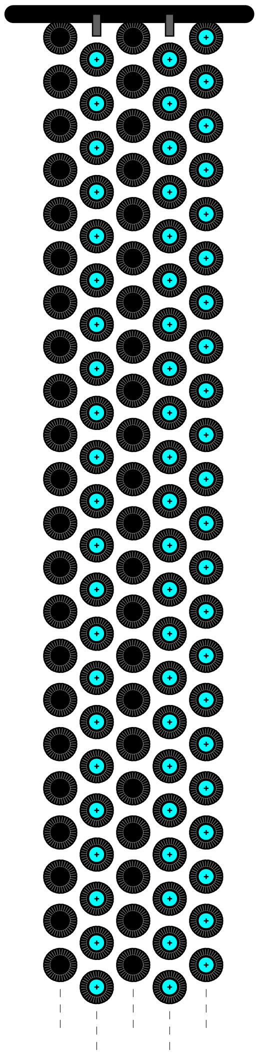
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPS
Date: 06/11/20	
Drawing No:	

IPB Hardware Design



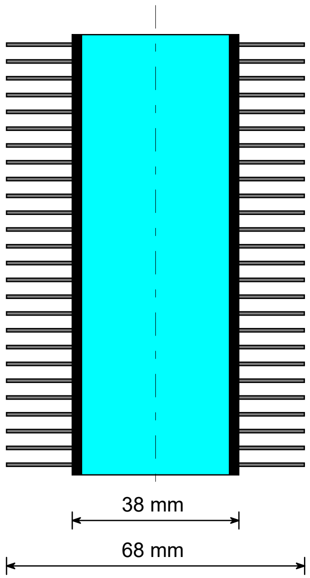
IPB
5 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

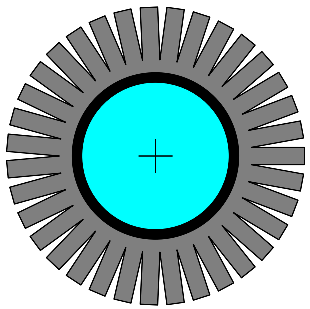
Gas Out
229.9 T
524.6 m

Gas In
260.7 T
524.6 m

Water In
23.78 p
214.4 T
917.8 h
9.293 m

Steam Out
23.78 p
221.3 T
2801.4 h
9.293 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.045 mm
Fin thickness	0.8 mm
Number of fins per meter	260
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	5
# of rows per pass	1.251
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	25540 m^2
Maximum gas velocity	4.465 m/s
Gas pressure drop	0.3805 millibar
Water side velocity	0.967 m/s
Water side pressure drop	0 bar
Heat transfer from gas	17596 kW
Heat transfer to steam/water	17508 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

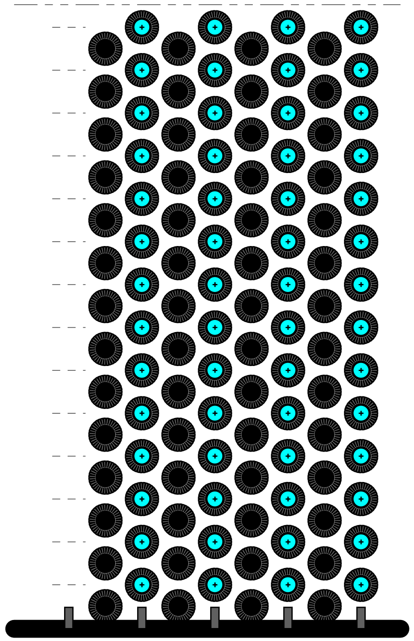
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPB
Date: 06/11/20	
Drawing No:	

IPE2 Hardware Design

Parallel HX



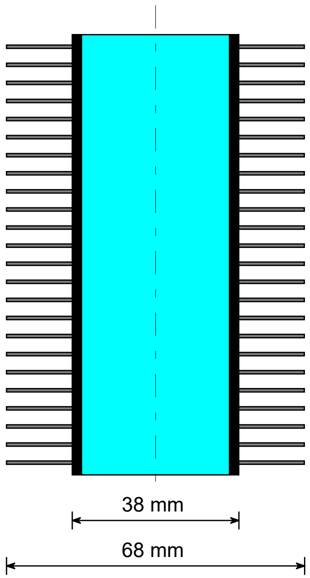
Gas Out
181.7 T
40.96 m

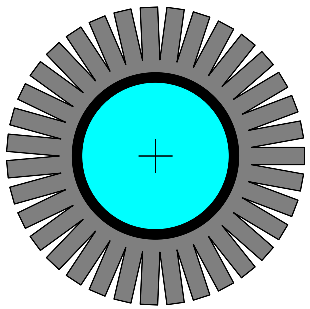
Water In
24.66 p
141.9 T
598.5 h
9.386 m

IPE2 (Parallel)
14 tube rows
14 tubes per row
Pl = 79 mm
Pt = 88.19 mm

Gas In
229.9 T
40.96 m

Water Out
23.78 p
214.4 T
917.8 h
9.386 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.339 mm
Fin thickness	0.8 mm
Number of fins per meter	241.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	88.19 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	14
Tube length	20.4 m
Gas path transverse width	1.279 m
Gas path frontal area	26.09 m^2
HX total outside surface area	5089 m^2
Maximum gas velocity	4.377 m/s
Gas pressure drop	1.055 millibar
Water side velocity	0.8404 m/s
Water side pressure drop	0.8893 bar
Heat transfer from gas	3012 kW
Heat transfer to water	2997.1 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

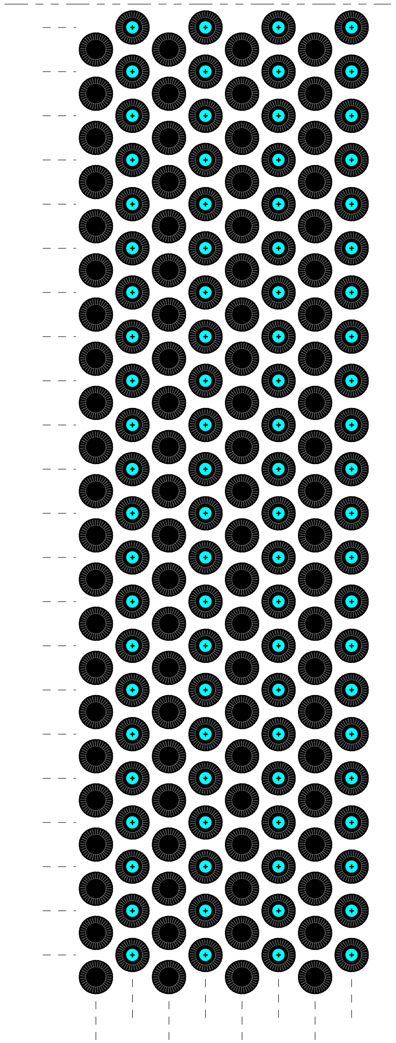
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPE2 (Parallel)
Date: 06/11/20	
Drawing No:	

HPE0 Hardware Design

Parallel HX



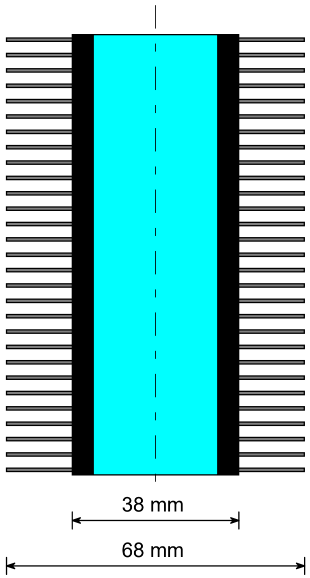
Gas Out
181.7 T
483.6 m

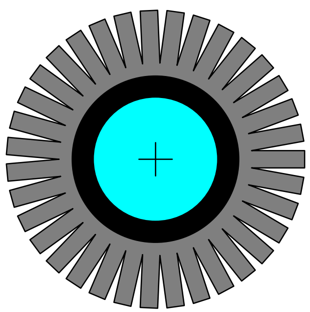
Water In
143.2 p
149.2 T
637.3 h
69.71 m

HPE0 (Parallel)
14 tube rows
170 tubes per row
Pl = 79 mm
Pt = 91.12 mm

Gas In
229.9 T
483.6 m

Water Out
141.9 p
227.9 T
982.9 h
69.71 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.699 mm
Fin thickness	0.8 mm
Number of fins per meter	285.8
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.12 mm
# of tube rows (longitudinal)	14
# of rows per pass	1
# of tubes per row (transverse)	170
Tube length	20.4 m
Gas path transverse width	15.54 m
Gas path frontal area	316.9 m^2
HX total outside surface area	72030 m^2
Maximum gas velocity	4.18 m/s
Gas pressure drop	1.055 millibar
Water side velocity	0.7276 m/s
Water side pressure drop	1.321 bar
Heat transfer from gas	24218 kW
Heat transfer to water	24098 kW

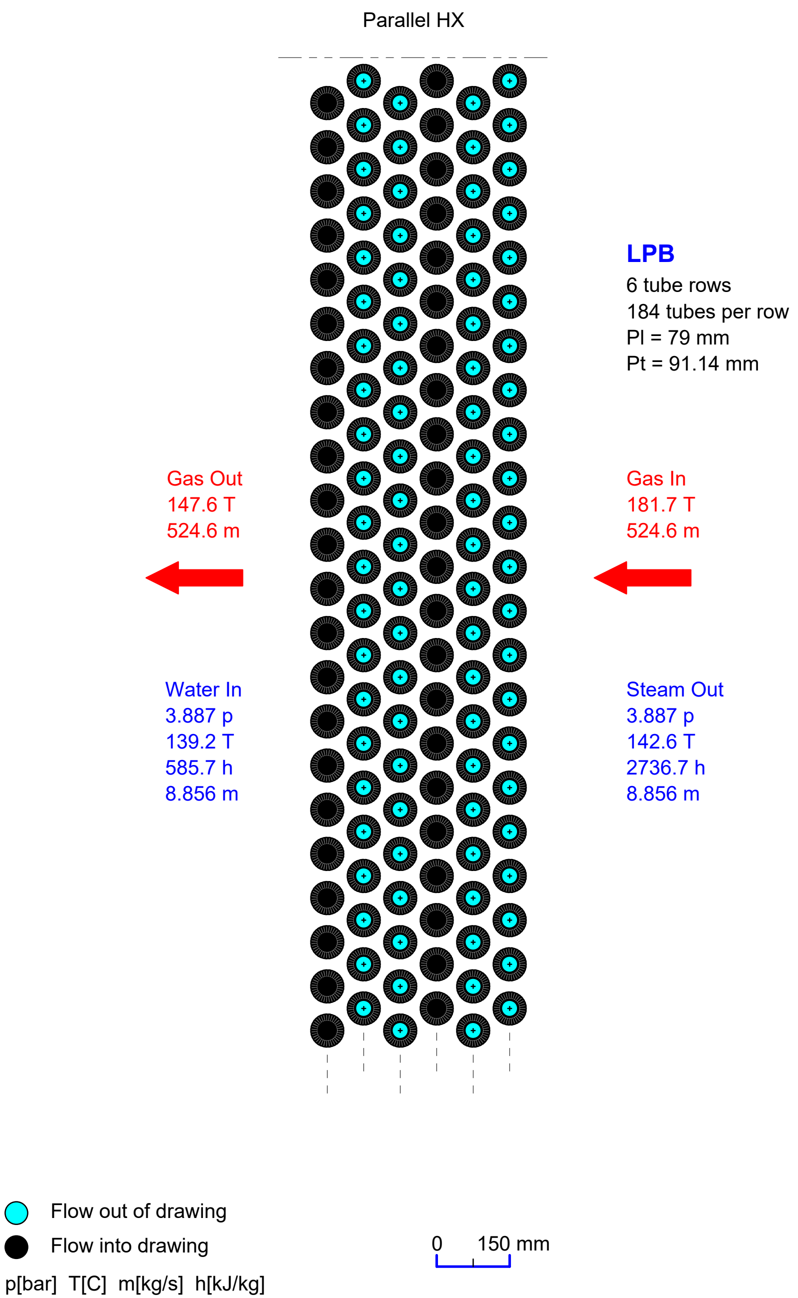
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

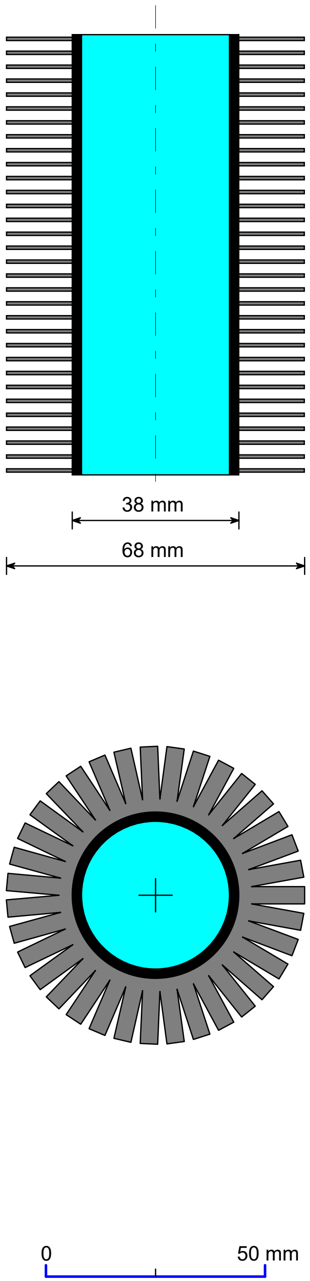
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE0 (Parallel)
Date: 06/11/20	
Drawing No:	

LPB Hardware Design



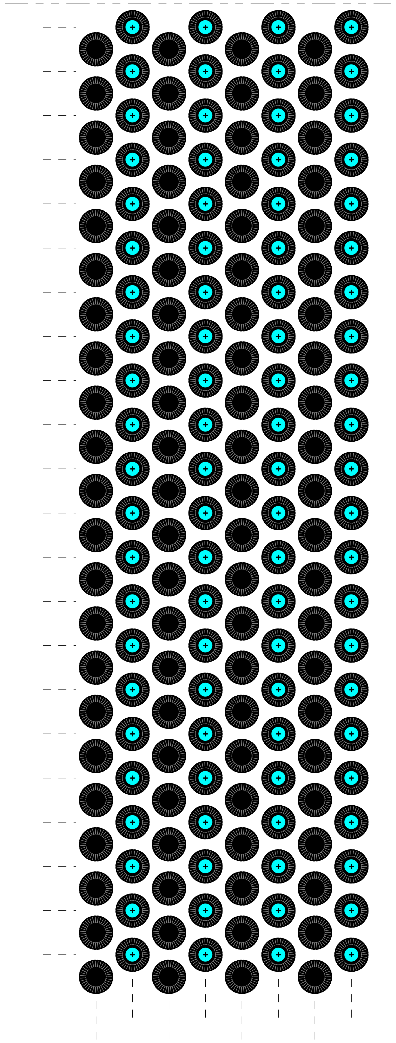


Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	2.359 mm
Fin thickness	0.8 mm
Number of fins per meter	316.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	6
# of rows per pass	1.501
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	36720 m^2
Maximum gas velocity	3.883 m/s
Gas pressure drop	0.4428 millibar
Water side velocity	0.6971 m/s
Water side pressure drop	0 bar
Heat transfer from gas	19146 kW
Heat transfer to steam/water	19051 kW

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPB
Date: 06/11/20	
Drawing No:	

LTE Hardware Design

Parallel HX



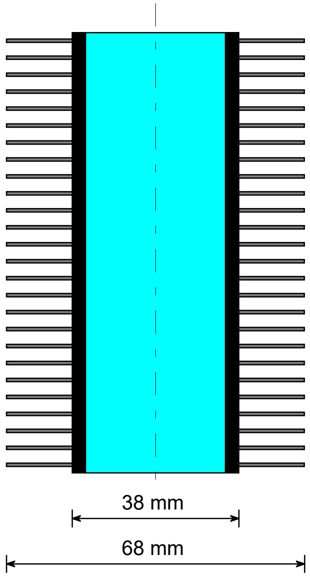
Gas Out
109.3 T
524.6 m

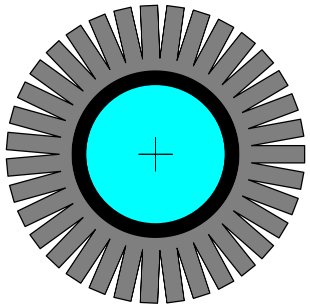
Water In
3.588 p
87.08 T
365.3 h
96.78 m

LTE
10 tube rows
184 tubes per row
Pl = 79 mm
Pt = 91.14 mm

Gas In
147.6 T
524.6 m

Water Out
3.53 p
139.2 T
585.6 h
96.78 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	3.048 mm
Fin height	15 mm
Fin spacing	3.077 mm
Fin thickness	0.8 mm
Number of fins per meter	257.9
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91.14 mm
# of tube rows (longitudinal)	10
# of rows per pass	1
# of tubes per row (transverse)	184
Tube length	20.4 m
Gas path transverse width	16.82 m
Gas path frontal area	343 m^2
HX total outside surface area	50703 m^2
Maximum gas velocity	3.455 m/s
Gas pressure drop	0.5522 millibar
Water side velocity	0.6936 m/s
Water side pressure drop	0.0581 bar
Heat transfer from gas	21432 kW
Heat transfer to water	21325 kW

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LTE
Date: 06/11/20	
Drawing No:	

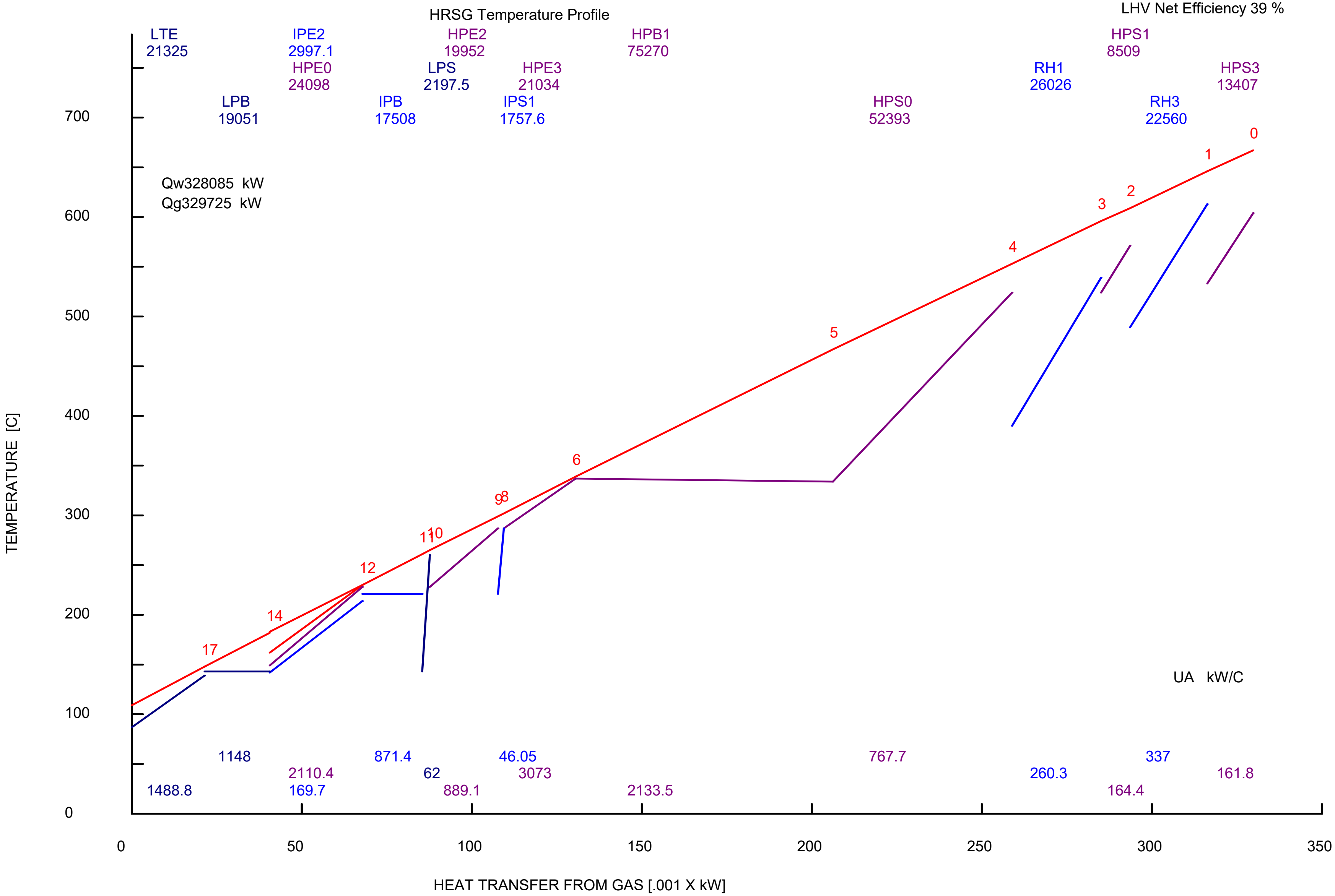
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

GT MASTER 29.0 AECOM

Net Power 217296 kW
LHV Net Heat Rate 9232 kJ/kWh
LHV Net Efficiency 39 %



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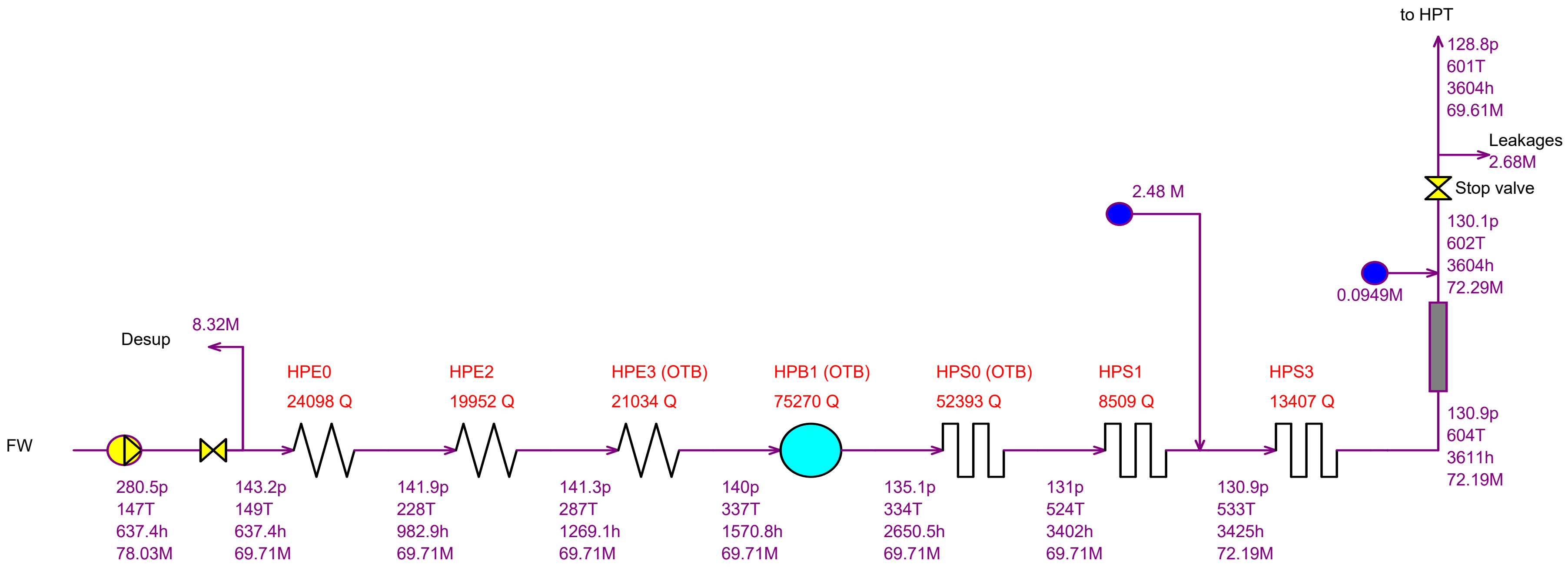
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

HP Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

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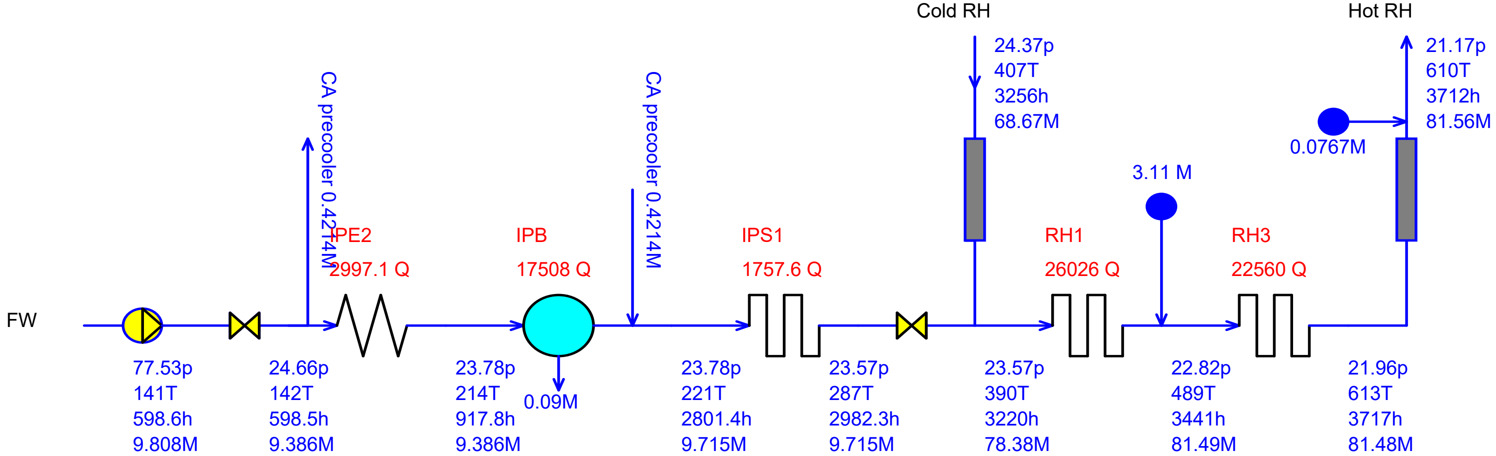
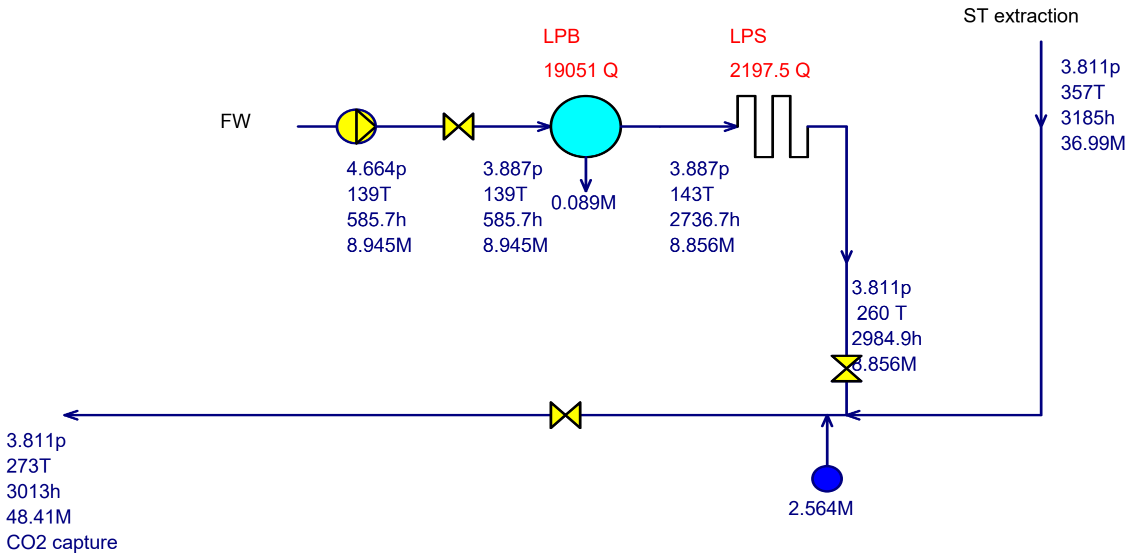
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

IP & Reheat Water Path



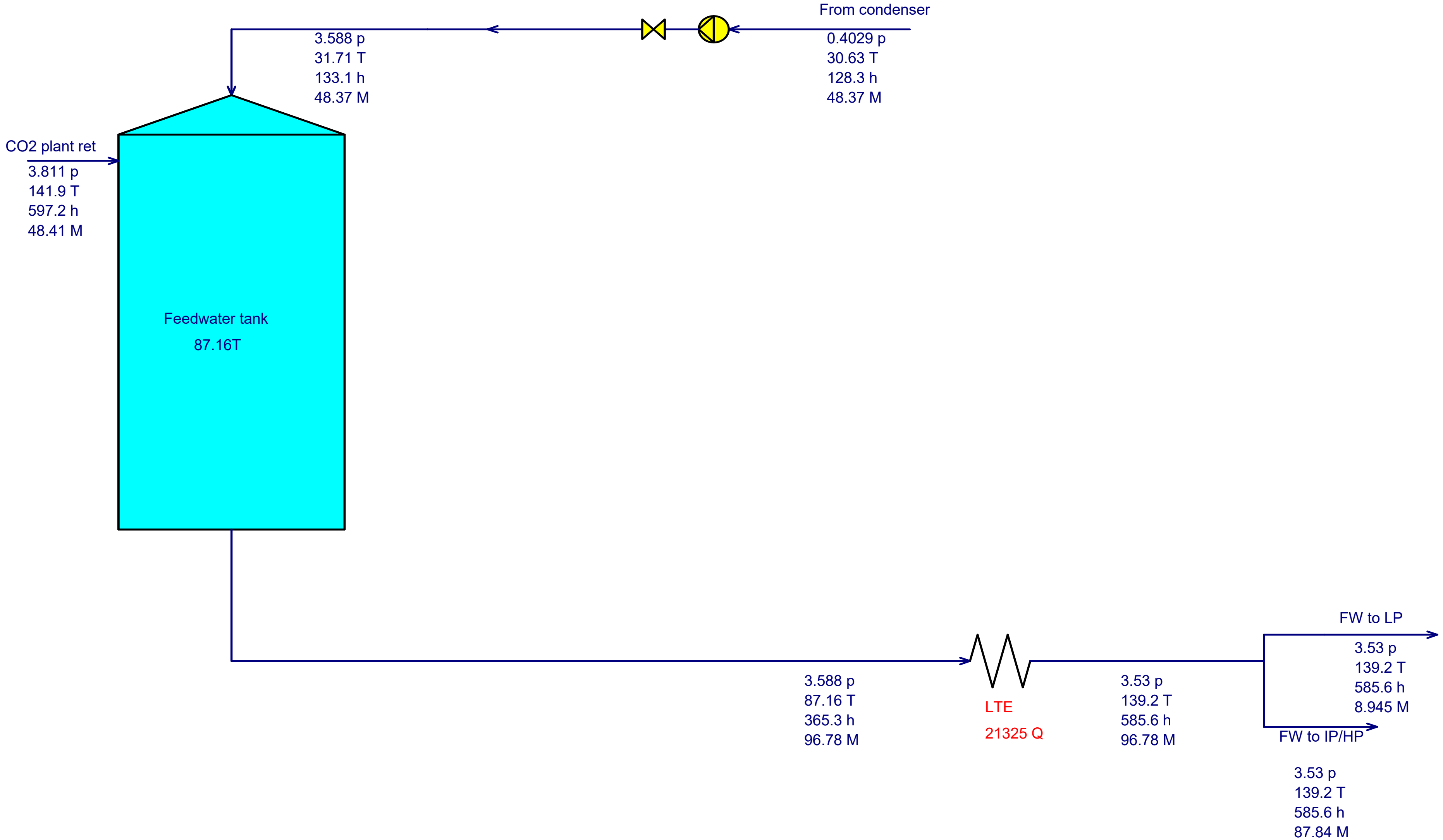
p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

LP Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

Feedwater Path

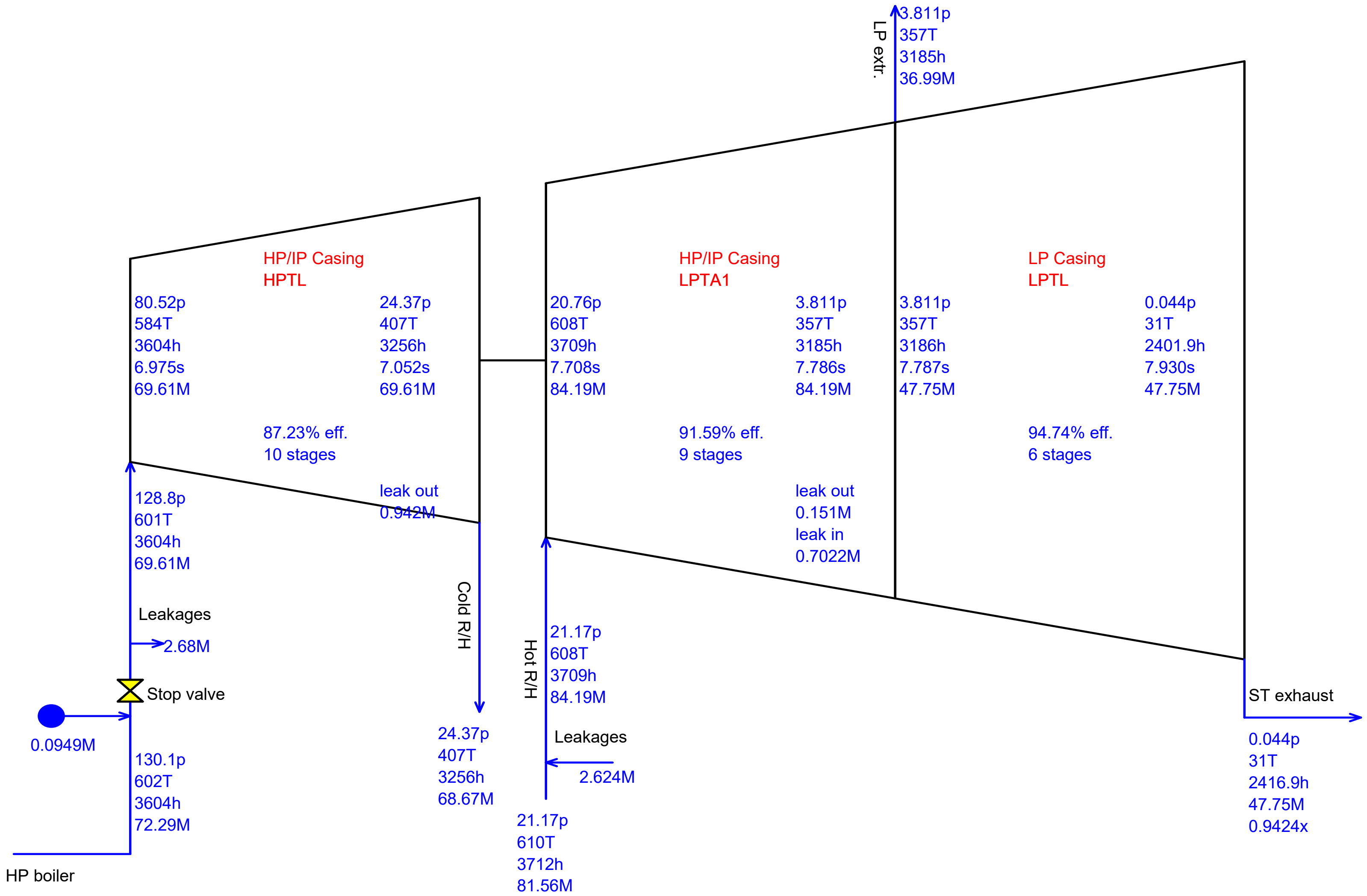


p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

GT MASTER 29.0 AECOM

ST Expansion Power 105086 kW
ST Generator Output 102965 kW

Steam Turbine Group Data

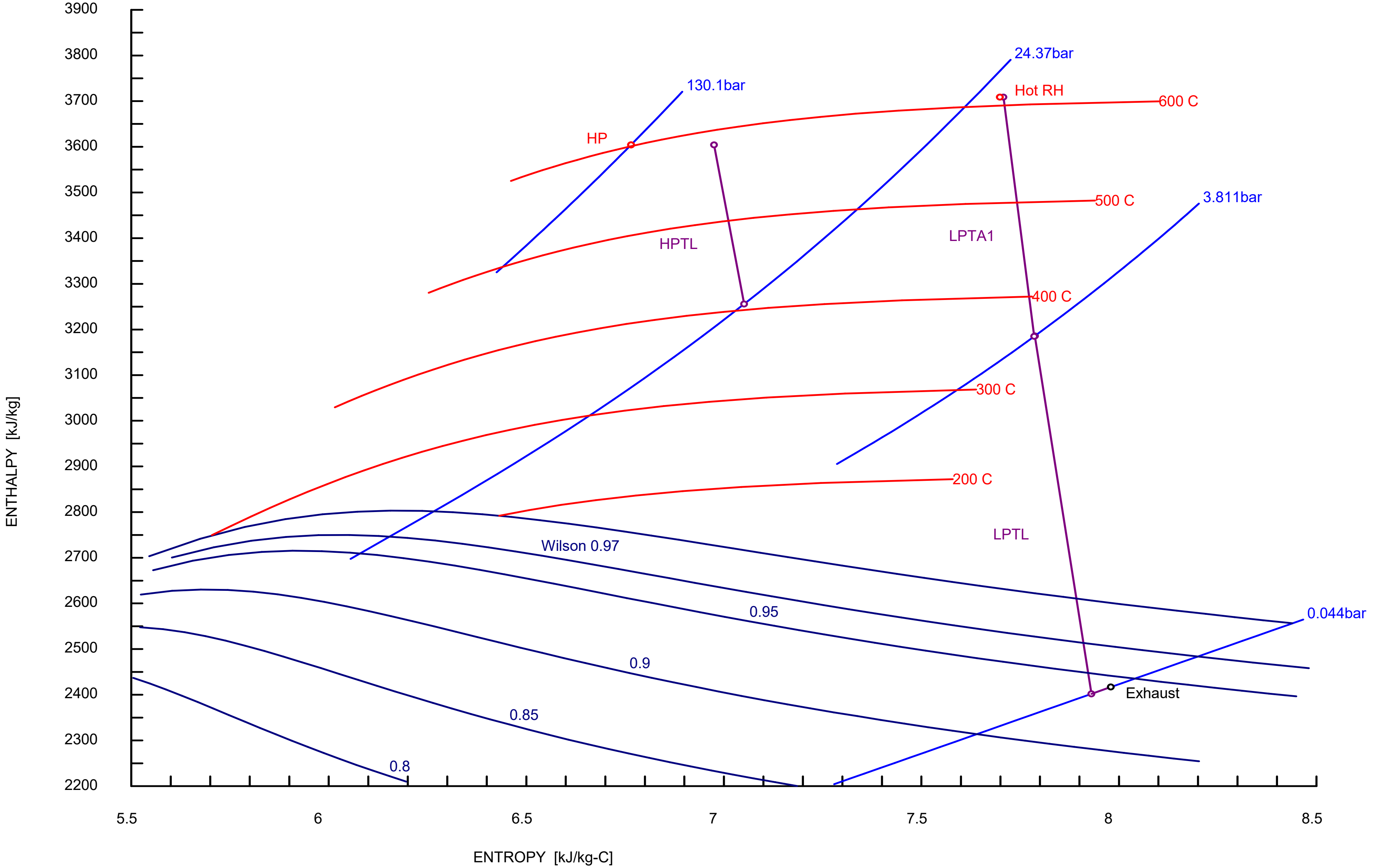


ST Model Adjustments: Disabled
p[bar], T[C], h[kJ/kg], s[kJ/kg-C], M[kg/s], Steam Properties: IAPWS-IF97
1220 06-11-2020 20:06:49 file=

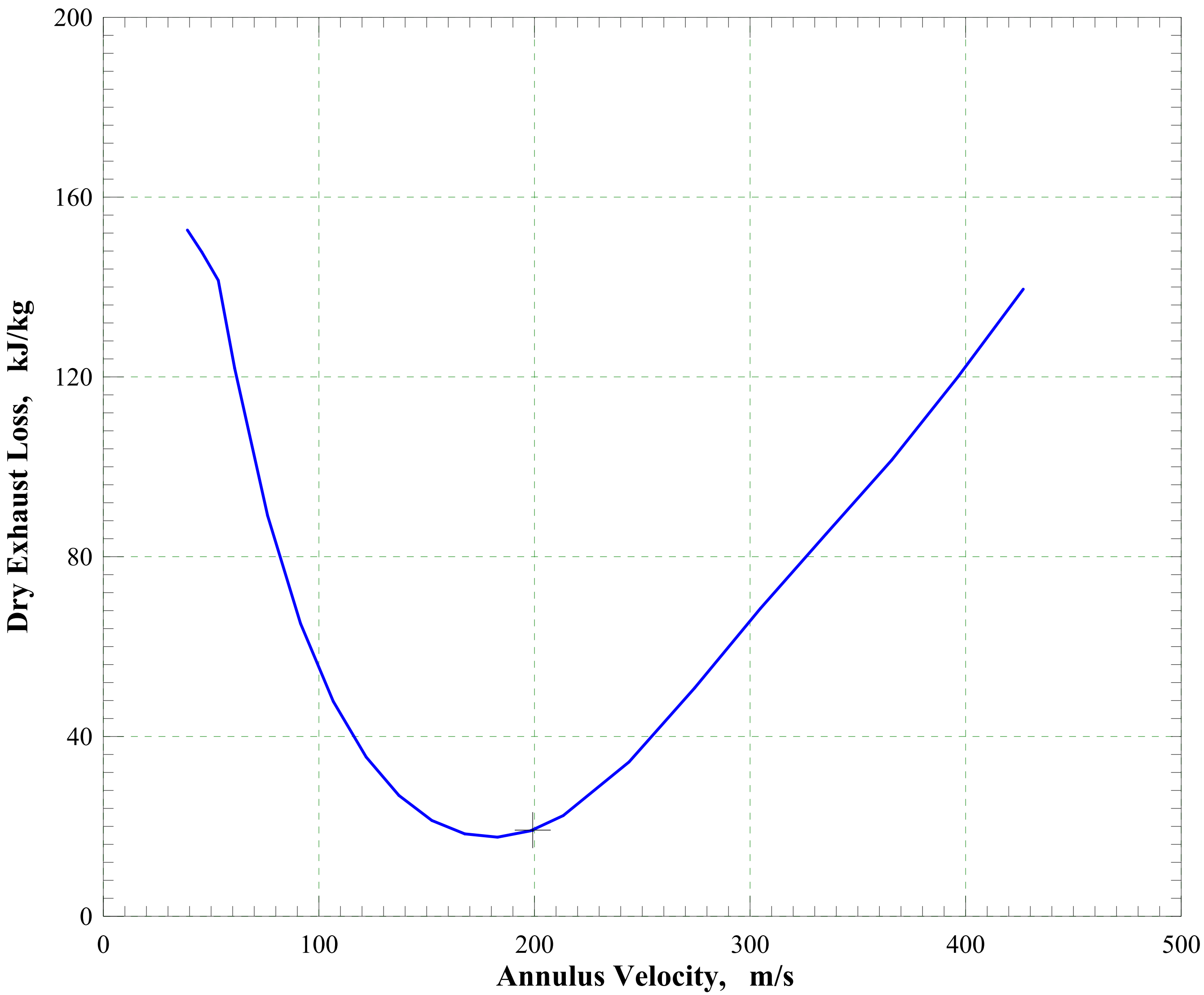
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

ST Expansion Power 105086 kW
ST Generator Output 102965 kW

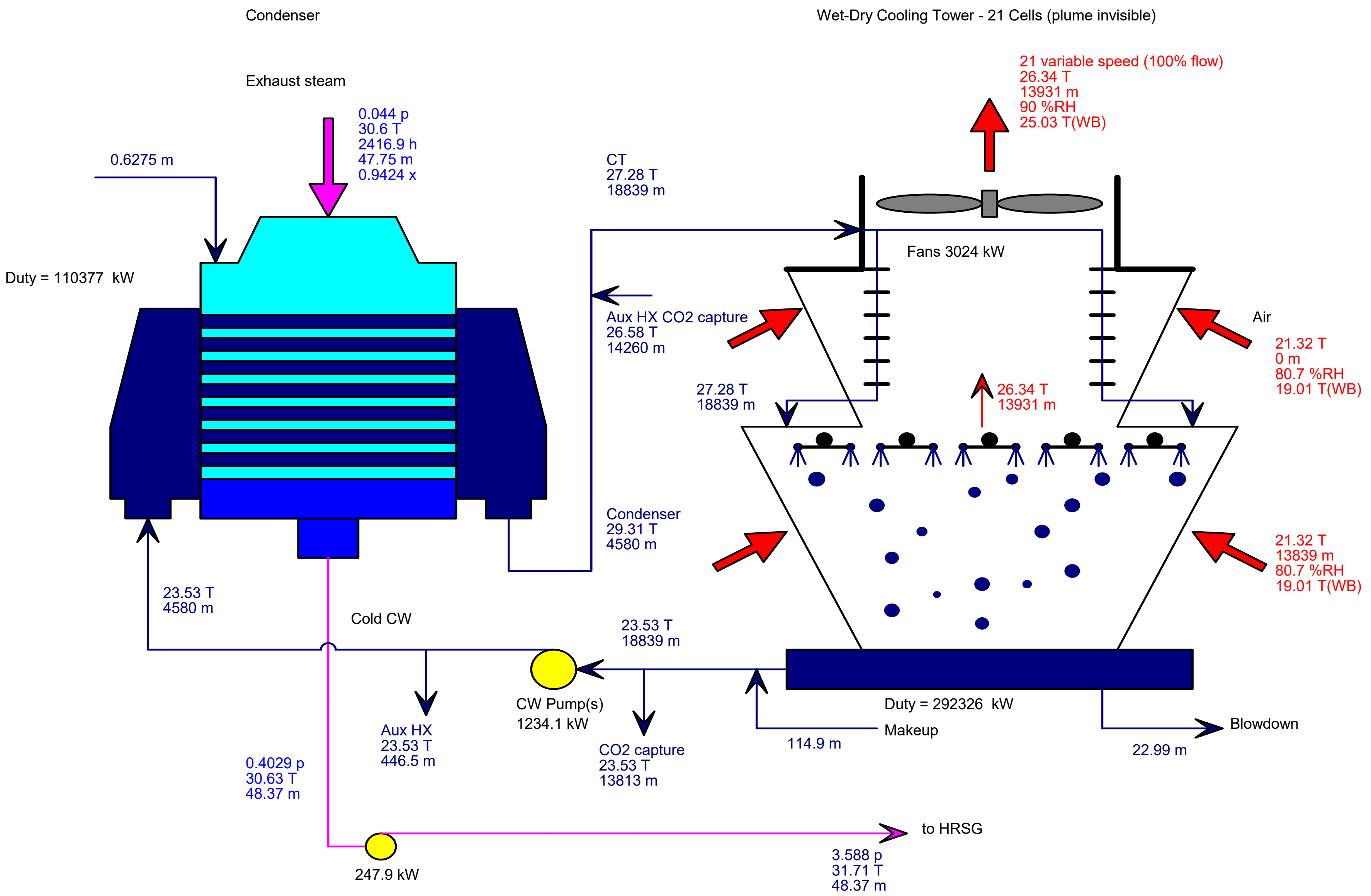
Steam Turbine Expansion Path



Steam Turbine Exhaust Loss



Cooling System



p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

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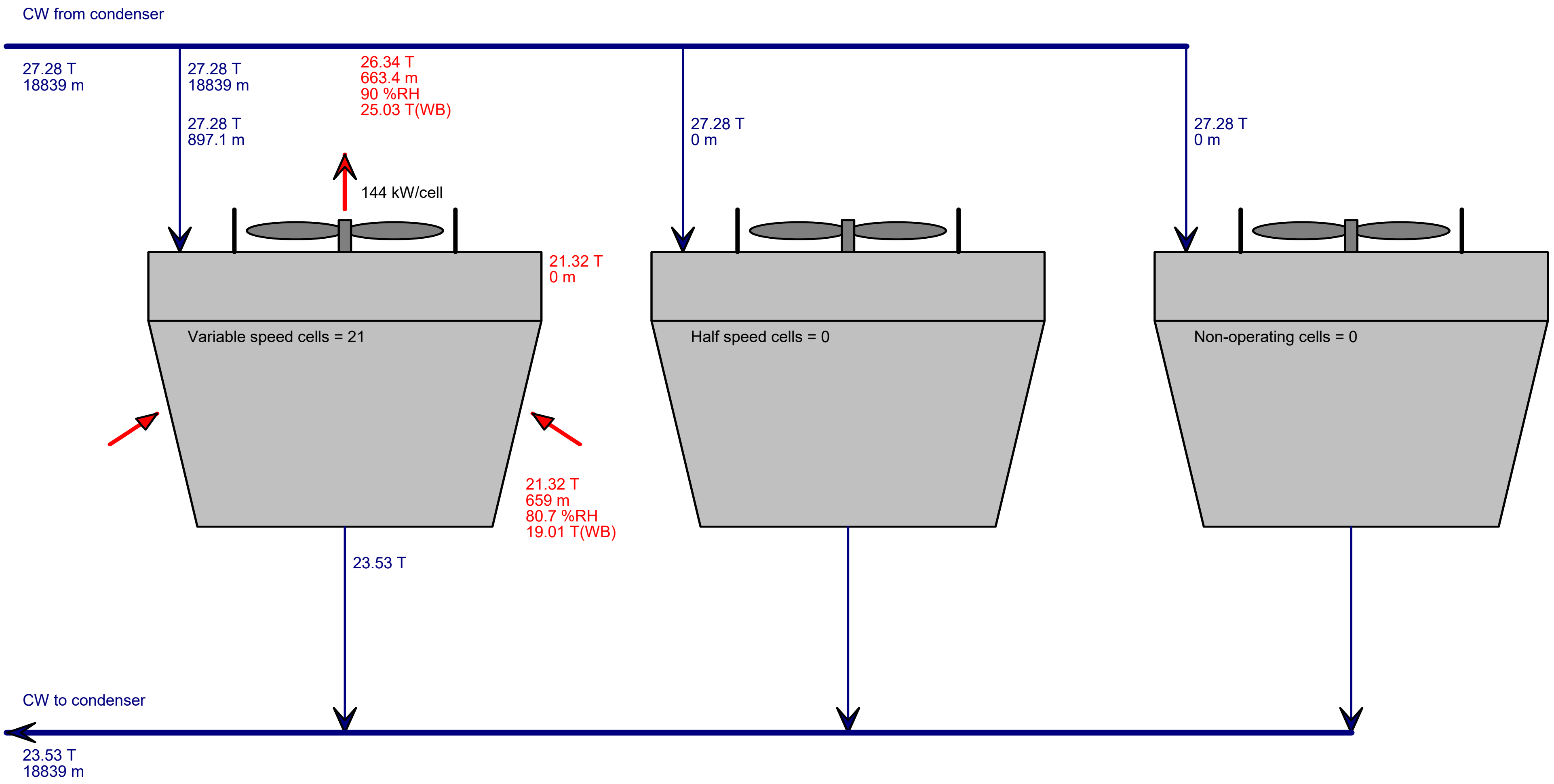
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Cooling Tower Cells - 21 existing cells



p[bar], T[C], m[kg/s], Steam Properties: IAPWS-IF97

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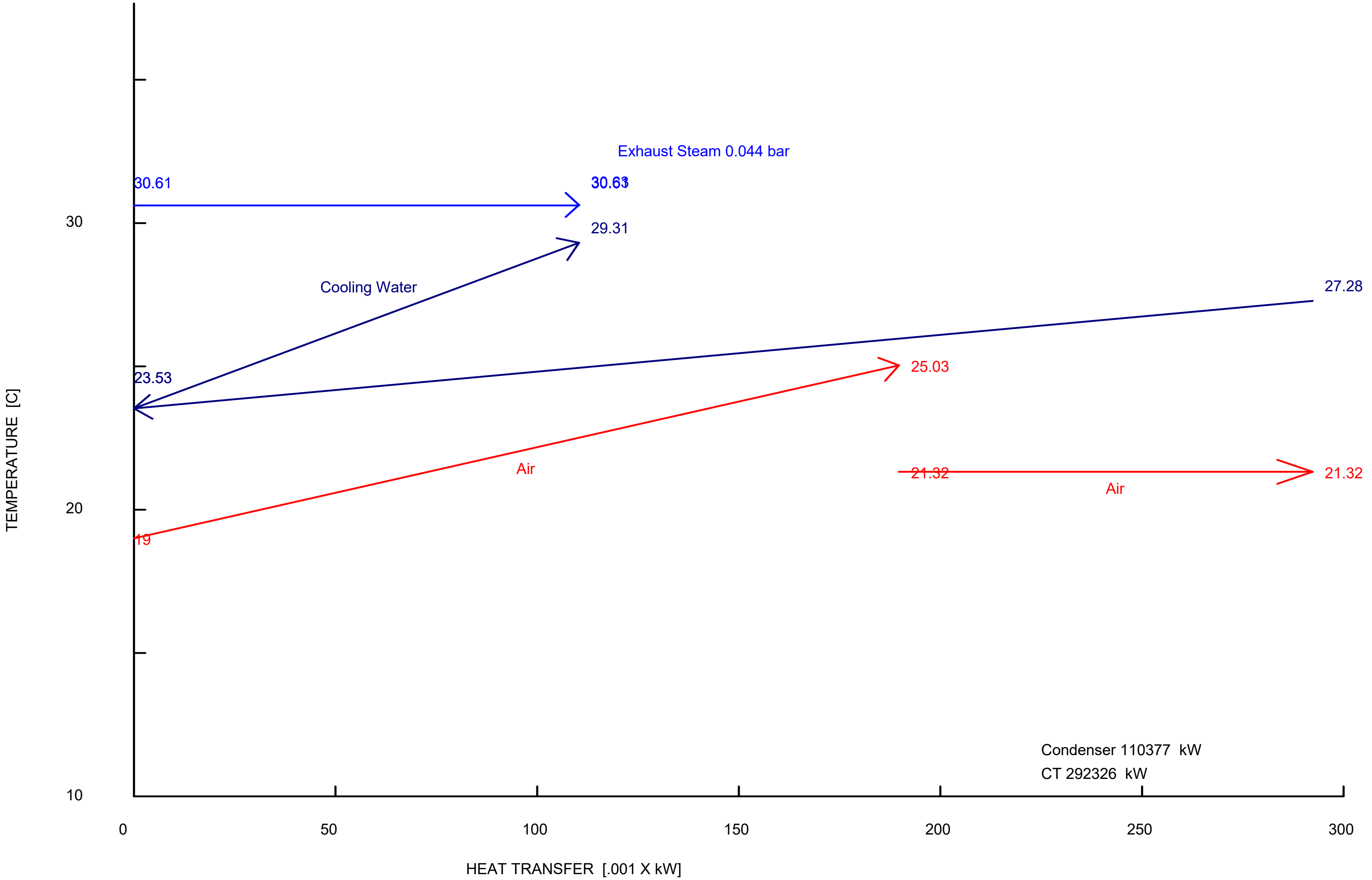
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck inc CCS95pc.GTM

Water Cooled Condenser and Wet-Dry Cooling Tower T-Q Diagram



AIR STATES:

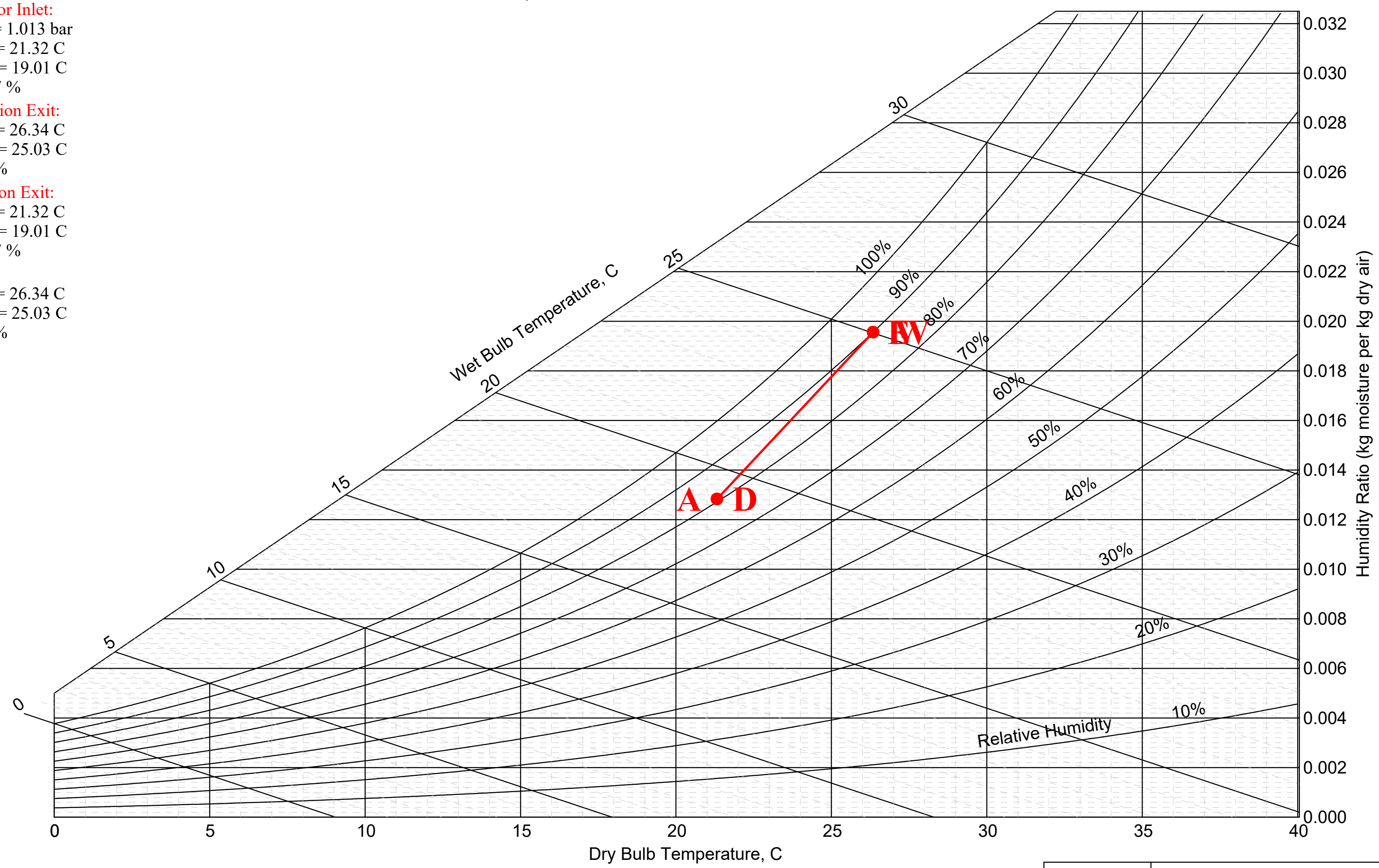
A) Ambient or Inlet:
Pressure = 1.013 bar
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %

W) Wet Section Exit:
Dry bulb = 26.34 C
Wet bulb = 25.03 C
RH = 90 %

D) Dry Section Exit:
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %

E) Air Exit:
Dry bulb = 26.34 C
Wet bulb = 25.03 C
RH = 90 %

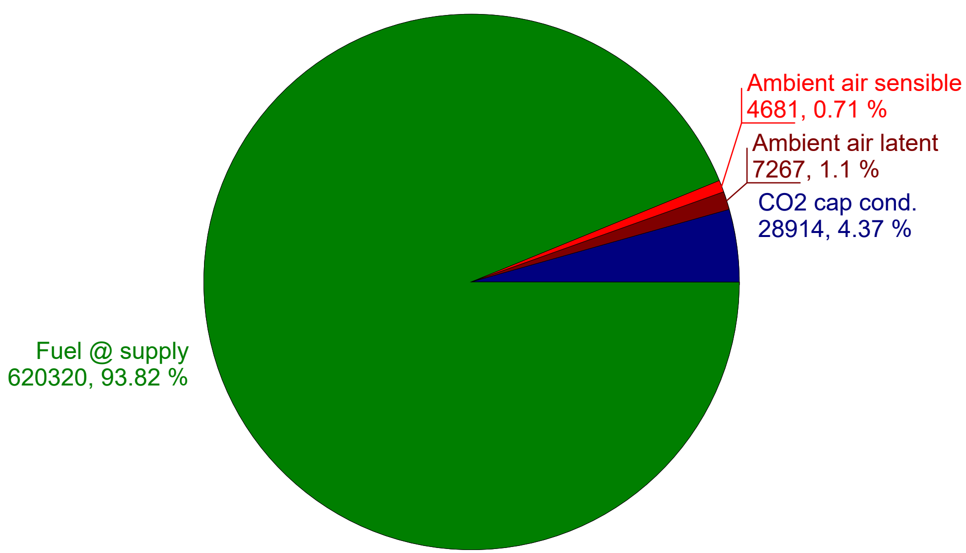
Psychrometric Chart



Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Cooling Tower
Date: 06/11/20	
Drawing No:	

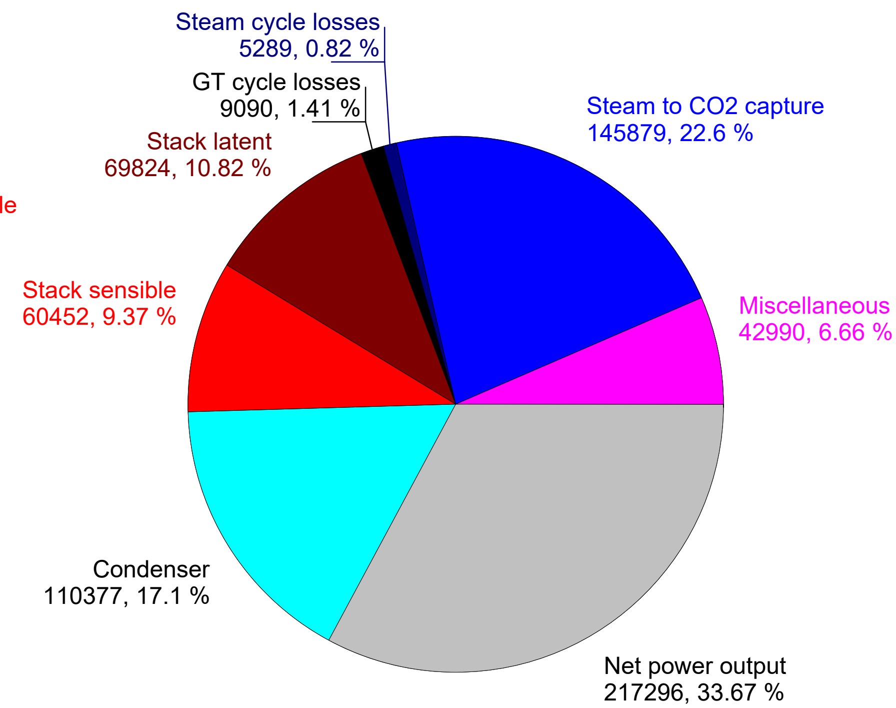
Plant Energy In [kW]

Plant energy in = 661196 kW
Plant fuel chemical LHV input = 557216 kW, HHV = 618295 kW
Plant net LHV elec. eff. = 39 % (100% * 217296 / 557216), Net HHV elec. eff. = 35.14 %



Plant Energy Out [kW]

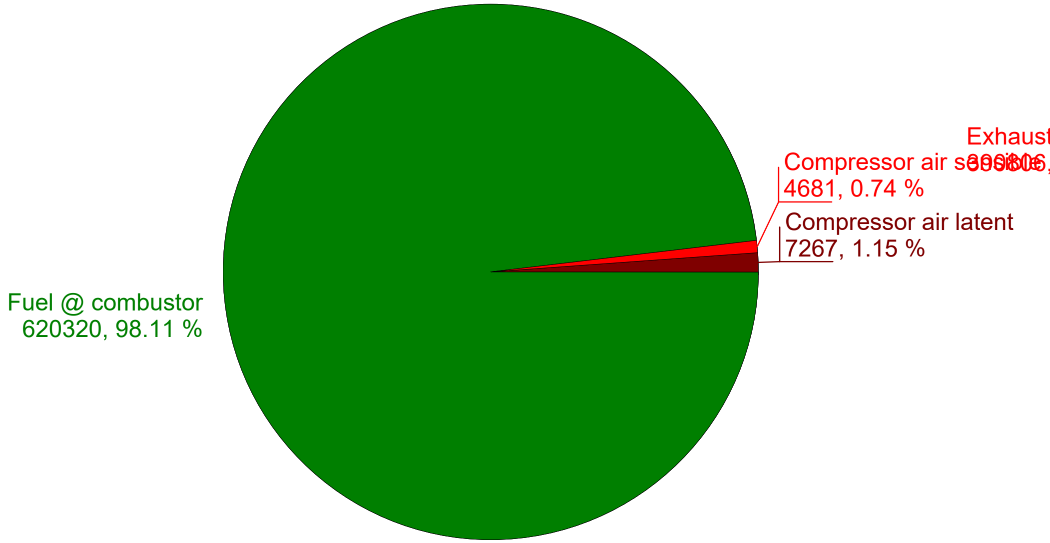
Plant energy out = 645419 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

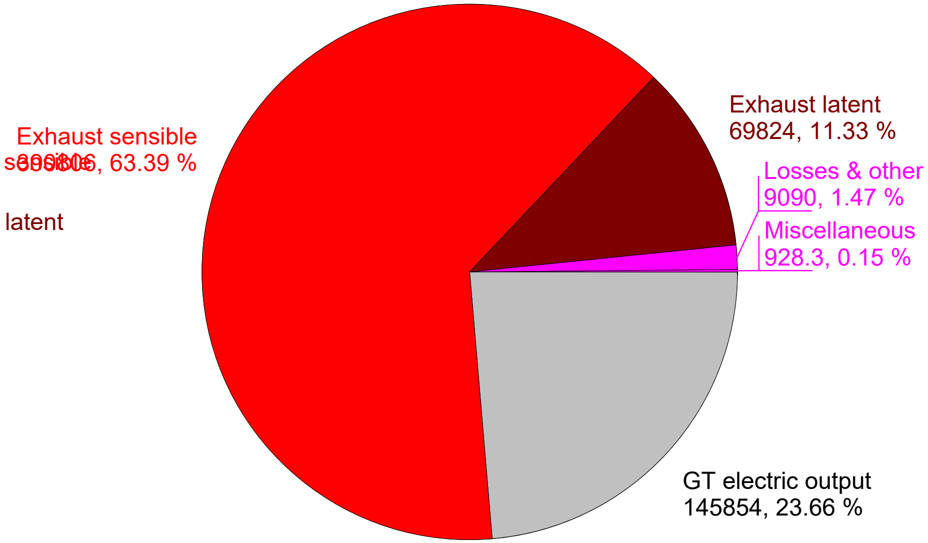
GT Cycle Energy In [kW]

GT cycle energy in = 632268 kW
GT fuel chemical LHV input = 557216 kW, HHV = 618295 kW



GT Cycle Energy Out [kW]

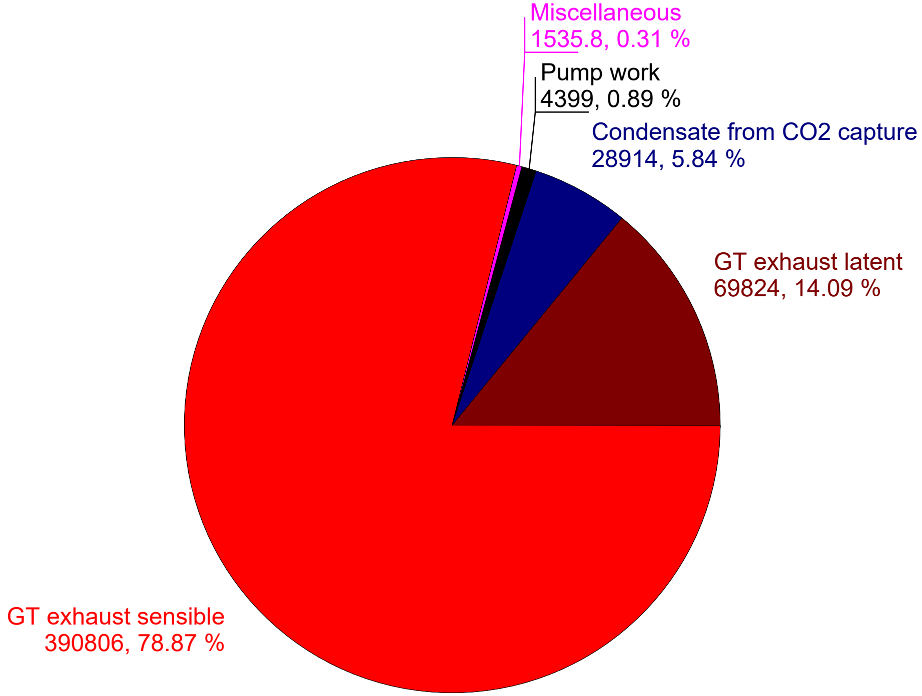
GT cycle energy out = 616503 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

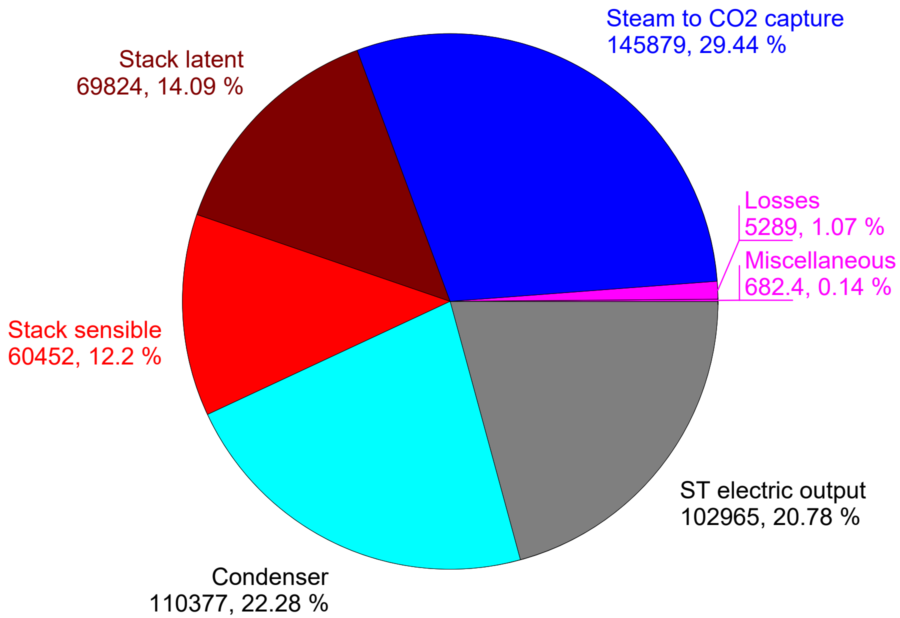
Steam Cycle Energy In [kW]

Steam cycle energy in = 495479 kW



Steam Cycle Energy Out [kW]

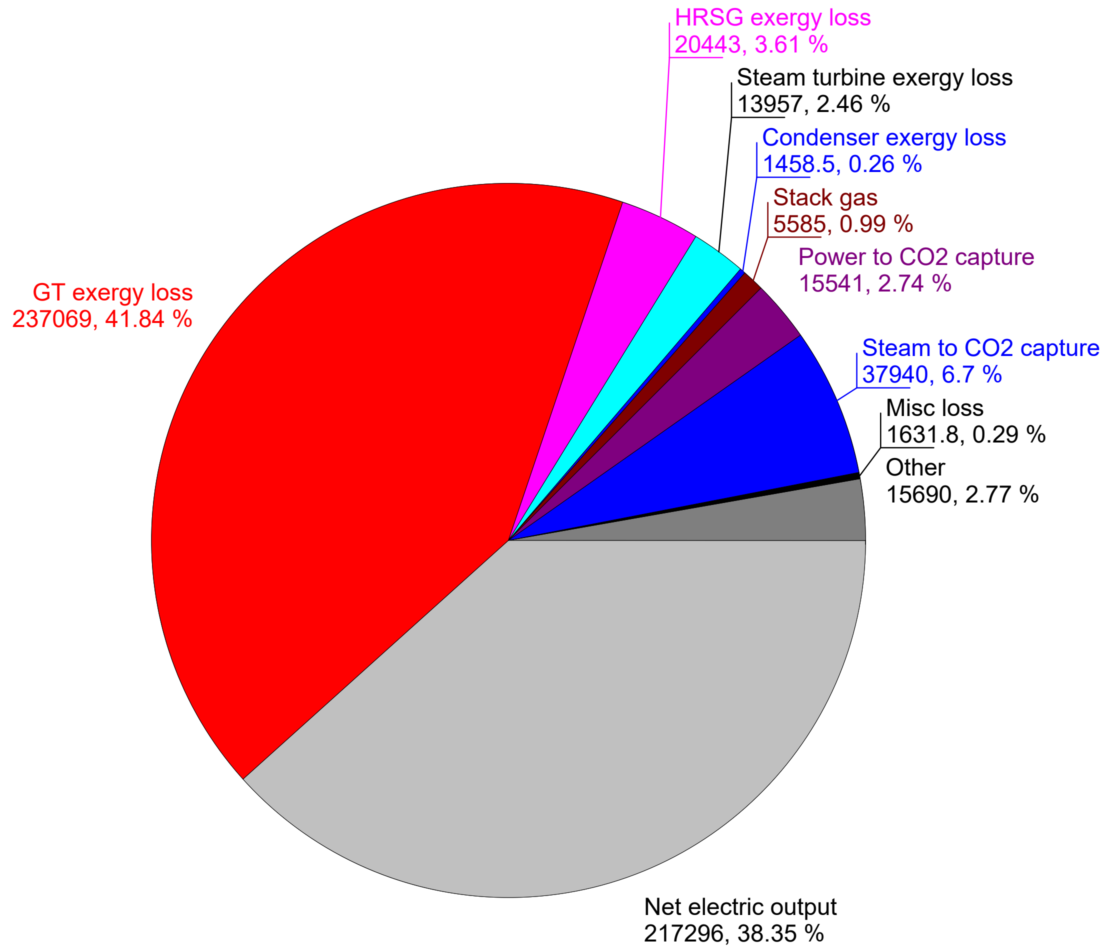
Steam cycle energy out = 495467 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Plant Exergy Analysis [kW]

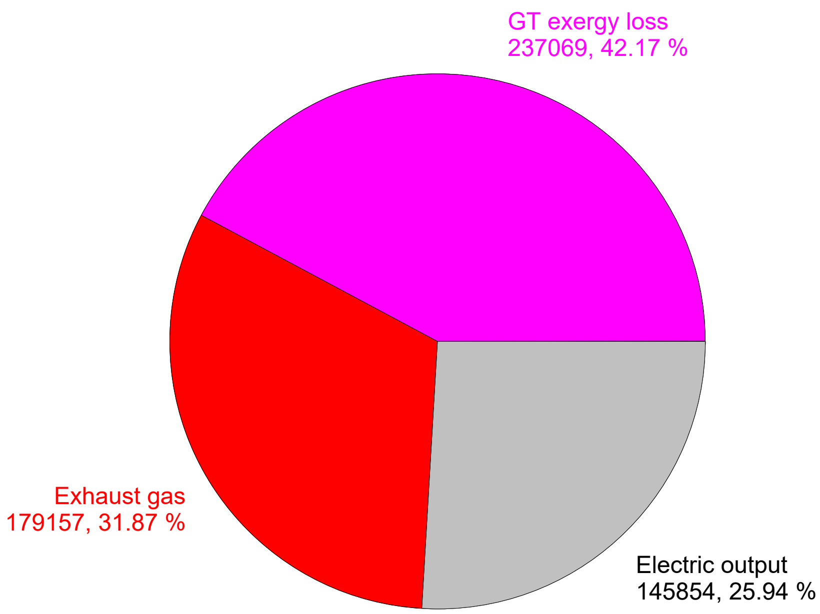
Plant exergy input = 566611 kW
Fuel exergy input = 562576 kW
Plant fuel chemical LHV input = 557216 kW, HHV = 618295 kW



Reference: 1.013 bar, 25 C, water as vapor.

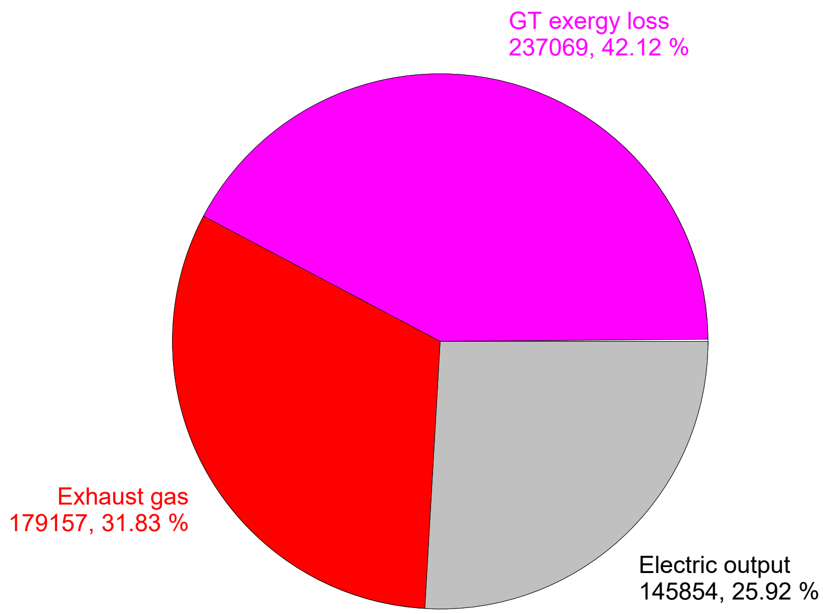
GT Exergy Analysis [kW]

GT exergy in = 562229 kW



GT & Peripheral Exergy Analysis [kW]

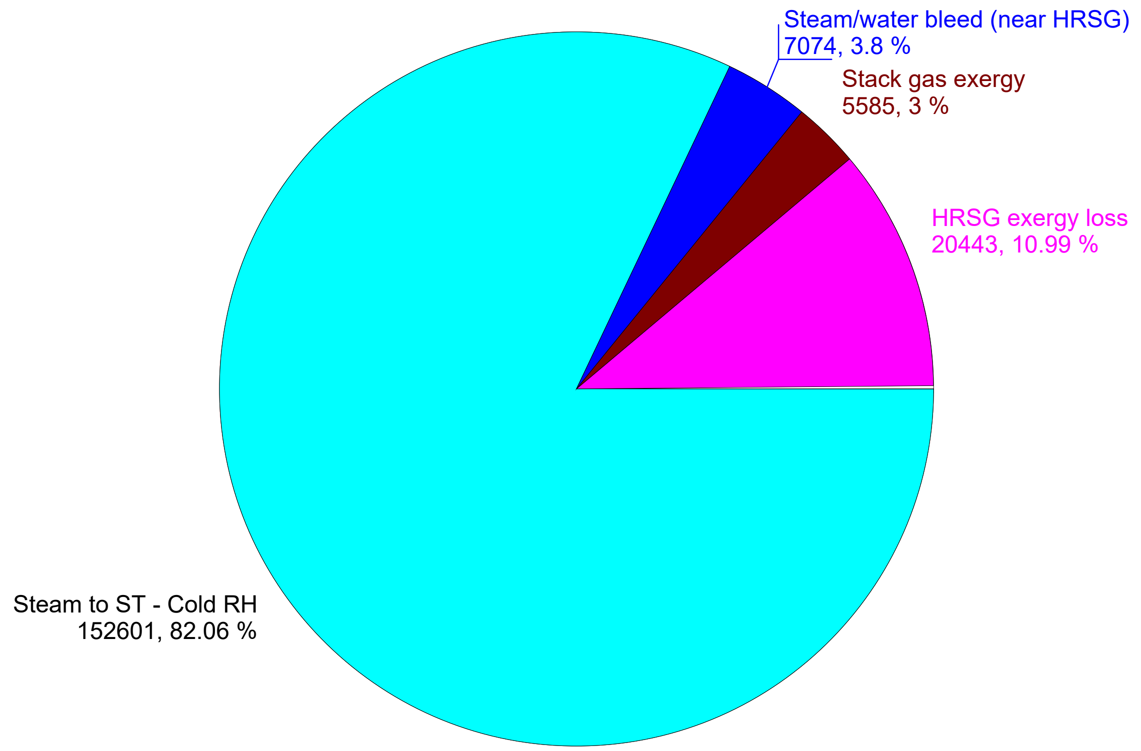
GT & peripheral exergy in = 562809 kW



Reference: 1.013 bar, 25 C, water as vapor.

HRSG Exergy Analysis [kW]

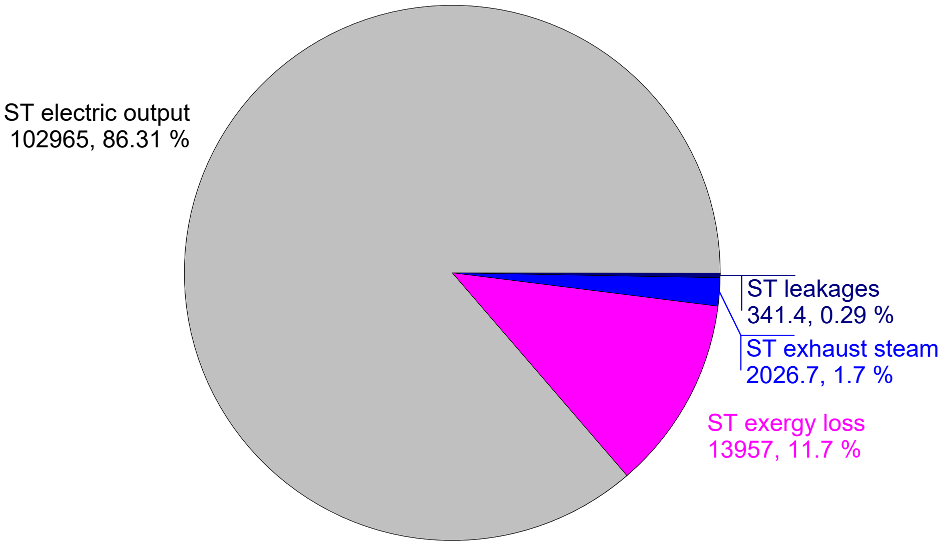
HRSG exergy in = 185959 kW



Reference: 1.013 bar, 25 C, water as vapor.

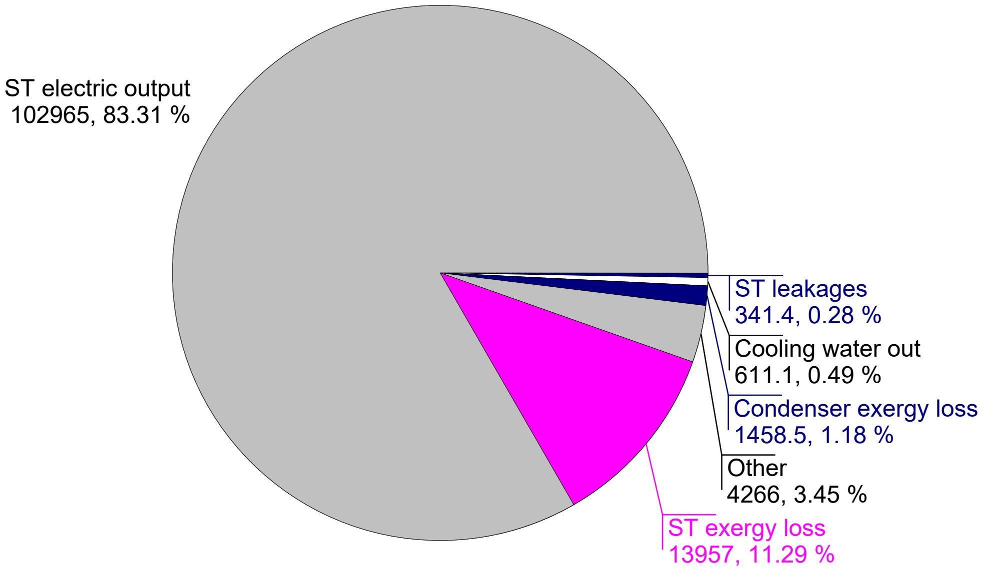
ST Exergy Analysis [kW]

ST exergy in = 119289 kW



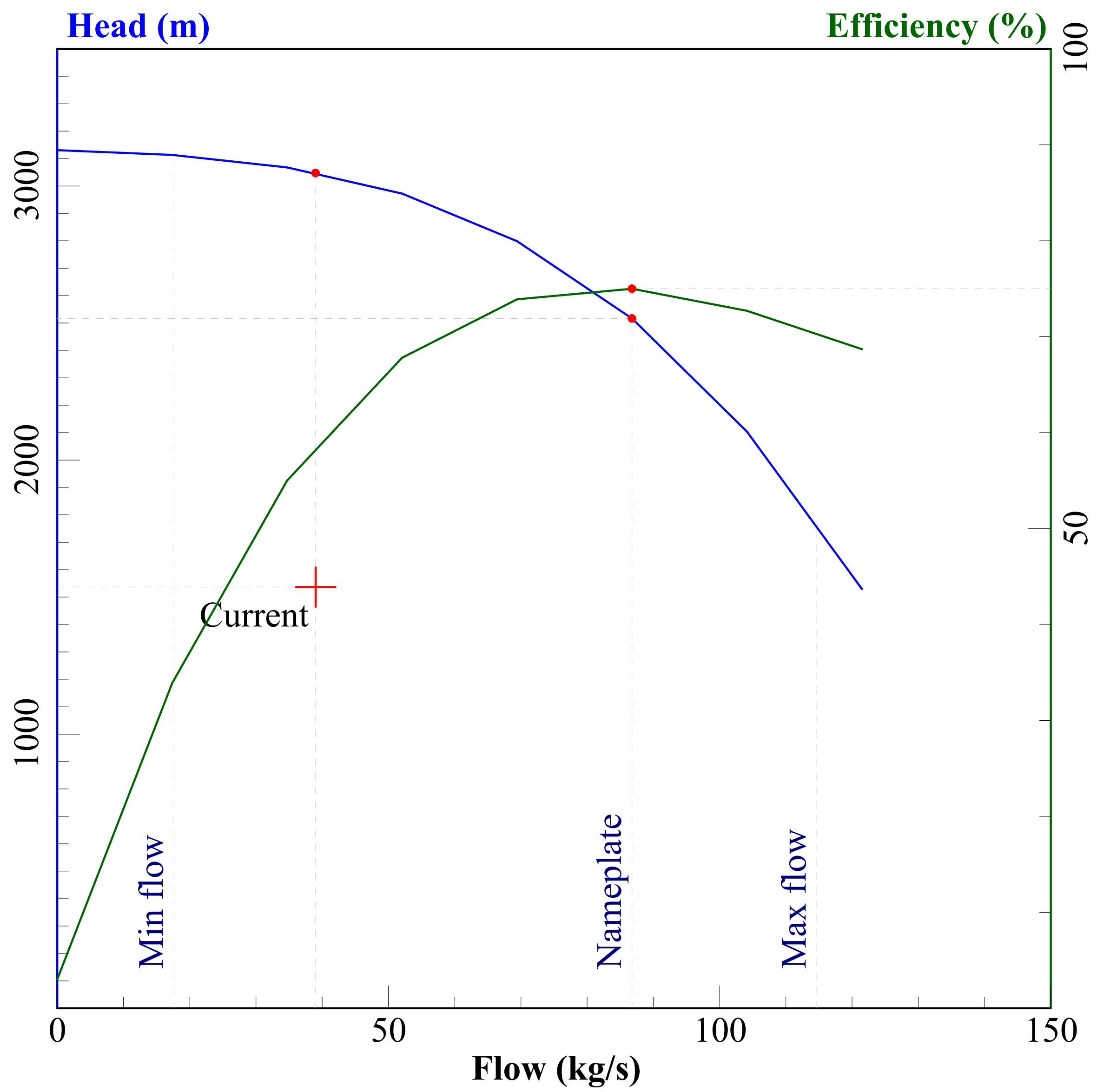
ST & Condenser Exergy Analysis [kW]

ST & condenser exergy in = 123598 kW



Reference: 1.013 bar, 25 C, water as vapor.

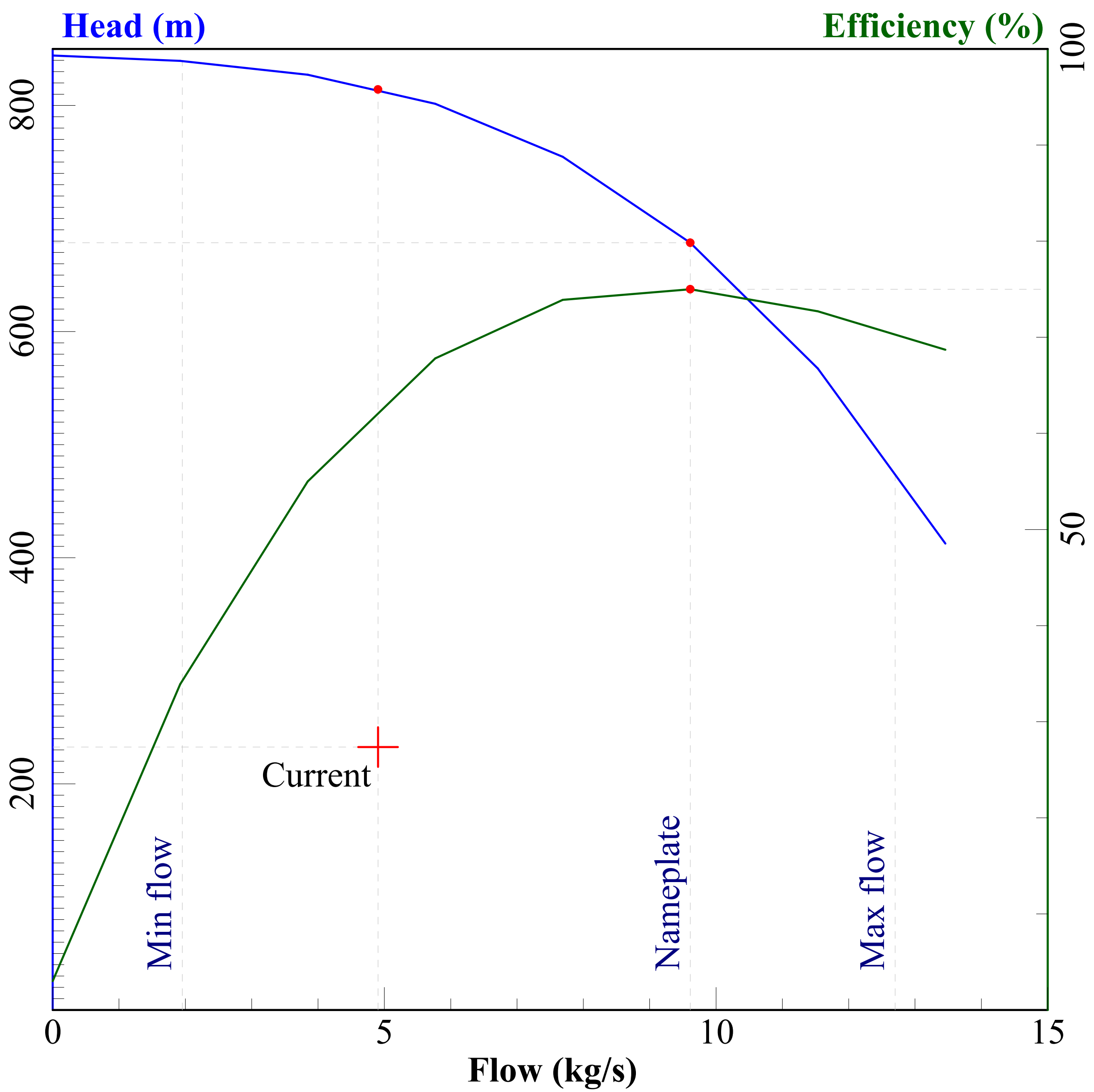
HP Feedwater Pump (P1)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	86.77 kg/s
Nameplate head	2516.5 m
Nameplate flow (nominal)	5678 lpm
Nameplate head (nominal)	2560.3 m
Nameplate RPM	3000
Current pump flow	39.02 kg/s
Current head	3047 m
Current head after valve	1536.3 m
Current RPM	3000
Minimum continuous flow	17.64 kg/s
Maximum continuous flow	114.7 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HP Feedwater Pump (P1)
Date: 06/11/20	
Drawing No:	

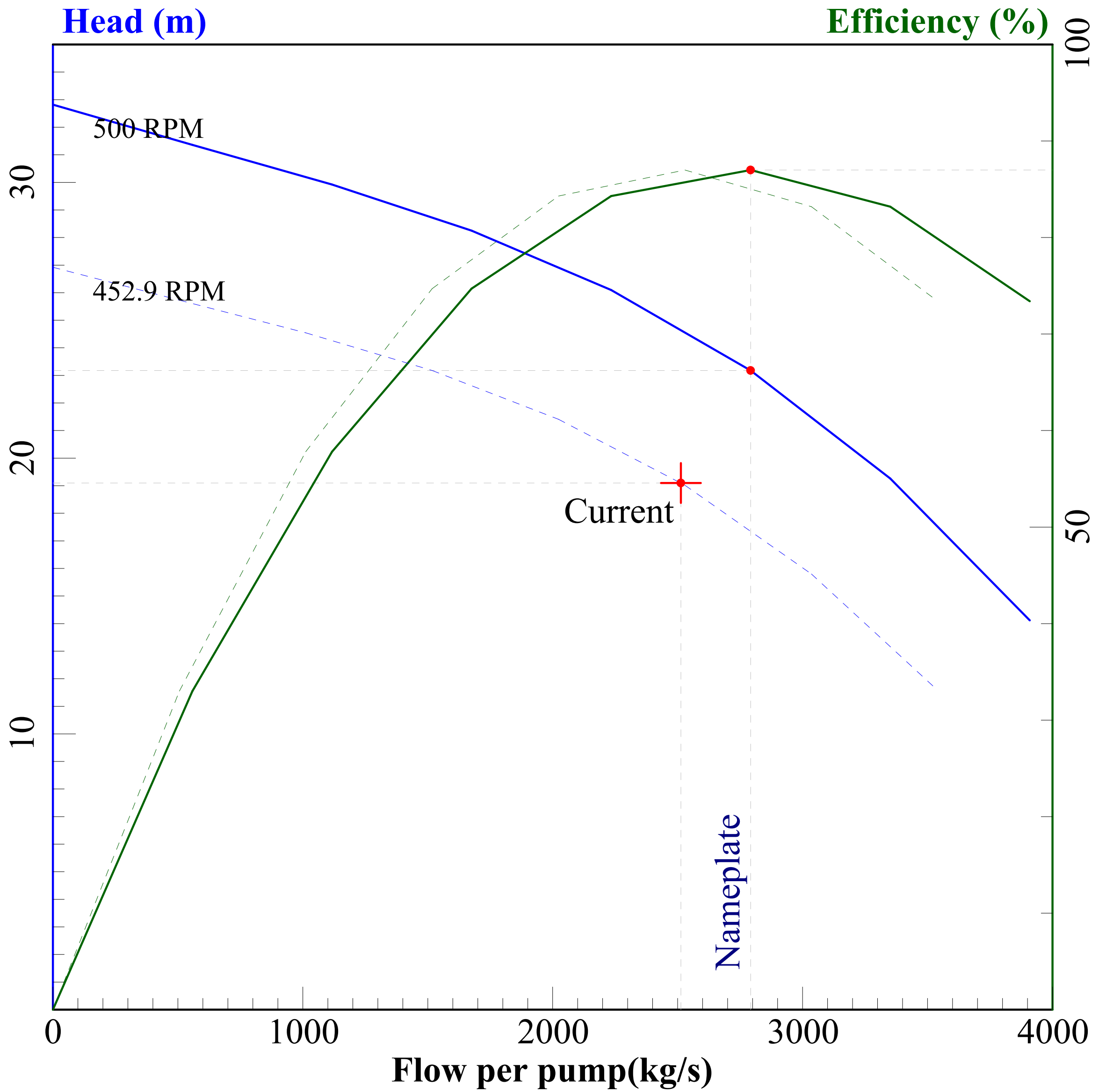
IP Feedwater Pump (P2)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	9.612 kg/s
Nameplate head	678.6 m
Nameplate flow (nominal)	662.4 lpm
Nameplate head (nominal)	701 m
Nameplate RPM	3000
Current pump flow	4.904 kg/s
Current head	814.1 m
Current head after valve	232.5 m
Current RPM	3000
Minimum continuous flow	1.954 kg/s
Maximum continuous flow	12.7 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IP Feedwater Pump (P2)
Date: 06/11/20	
Drawing No:	

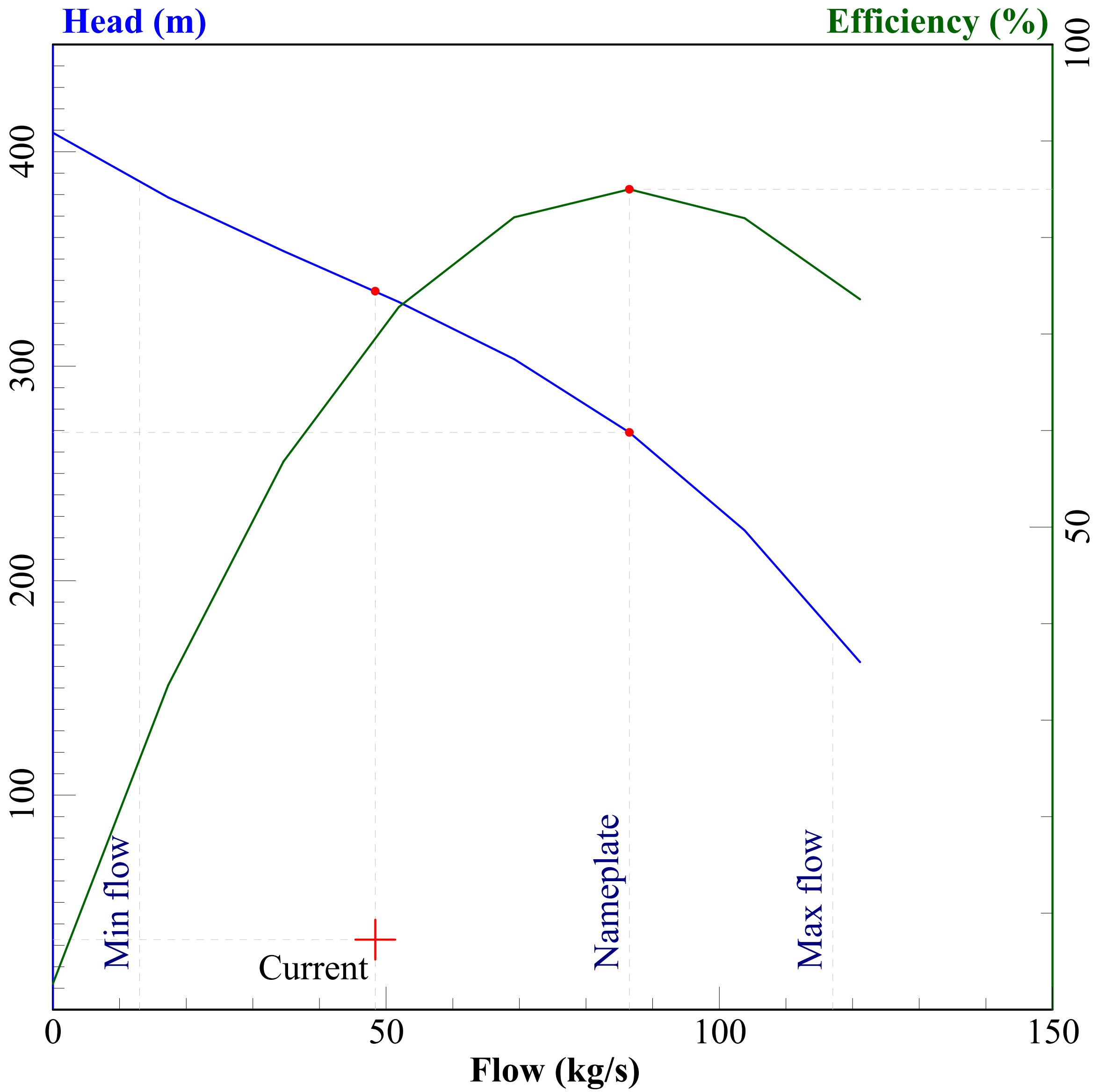
Condenser C.W. Pump (P4)



No. per Condenser	2
No. operating per Condenser	2
Nameplate flow	2792.3 kg/s
Nameplate head	23.18 m
Nameplate flow (nominal)	170344 lpm
Nameplate head (nominal)	24.38 m
Nameplate RPM	500
Current pump flow	2513 kg/s
Current head	19.1 m
Current head after valve	19.1 m
Current RPM	452.9

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condenser C.W. Pump (P4)
Date: 06/11/20	
Drawing No:	

Condensate Forwarding Pump (P6)

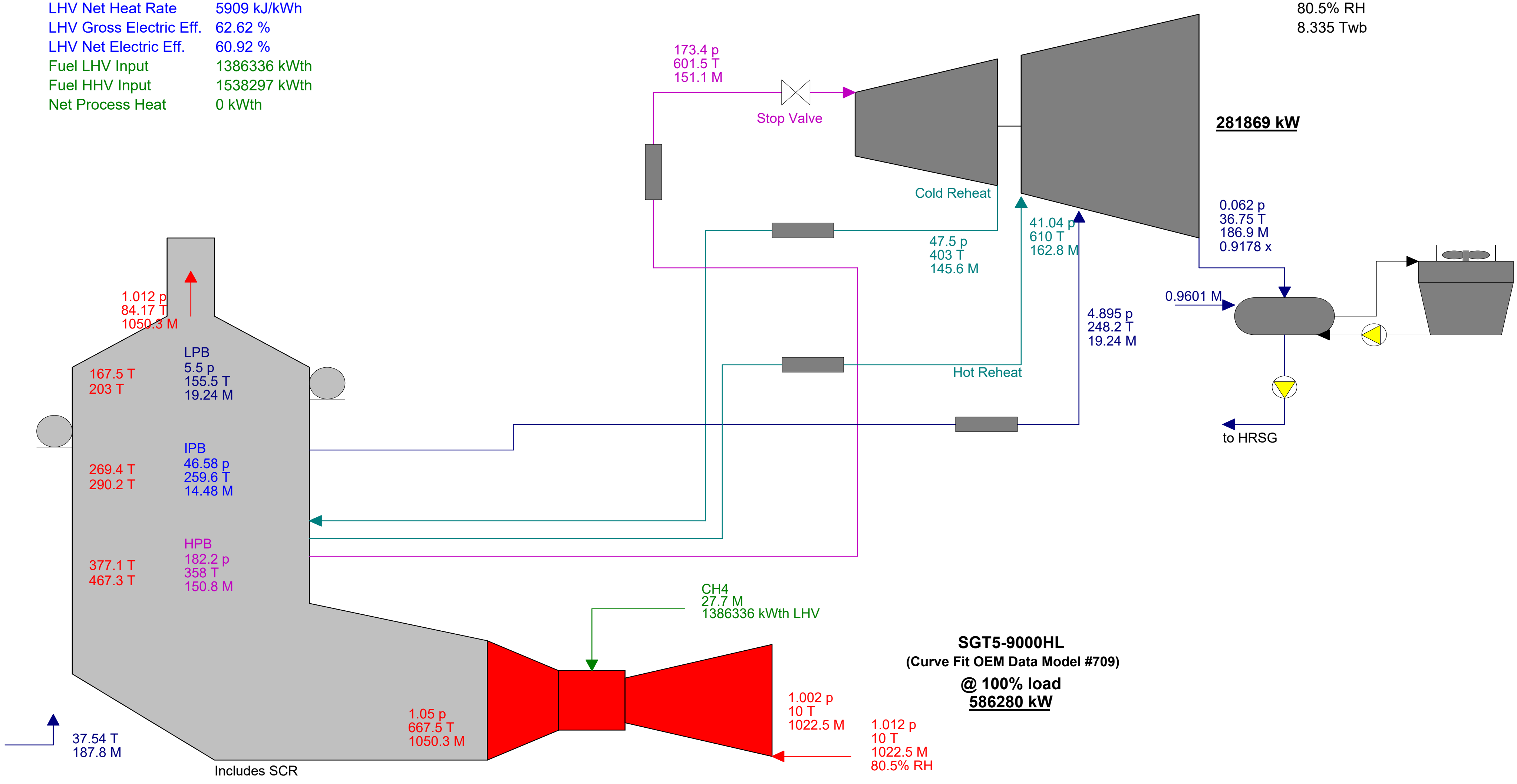


No. per Condenser	2
No. operating per Condenser	1
Nameplate flow	86.51 kg/s
Nameplate head	269.2 m
Nameplate flow (nominal)	5300 lpm
Nameplate head (nominal)	274.3 m
Nameplate RPM	1500
Current pump flow	48.37 kg/s
Current head	335 m
Current head after valve	32.63 m
Current RPM	1500
Minimum continuous flow	13 kg/s
Maximum continuous flow	117 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condensate Forwarding Pump (P6)
Date: 06/11/20	
Drawing No:	

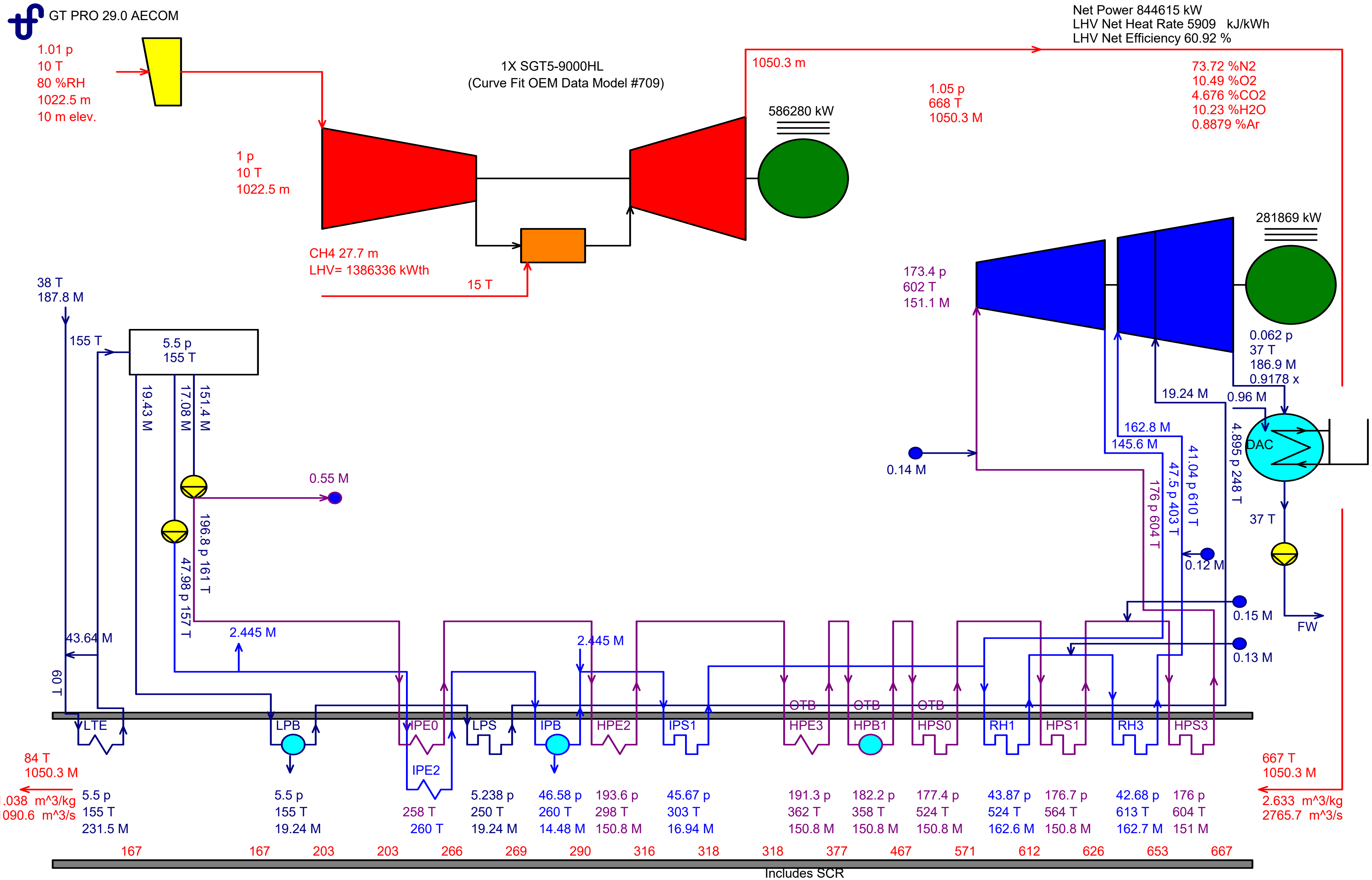
GT PRO 29.0 AECOM

Gross Power	868149 kW
Net Power	844615 kW
Aux. & Losses	23534 kW
LHV Gross Heat Rate	5749 kJ/kWh
LHV Net Heat Rate	5909 kJ/kWh
LHV Gross Electric Eff.	62.62 %
LHV Net Electric Eff.	60.92 %
Fuel LHV Input	1386336 kWth
Fuel HHV Input	1538297 kWth
Net Process Heat	0 kWth



p [bar] T [C] M [kg/s], Steam Properties: IAPWS-IF97
1220 06-15-2020 14:40:07 file=

GT PRO 29.0 AECOM
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck.GTP



p[bar], T[C], M[kg/s], Steam Properties: IAPWS-IF97

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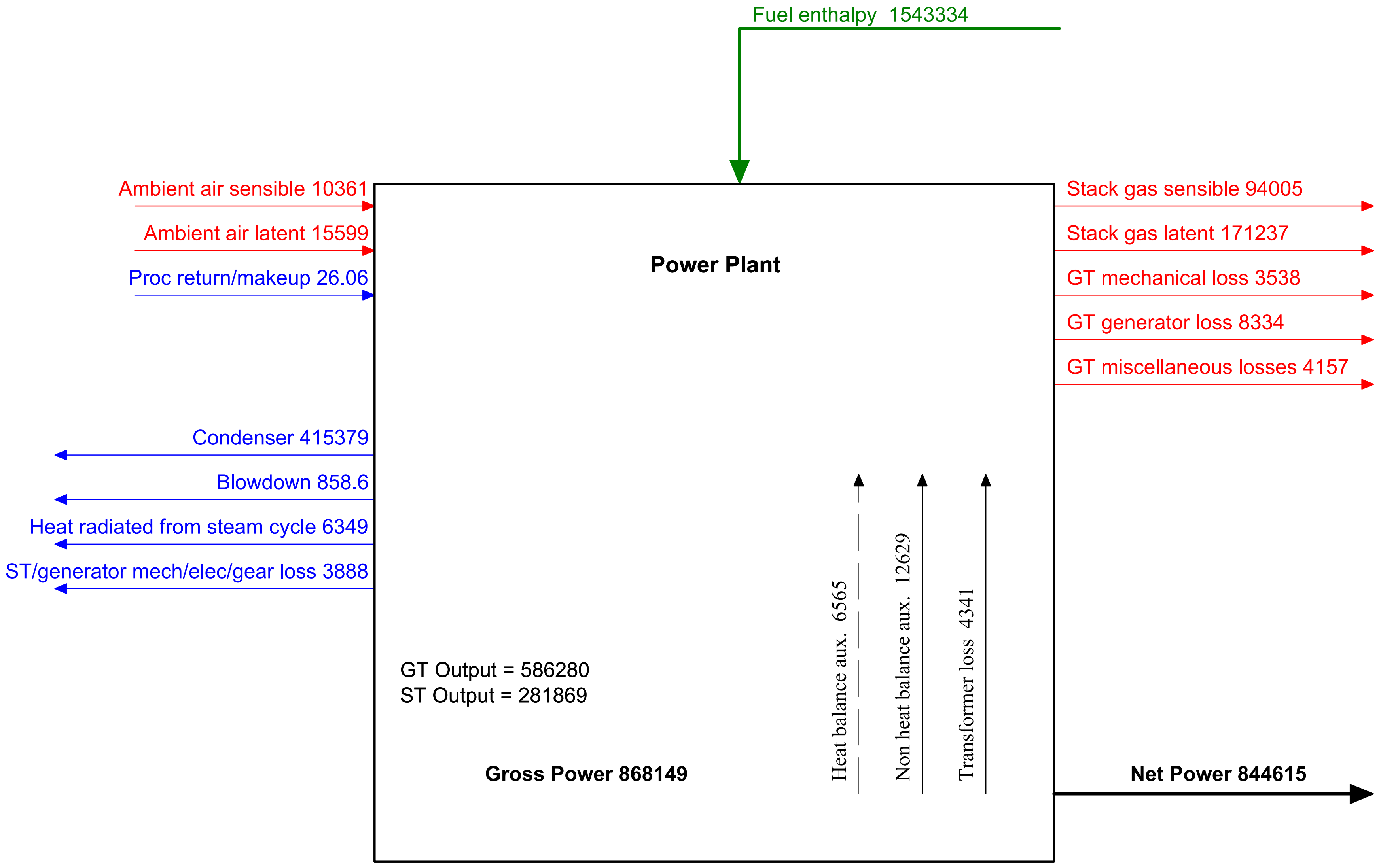
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck.GTP

Fuel chemical LHV input = 1386336 kW
Fuel chemical HHV input = 1538297 kW

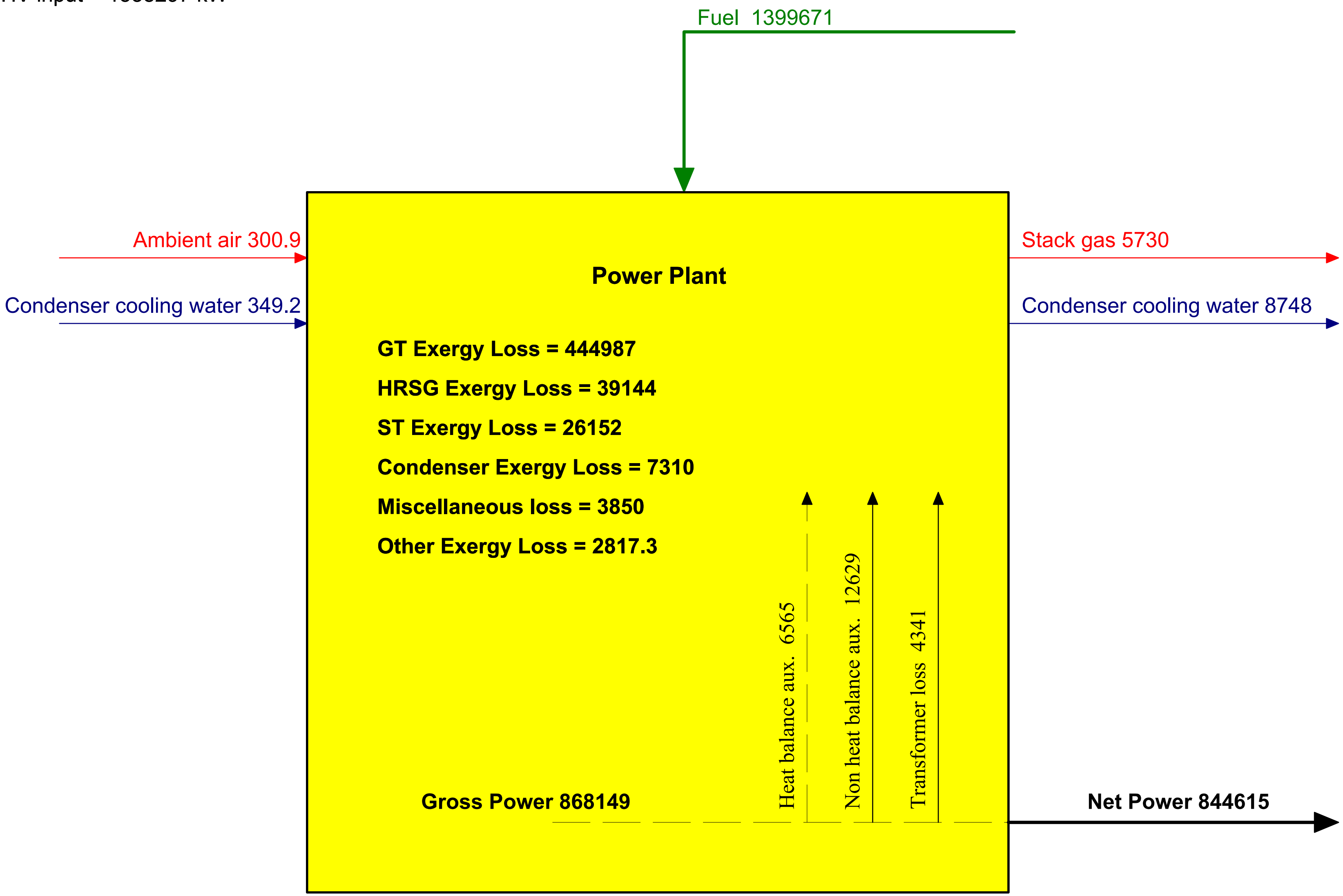
Power Plant Energy Flow Schematic [kW]



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Fuel exergy input = 1399671 kW
Fuel chemical LHV input = 1386336 kW
Fuel chemical HHV input = 1538297 kW

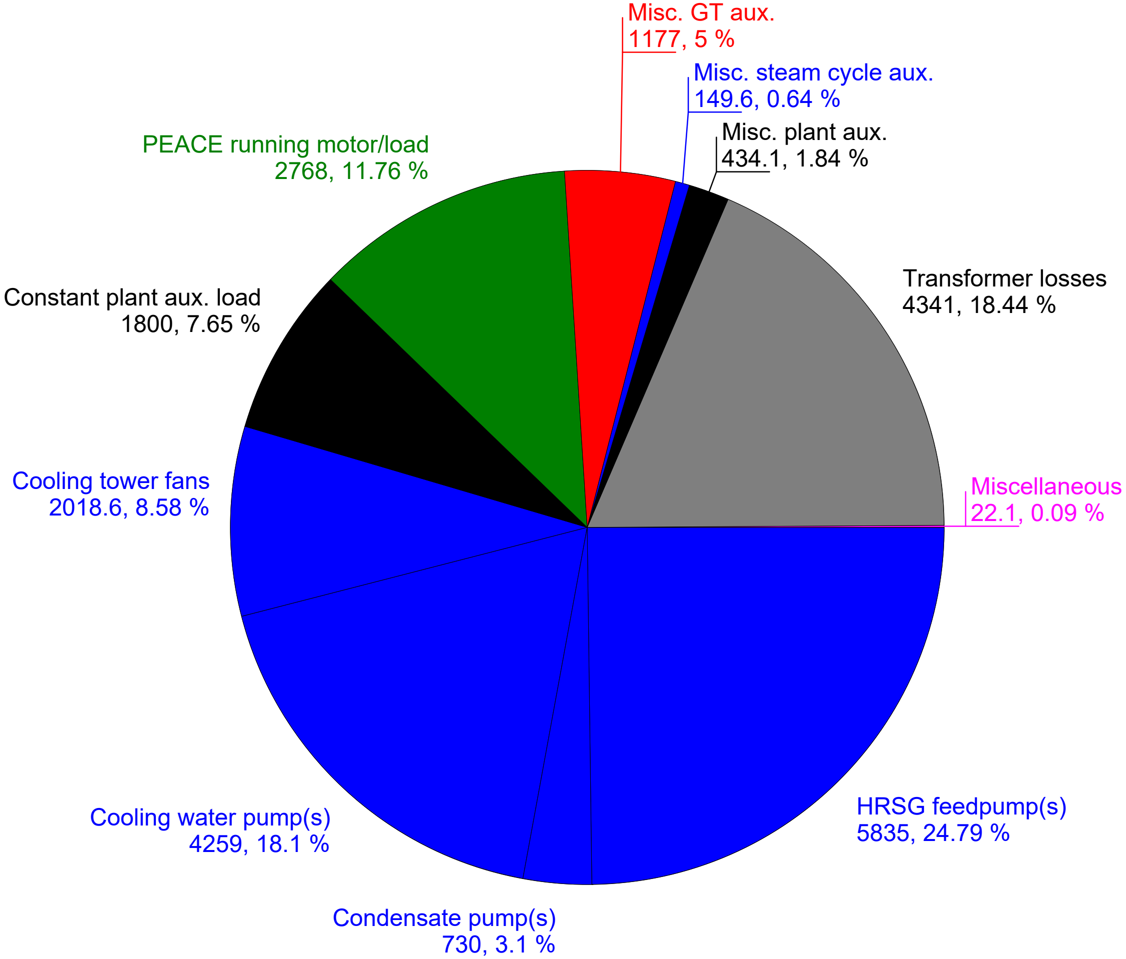
Power Plant Exergy Flow Schematic [kW]



Reference: 1.013 bar, 25 C, water as vapor.

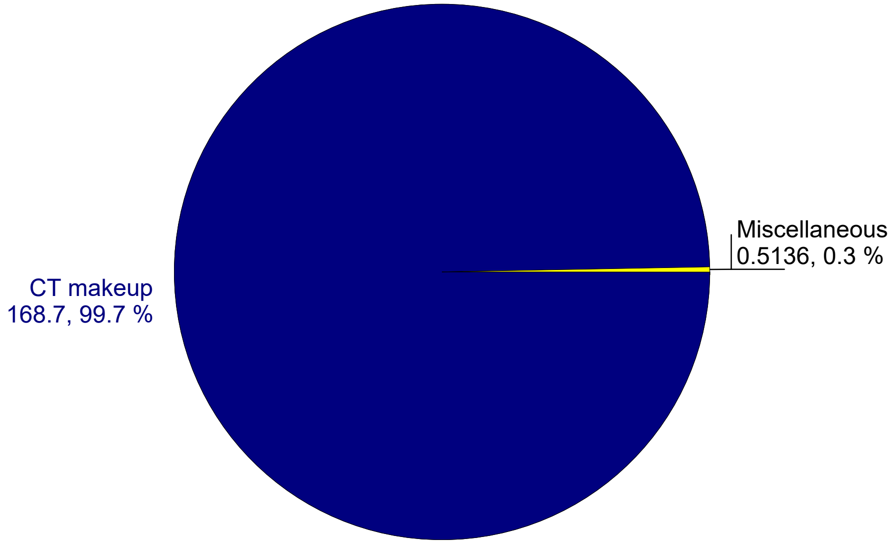
Auxiliaries & Losses [kW]

Total auxiliaries & transformer losses = 23534 kW



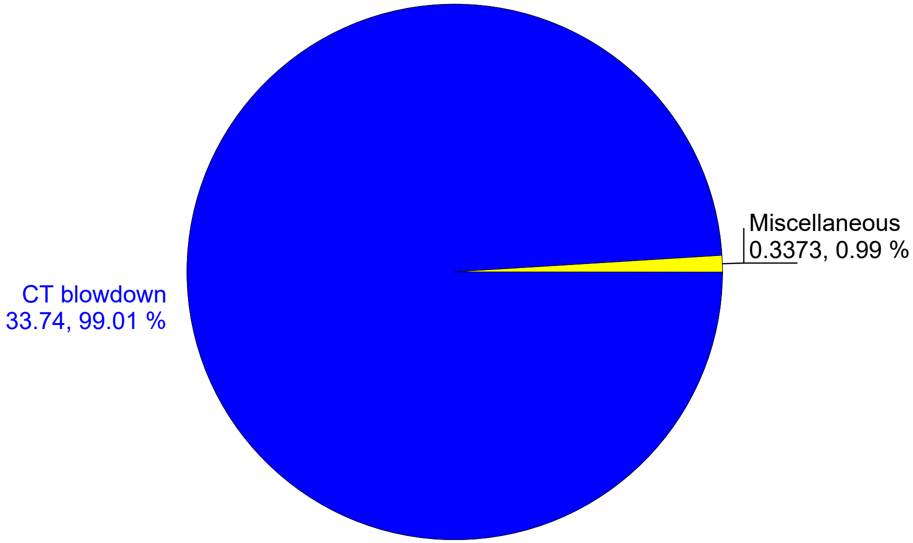
Plant Water Consumption [kg/s]

Plant water consumption = 169.2 kg/s

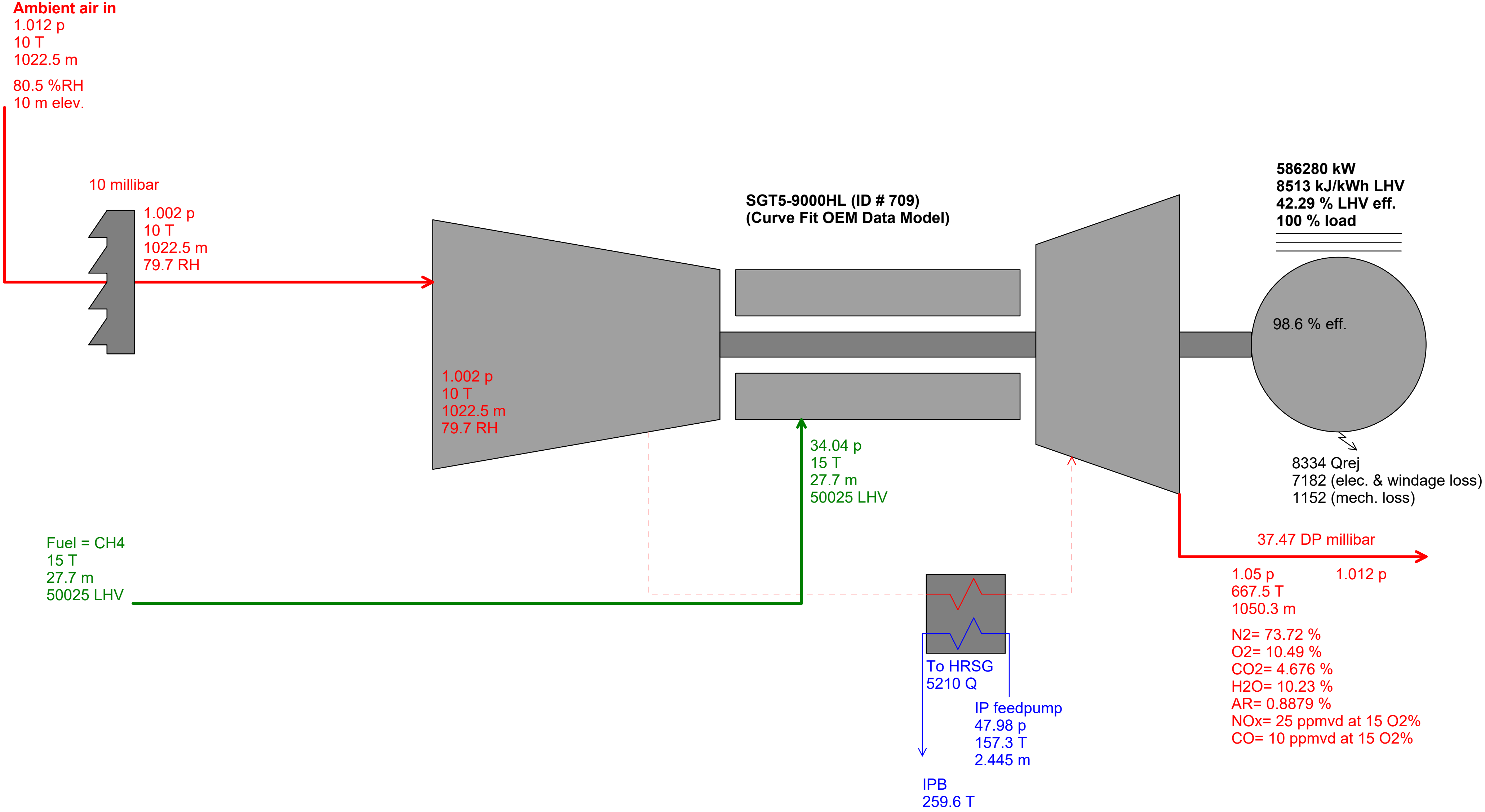


Plant Water Discharge [kg/s]

Plant water discharge = 34.08 kg/s

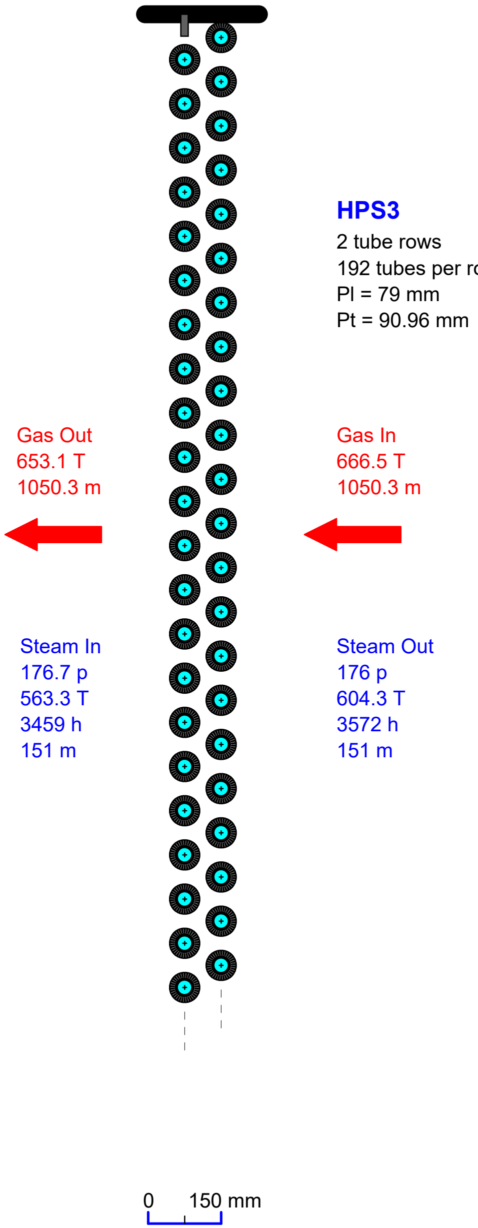


GT generator power = 586280 kW
GT Heat Rate @ gen term = 8513 kJ/kWh
GT efficiency @ gen term = 38.11% HHV = 42.29% LHV
GT @ 100 % rating

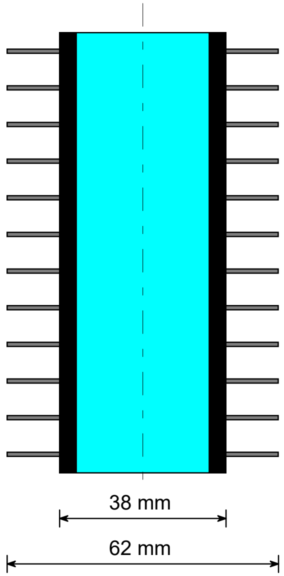


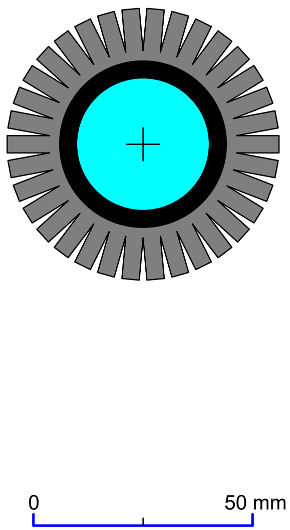
p[bar], T[C], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

HPS3 Hardware Design (water/steam DP by user)



HPS3
2 tube rows
192 tubes per row
Pl = 79 mm
Pt = 90.96 mm



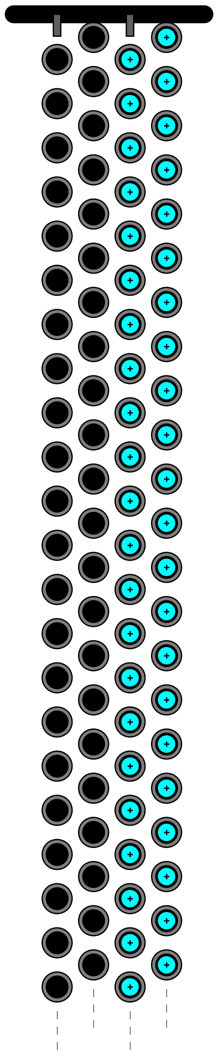


Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP304
Tube material	TP347HFG
Tube outer diameter	38 mm
Tube wall thickness	3.81 mm
Fin height	12 mm
Fin spacing	7.371 mm
Fin thickness	1 mm
Number of fins per meter	119.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	4540 m^2
Maximum gas velocity	14.51 m/s
Gas pressure drop	0.5189 millibar
Steam side velocity	11.03 m/s
Steam side DP from hardware	0.3271 bar
Heat transfer from gas	17118 kW
Heat transfer to steam	17033 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS3
Date: 07/02/20	
Drawing No:	

RH3 Hardware Design (water/steam DP by user)



RH3

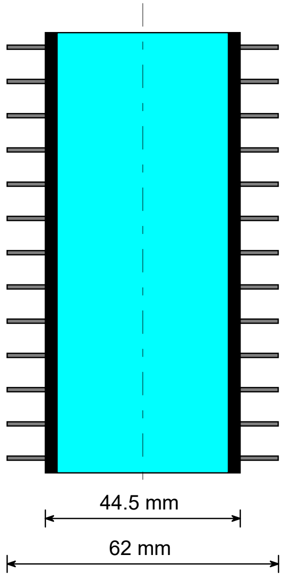
4 tube rows
192 tubes per row
Pl = 79 mm
Pt = 90.96 mm

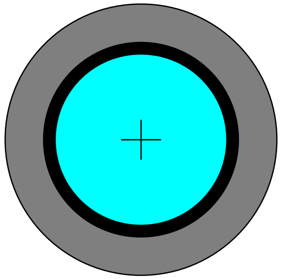
Gas Out
626.3 T
1050.3 m

Gas In
653.1 T
1050.3 m

Steam In
43.87 p
522.8 T
3494 h
162.7 m

Steam Out
42.68 p
612.6 T
3702 h
162.7 m





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	TP347HFG
Tube outer diameter	44.5 mm
Tube wall thickness	2.667 mm
Fin height	8.75 mm
Fin spacing	6.835 mm
Fin thickness	1 mm
Number of fins per meter	127.6
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	8148 m^2
Maximum gas velocity	16.08 m/s
Gas pressure drop	1.061 millibar
Steam side velocity	30.79 m/s
Steam side DP from hardware	0.9051 bar
Heat transfer from gas	34012 kW
Heat transfer to steam	33843 kW

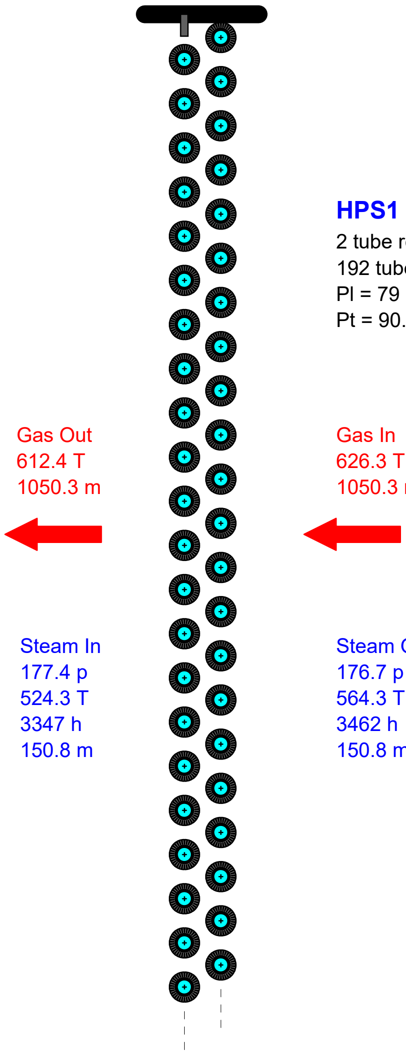
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH3
Date: 07/02/20	
Drawing No:	

HPS1 Hardware Design (water/steam DP by user)



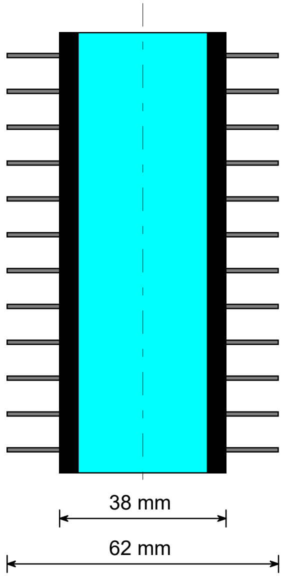
HPS1
2 tube rows
192 tubes per row
Pl = 79 mm
Pt = 90.96 mm

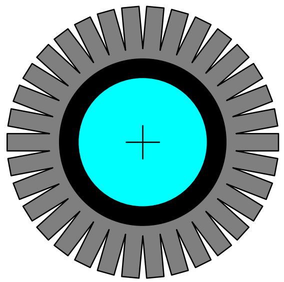
Gas Out
612.4 T
1050.3 m

Gas In
626.3 T
1050.3 m

Steam In
177.4 p
524.3 T
3347 h
150.8 m

Steam Out
176.7 p
564.3 T
3462 h
150.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T91
Tube outer diameter	38 mm
Tube wall thickness	4.191 mm
Fin height	12 mm
Fin spacing	7.217 mm
Fin thickness	1 mm
Number of fins per meter	121.7
Serrated fin segment width	3.97 mm
# of serrated fin segments	33.87
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	2
# of rows per pass	2
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	4608 m^2
Maximum gas velocity	13.9 m/s
Gas pressure drop	0.4959 millibar
Steam side velocity	10.74 m/s
Steam side DP from hardware	0.3377 bar
Heat transfer from gas	17474 kW
Heat transfer to steam	17387 kW

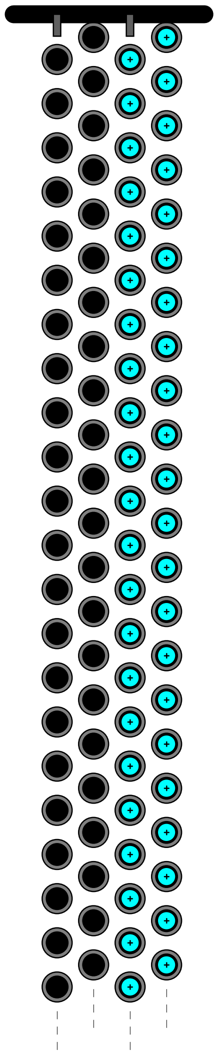
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS1
Date: 07/02/20	
Drawing No:	

RH1 Hardware Design (water/steam DP by user)



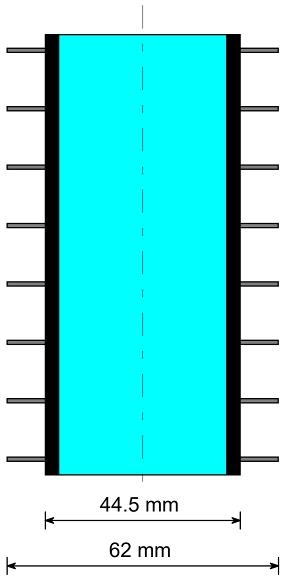
RH1
4 tube rows
192 tubes per row
Pl = 79 mm
Pt = 90.96 mm

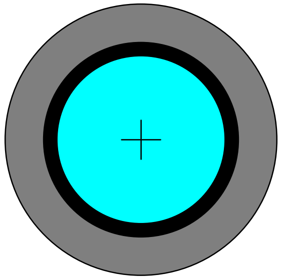
Gas Out
571.2 T
1050.3 m

Gas In
612.4 T
1050.3 m

Steam In
45.67 p
389.7 T
3179 h
162.6 m

Steam Out
43.87 p
523.8 T
3496 h
162.6 m





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	TP409
Tube material	T22
Tube outer diameter	44.5 mm
Tube wall thickness	3.048 mm
Fin height	8.75 mm
Fin spacing	12.34 mm
Fin thickness	1 mm
Number of fins per meter	74.94
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	4
# of rows per pass	2
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	5687 m^2
Maximum gas velocity	14.93 m/s
Gas pressure drop	0.7771 millibar
Steam side velocity	26.29 m/s
Steam side DP from hardware	0.792 bar
Heat transfer from gas	51759 kW
Heat transfer to steam	51501 kW

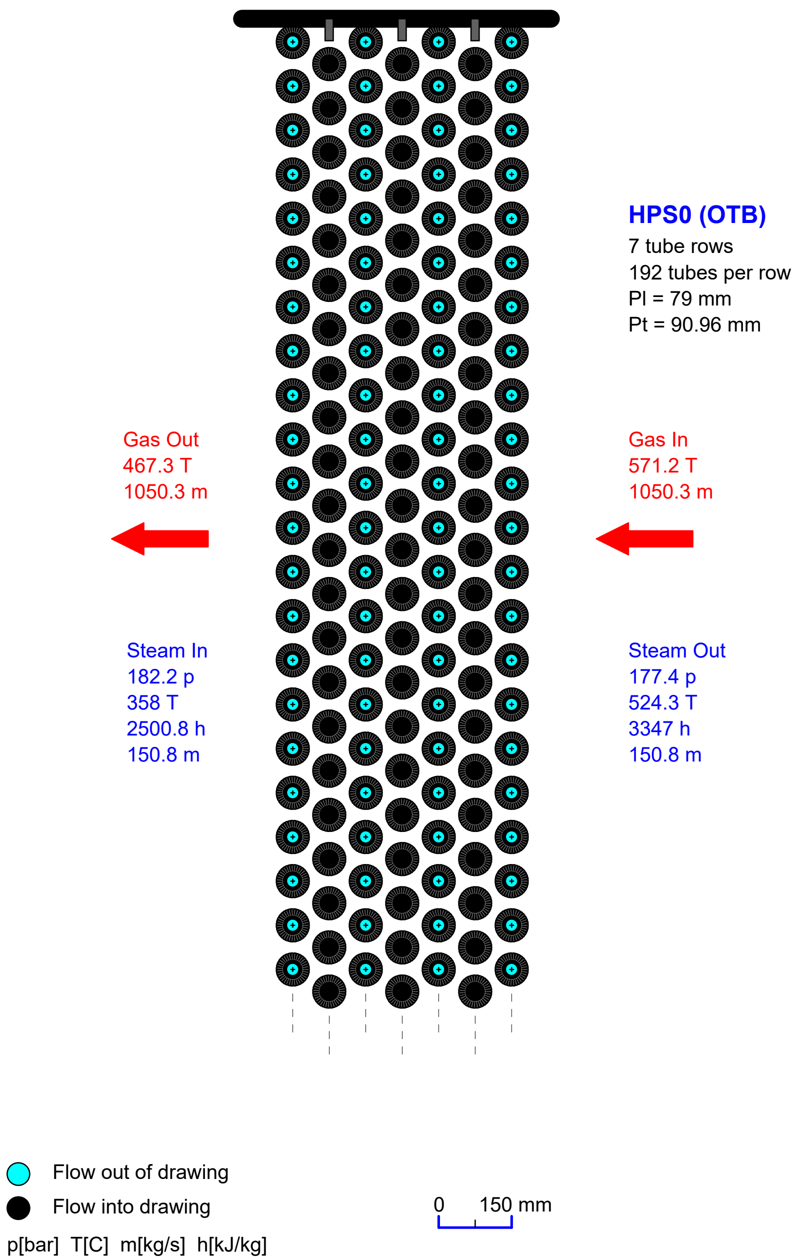
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

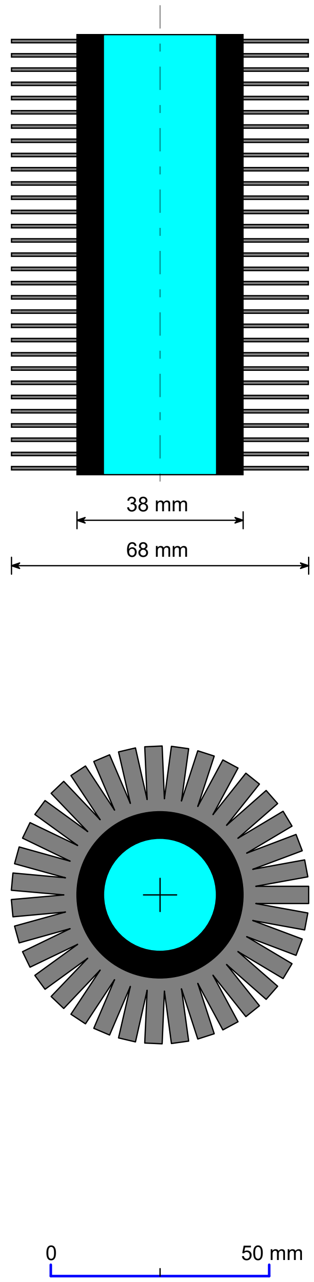
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	RH1
Date: 07/02/20	
Drawing No:	

HPS0 (OTB) Hardware Design (water/steam DP by user)

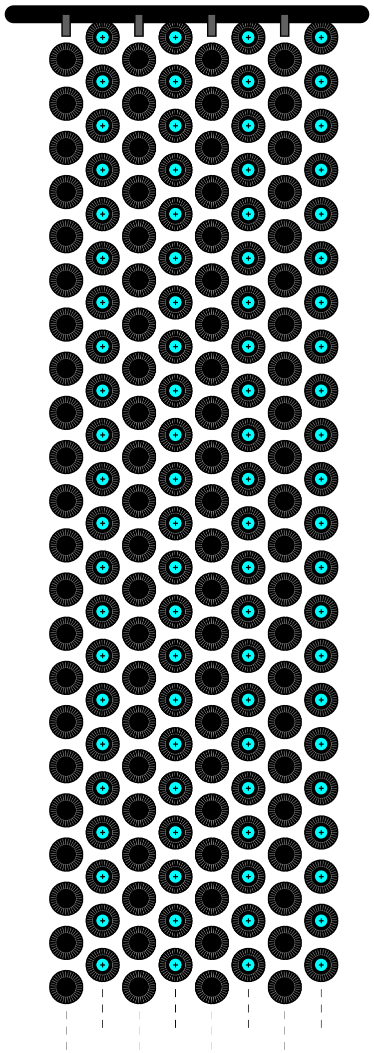




Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	6.045 mm
Fin height	15 mm
Fin spacing	2.441 mm
Fin thickness	0.8 mm
Number of fins per meter	308.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	7
# of rows per pass	1
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	43778 m^2
Maximum gas velocity	13.55 m/s
Gas pressure drop	3.127 millibar
Steam side velocity	21.23 m/s
Steam side DP from hardware	10.11 bar
Heat transfer from gas	128224 kW
Heat transfer to steam	127586 kW

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPS0 (OTB)
Date: 07/02/20	
Drawing No:	

HPB1 (OTB) Hardware Design



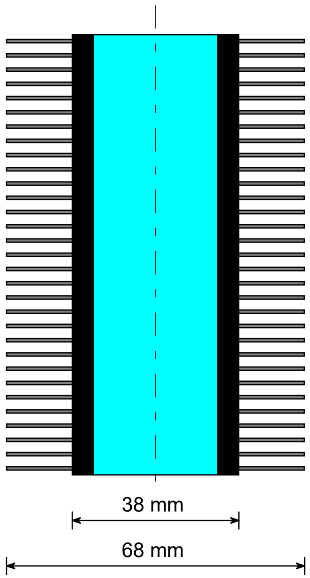
Gas Out
377.1 T
1050.3 m

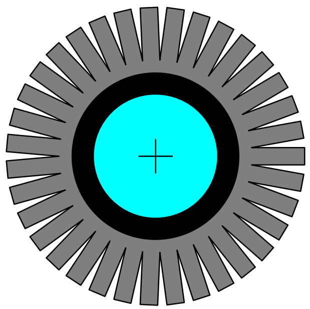
Gas In
467.3 T
1050.3 m

Water In
191.3 p
362 T
1783 h
150.8 m

Steam Out
182.2 p
358 T
2500.8 h
150.8 m

HPB1 (OTB)
8 tube rows
192 tubes per row
Pl = 79 mm
Pt = 90.96 mm





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.441 mm
Fin thickness	0.8 mm
Number of fins per meter	308.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	8
# of rows per pass	1
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	49743 m^2
Maximum gas velocity	11.89 m/s
Gas pressure drop	3.041 millibar
Water side velocity	2.34 m/s
Water side DP from hardware	2.996 bar
Heat transfer from gas	108784 kW
Heat transfer to steam/water	108243 kW

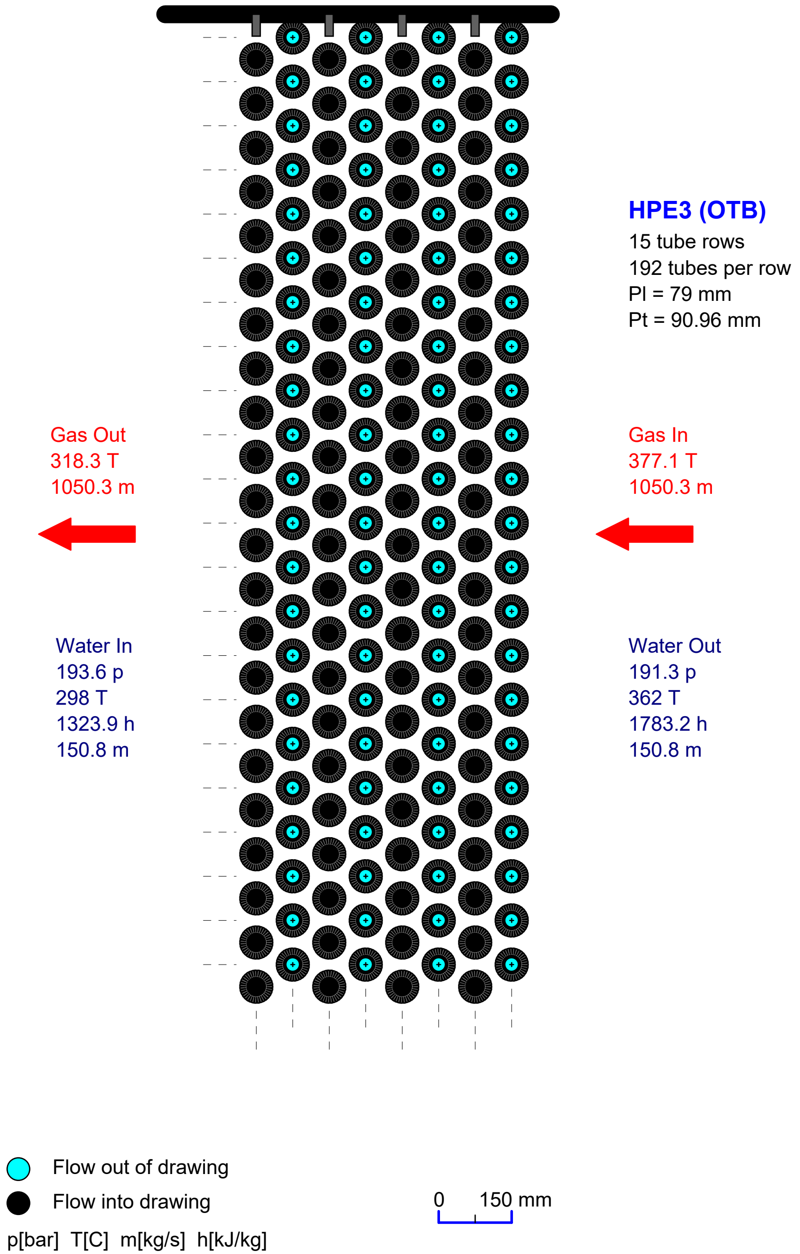
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

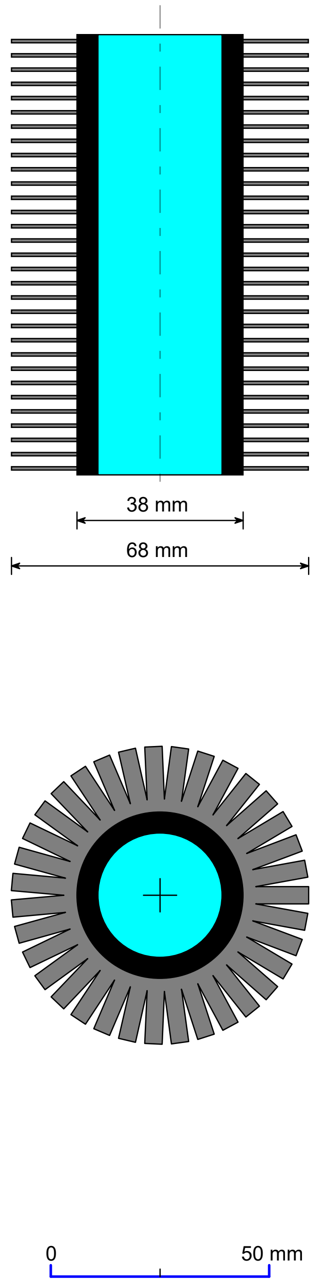
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPB1 (OTB)
Date: 07/02/20	
Drawing No:	

HPE3 (OTB) Hardware Design (water/steam DP by user)

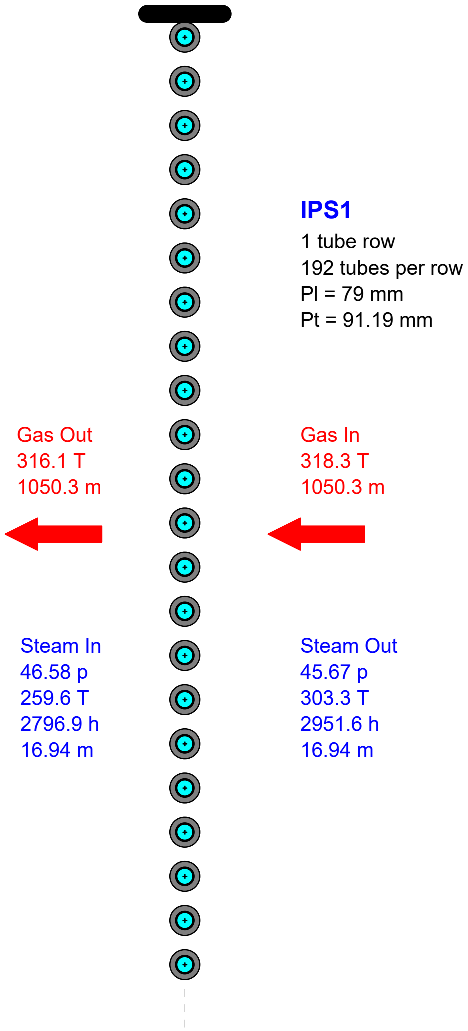


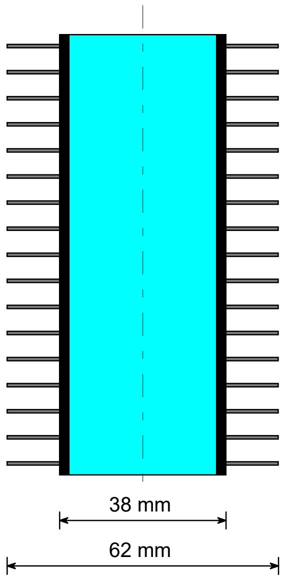


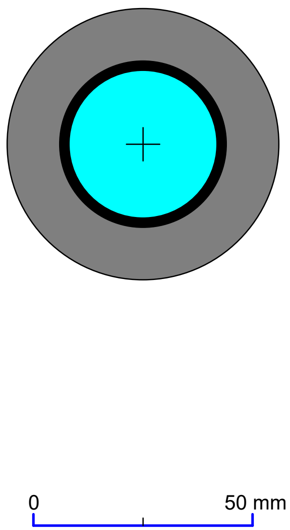
Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	2.441 mm
Fin thickness	0.8 mm
Number of fins per meter	308.5
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	15
# of rows per pass	1
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	93554 m^2
Maximum gas velocity	10.62 m/s
Gas pressure drop	5.068 millibar
Water side velocity	1.86 m/s
Water side DP from hardware	1.768 bar
Heat transfer from gas	69583 kW
Heat transfer to water	69237 kW

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE3 (OTB)
Date: 07/02/20	
Drawing No:	

IPS1 Hardware Design (water/steam DP by user)







Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	5.171 mm
Fin thickness	0.8 mm
Number of fins per meter	167.5
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.19 mm
# of tube rows (longitudinal)	1
# of rows per pass	1
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	2983.2 m^2
Maximum gas velocity	9.203 m/s
Gas pressure drop	0.1707 millibar
Steam side velocity	4.622 m/s
Steam side DP from hardware	0.0271 bar
Heat transfer from gas	2632.4 kW
Heat transfer to steam	2619.3 kW

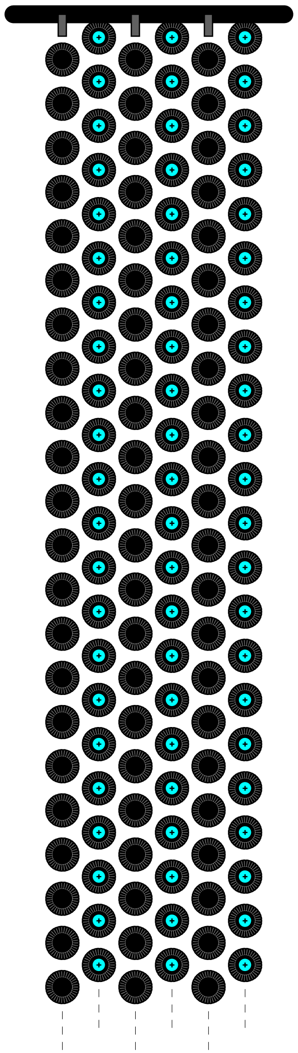
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPS1
Date: 07/02/20	
Drawing No:	

1 2 3 4 5 6 7 8

A B C D E F

HPE2 Hardware Design (water/steam DP by user)



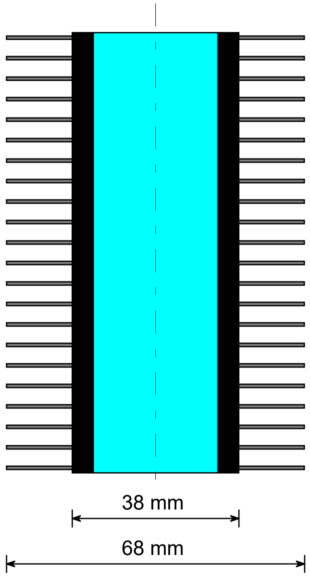
HPE2
6 tube rows
192 tubes per row
Pl = 79 mm
Pt = 90.96 mm

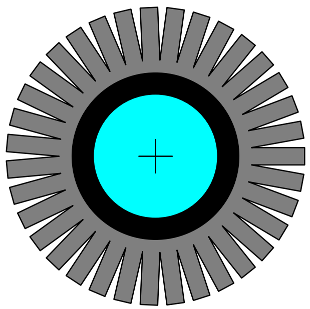
Gas Out
290.2 T
1050.3 m

Gas In
316.1 T
1050.3 m

Water In
194.6 p
258 T
1124.1 h
150.8 m

Water Out
193.6 p
298 T
1323.9 h
150.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	3.886 mm
Fin thickness	0.8 mm
Number of fins per meter	213.4
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	6
# of rows per pass	1
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	26735 m^2
Maximum gas velocity	9.386 m/s
Gas pressure drop	1.348 millibar
Water side velocity	1.598 m/s
Water side DP from hardware	0.644 bar
Heat transfer from gas	30289 kW
Heat transfer to water	30138 kW

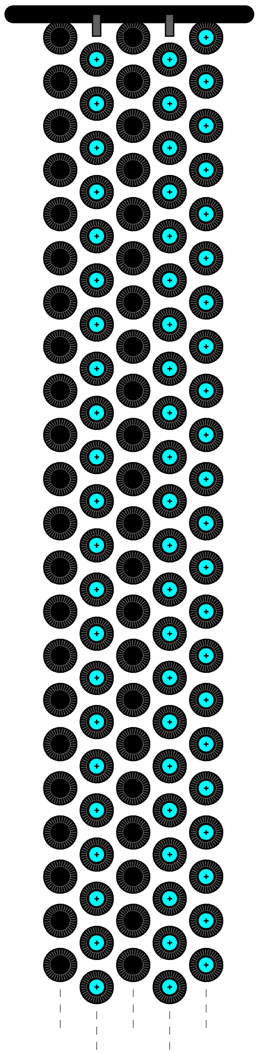
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE2
Date: 07/02/20	
Drawing No:	

IPB Hardware Design



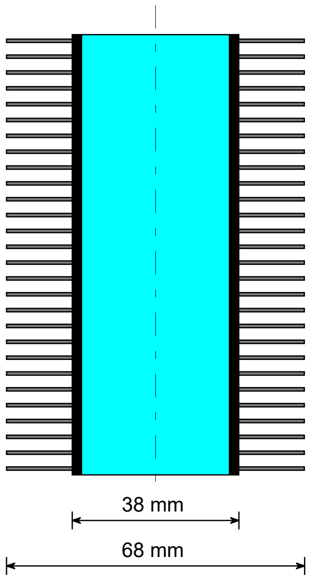
IPB
5 tube rows
192 tubes per row
Pl = 79 mm
Pt = 90.96 mm

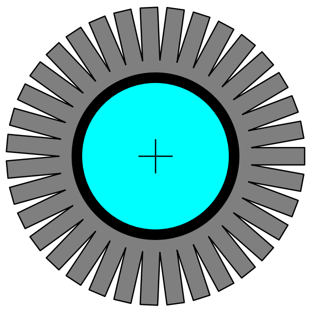
Gas Out
269.4 T
1050.3 m

Gas In
290.2 T
1050.3 m

Water In
46.58 p
259.5 T
1132.6 h
14.64 m

Steam Out
46.58 p
259.6 T
2796.9 h
14.48 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	2.803 mm
Fin thickness	0.8 mm
Number of fins per meter	277.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	5
# of rows per pass	1.2
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	28271 m^2
Maximum gas velocity	9.305 m/s
Gas pressure drop	1.326 millibar
Water side velocity	1.546 m/s
Water side DP from hardware	0 bar
Heat transfer from gas	24237 kW
Heat transfer to steam/water	24116 kW

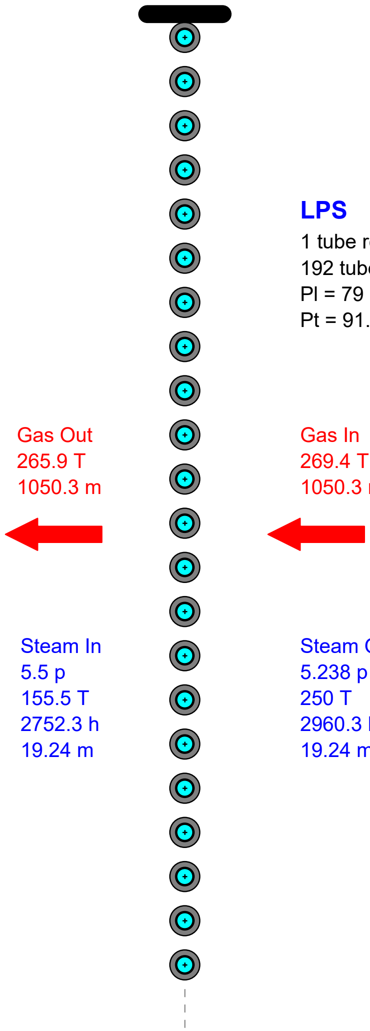
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPB
Date: 07/02/20	
Drawing No:	

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

LPS Hardware Design (water/steam DP by user)



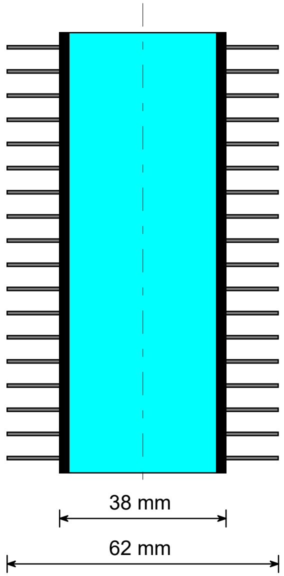
LPS
1 tube row
192 tubes per row
Pl = 79 mm
Pt = 91.19 mm

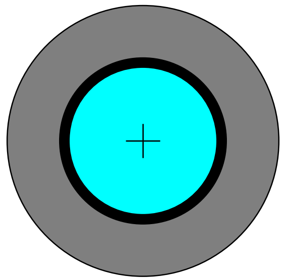
Gas Out
265.9 T
1050.3 m

Gas In
269.4 T
1050.3 m

Steam In
5.5 p
155.5 T
2752.3 h
19.24 m

Steam Out
5.238 p
250 T
2960.3 h
19.24 m





Fin-tube type	Solid fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	12 mm
Fin spacing	4.732 mm
Fin thickness	0.8 mm
Number of fins per meter	180.8
Serrated fin segment width	N/A
# of serrated fin segments	N/A
Un-serrated height / fin height	N/A
Longitudinal row pitch	79 mm
Transverse tube pitch	91.19 mm
# of tube rows (longitudinal)	1
# of rows per pass	1
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	3183 m^2
Maximum gas velocity	8.474 m/s
Gas pressure drop	0.158 millibar
Steam side velocity	44.42 m/s
Steam side DP from hardware	0.2823 bar
Heat transfer from gas	4020 kW
Heat transfer to steam	4000 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

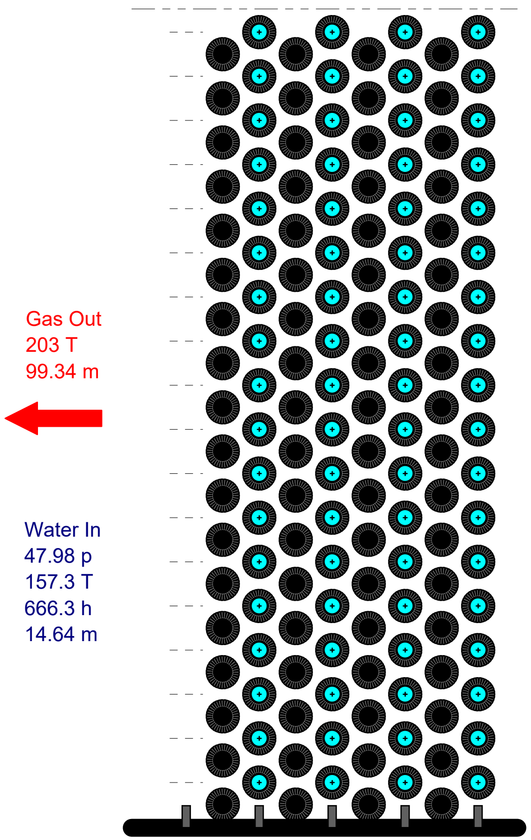
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPS
Date: 07/02/20	
Drawing No:	

IPE2 Hardware Design (water/steam DP by user)

Parallel HX



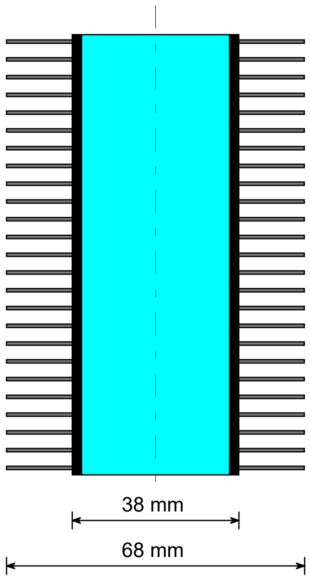
Gas Out
203 T
99.34 m

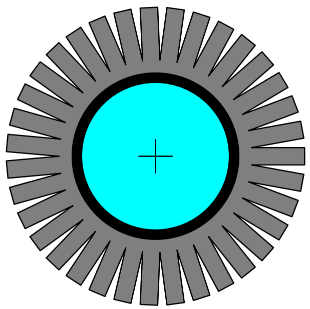
Water In
47.98 p
157.3 T
666.3 h
14.64 m

IPE2 (Parallel)
16 tube rows
18 tubes per row
Pl = 79 mm
Pt = 91 mm

Gas In
265.9 T
99.34 m

Water Out
46.58 p
259.5 T
1132.6 h
14.64 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	3.252 mm
Fin thickness	0.8 mm
Number of fins per meter	246.8
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	91 mm
# of tube rows (longitudinal)	16
# of rows per pass	1
# of tubes per row (transverse)	18
Tube length	20.4 m
Gas path transverse width	1.682 m
Gas path frontal area	34.3 m^2
HX total outside surface area	7616 m^2
Maximum gas velocity	8.487 m/s
Gas pressure drop	3.506 millibar
Water side velocity	1.06 m/s
Water side DP from hardware	0.7598 bar
Heat transfer from gas	6859 kW
Heat transfer to water	6825 kW

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IPE2 (Parallel)
Date: 07/02/20	
Drawing No:	

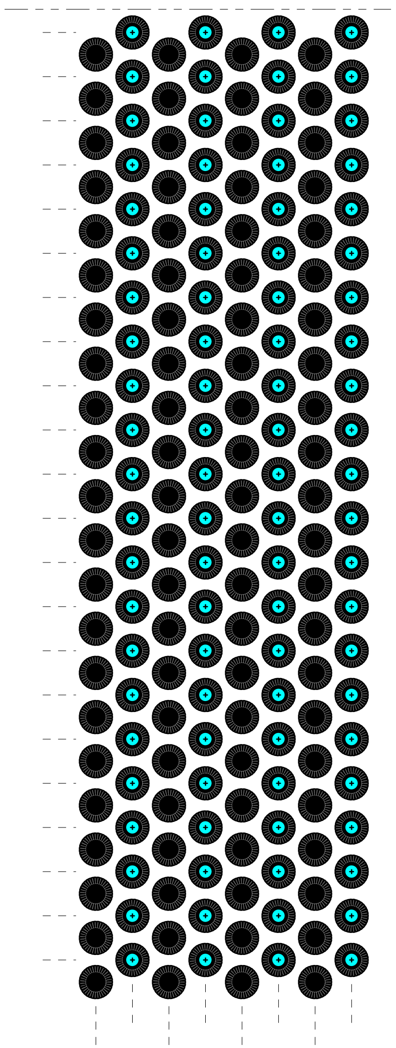
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

0 50 mm

HPE0 Hardware Design (water/steam DP by user)

Parallel HX



HPE0 (Parallel)

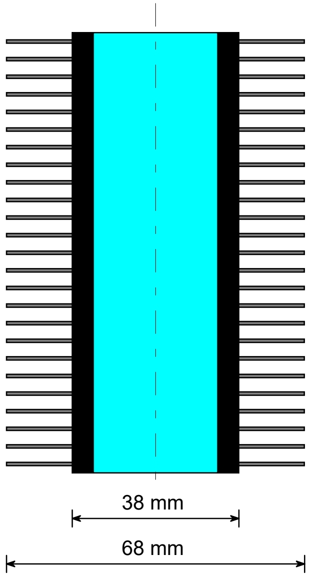
16 tube rows
174 tubes per row
Pl = 79 mm
Pt = 90.73 mm

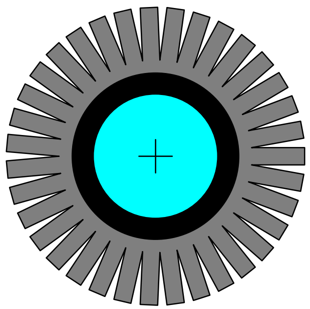
Gas Out
203 T
950.9 m

Gas In
265.9 T
950.9 m

Water In
196.8 p
160.9 T
690.9 h
151.4 m

Water Out
194.6 p
258 T
1124.1 h
150.8 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	4.775 mm
Fin height	15 mm
Fin spacing	3.219 mm
Fin thickness	0.8 mm
Number of fins per meter	248.8
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.73 mm
# of tube rows (longitudinal)	16
# of rows per pass	1
# of tubes per row (transverse)	174
Tube length	20.4 m
Gas path transverse width	15.83 m
Gas path frontal area	322.9 m^2
HX total outside surface area	74191 m^2
Maximum gas velocity	8.453 m/s
Gas pressure drop	3.505 millibar
Water side velocity	1.573 m/s
Water side DP from hardware	1.906 bar
Heat transfer from gas	65663 kW
Heat transfer to water	65336 kW

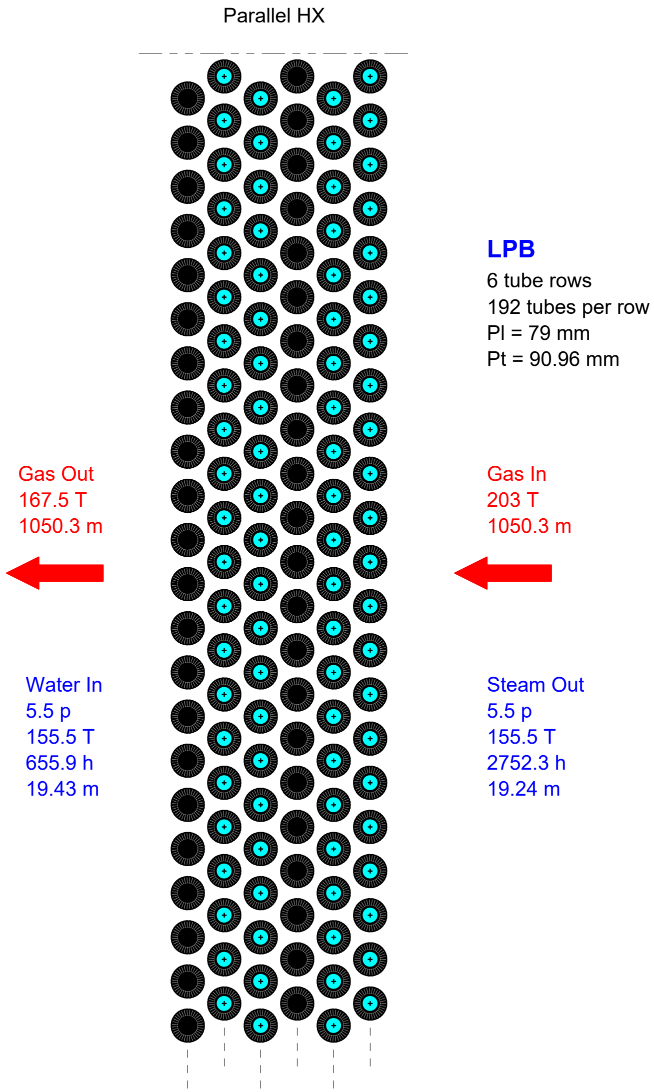
Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

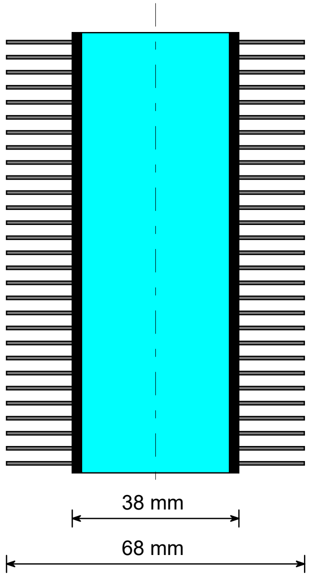
0 150 mm

0 50 mm

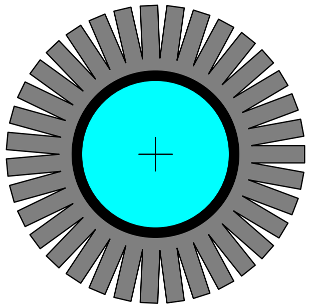
Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HPE0 (Parallel)
Date: 07/02/20	
Drawing No:	

LPB Hardware Design





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	2.108 mm
Fin height	15 mm
Fin spacing	2.642 mm
Fin thickness	0.8 mm
Number of fins per meter	290.6
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	6
# of rows per pass	1.5
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	35400 m^2
Maximum gas velocity	7.766 m/s
Gas pressure drop	1.308 millibar
Water side velocity	1.471 m/s
Water side DP from hardware	0 bar
Heat transfer from gas	40528 kW
Heat transfer to steam/water	40326 kW



Flow out of drawing

Flow into drawing

p[bar] T[C] m[kg/s] h[kJ/kg]

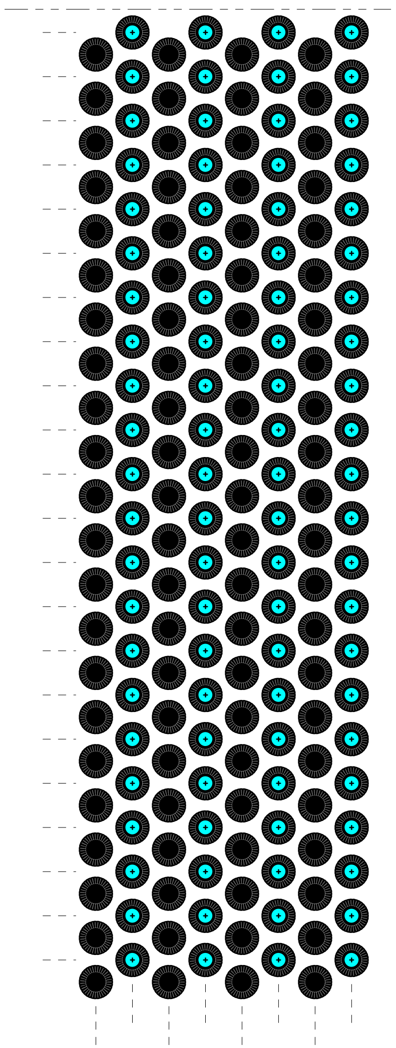
0 150 mm

0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LPB
Date: 07/02/20	
Drawing No:	

LTE Hardware Design (water/steam DP by user)

Parallel HX



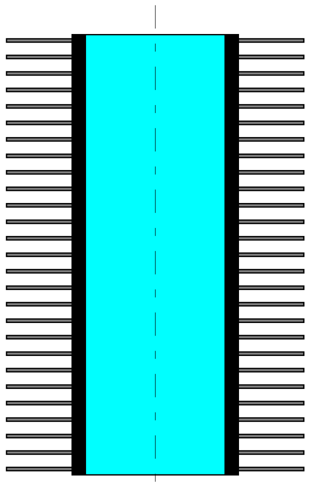
LTE
24 tube rows
192 tubes per row
Pl = 79 mm
Pt = 90.96 mm

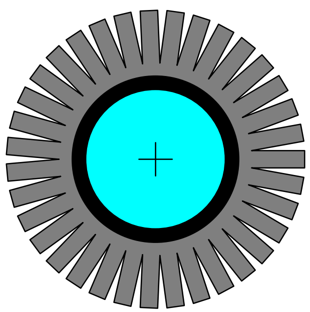
Gas Out
84.17 T
1050.3 m

Gas In
167.5 T
1050.3 m

Water In
5.665 p
60 T
251.6 h
231.5 m

Water Out
5.5 p
155.5 T
655.9 h
231.5 m





Fin-tube type	Serrated fins
Tube arrangement	Staggered
Fin material	CS
Tube material	CS
Tube outer diameter	38 mm
Tube wall thickness	3.048 mm
Fin height	15 mm
Fin spacing	2.976 mm
Fin thickness	0.8 mm
Number of fins per meter	264.8
Serrated fin segment width	3.97 mm
# of serrated fin segments	34.82
Un-serrated height / fin height	0.2
Longitudinal row pitch	79 mm
Transverse tube pitch	90.96 mm
# of tube rows (longitudinal)	24
# of rows per pass	1
# of tubes per row (transverse)	192
Tube length	20.4 m
Gas path transverse width	17.51 m
Gas path frontal area	357.2 m^2
HX total outside surface area	130056 m^2
Maximum gas velocity	6.67 m/s
Gas pressure drop	4.09 millibar
Water side velocity	1.582 m/s
Water side DP from hardware	3.118 bar
Heat transfer from gas	94049 kW
Heat transfer to water	93581 kW

Flow out of drawing
Flow into drawing
p[bar] T[C] m[kg/s] h[kJ/kg]

0 150 mm

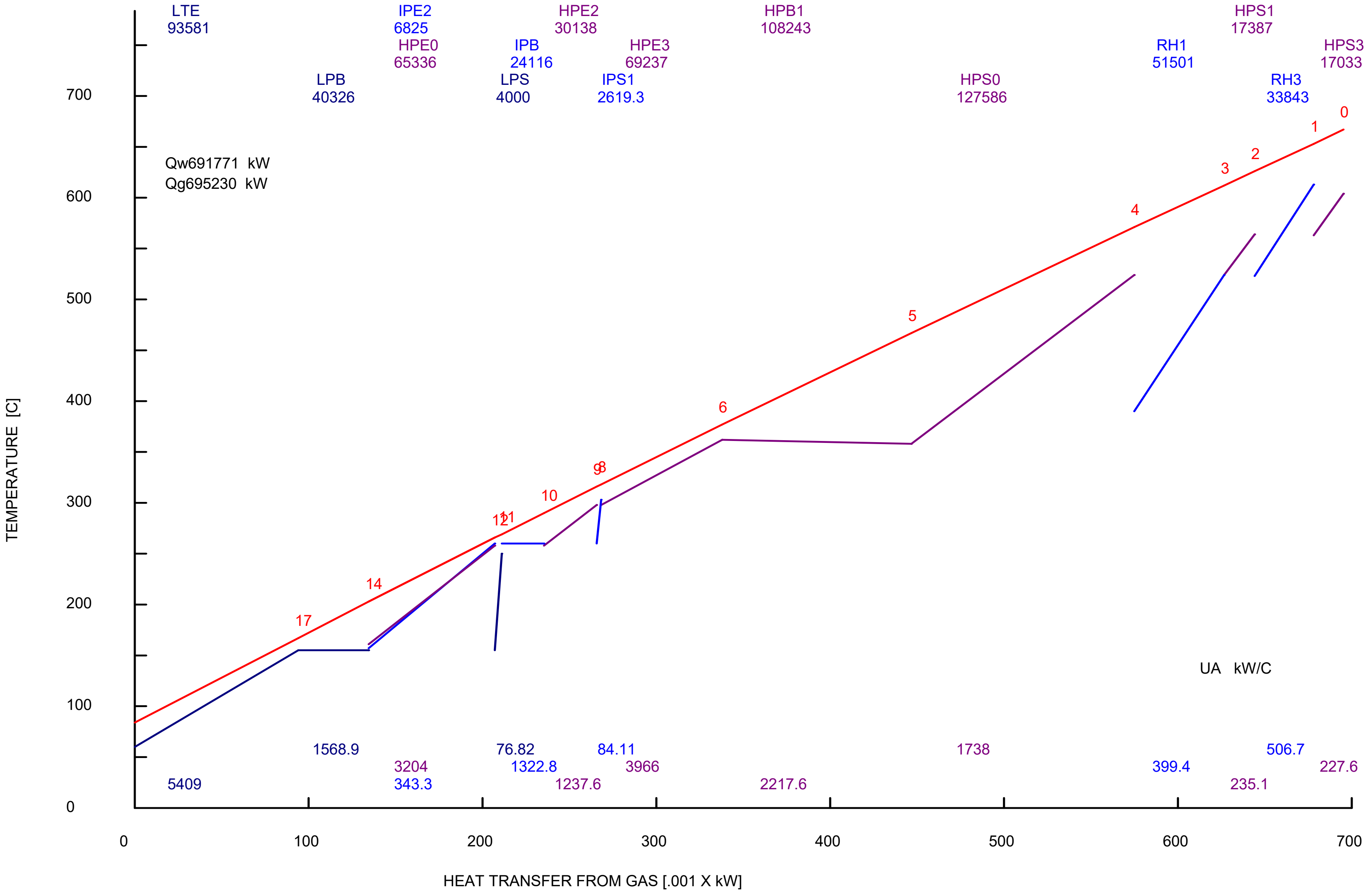
0 50 mm

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	LTE
Date: 07/02/20	
Drawing No:	

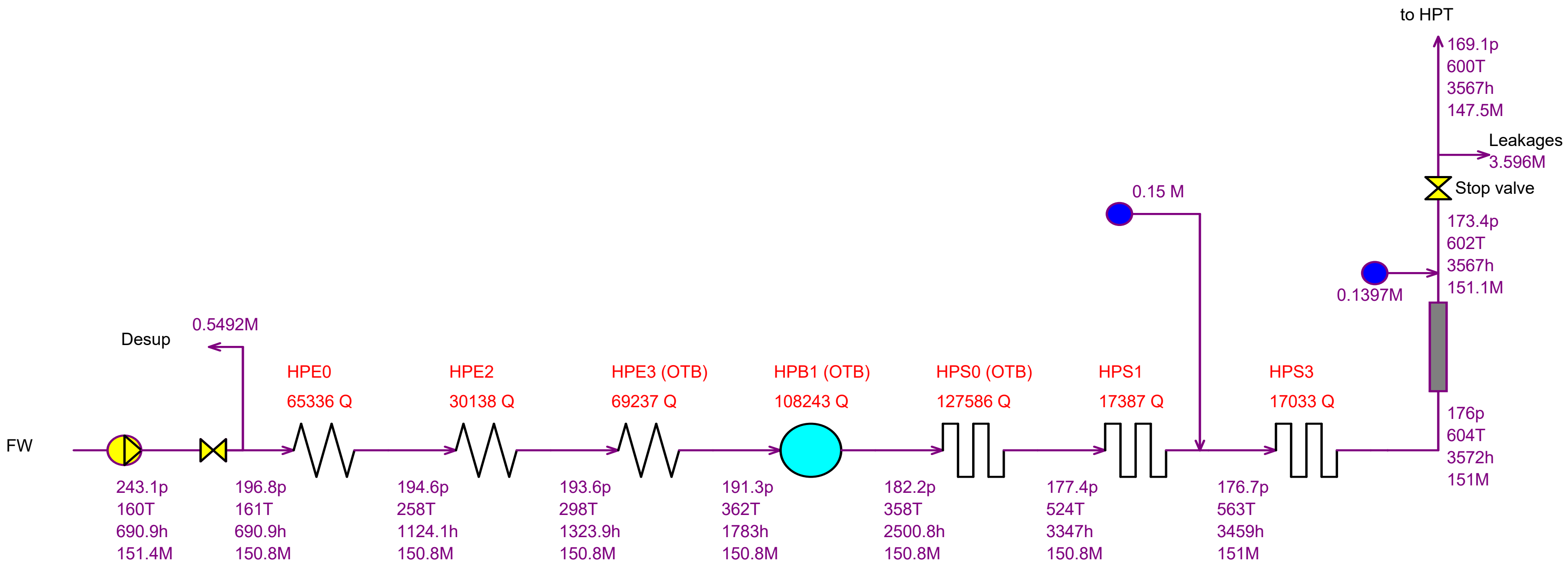
GT PRO 29.0 AECOM

Net Power 844615 kW
LHV Net Heat Rate 5909 kJ/kWh
LHV Net Efficiency 60.92 %

HRSG Temperature Profile



HP Water Path

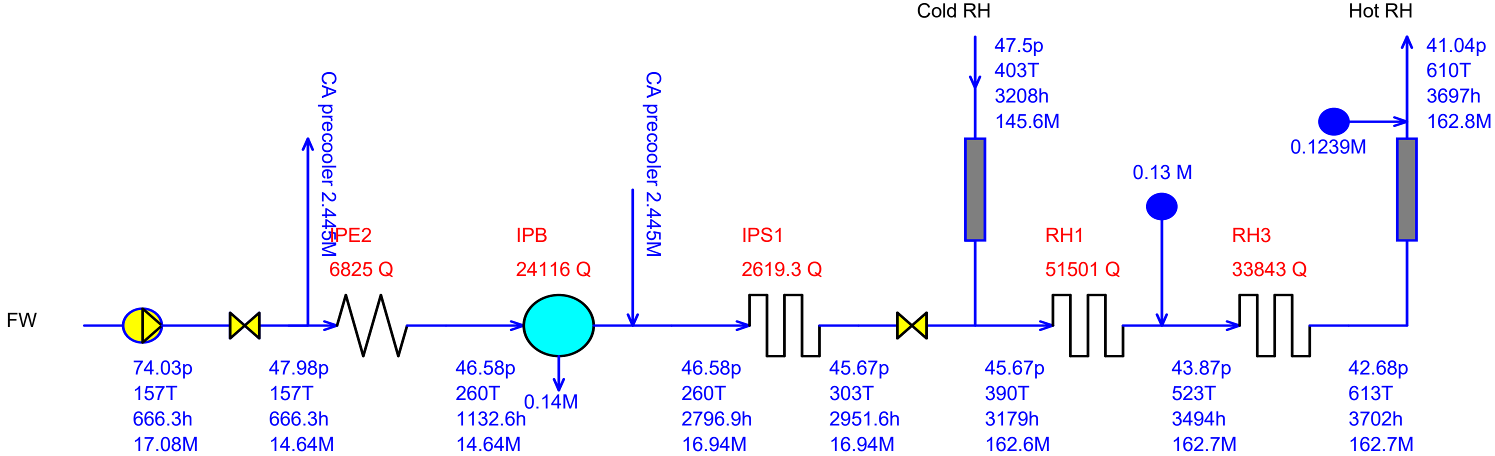


p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

1220 06-15-2020 14:40:07 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck.GTP

IP & Reheat Water Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

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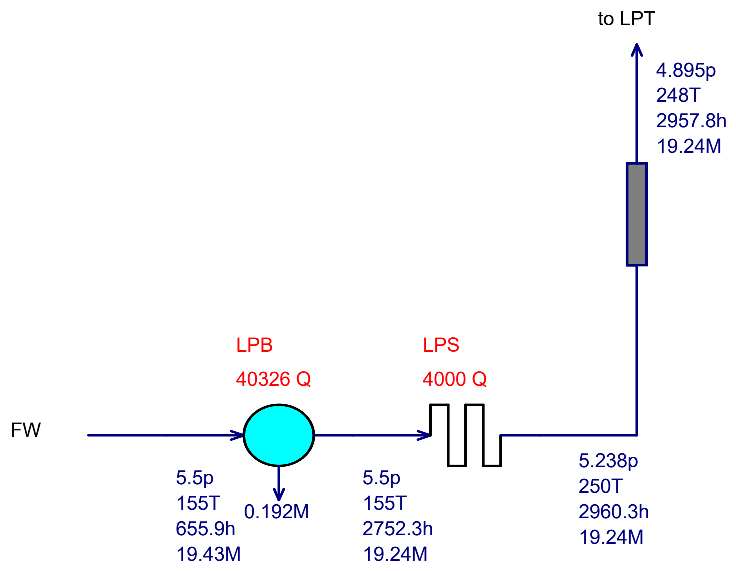
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck.GTP

LP Water Path

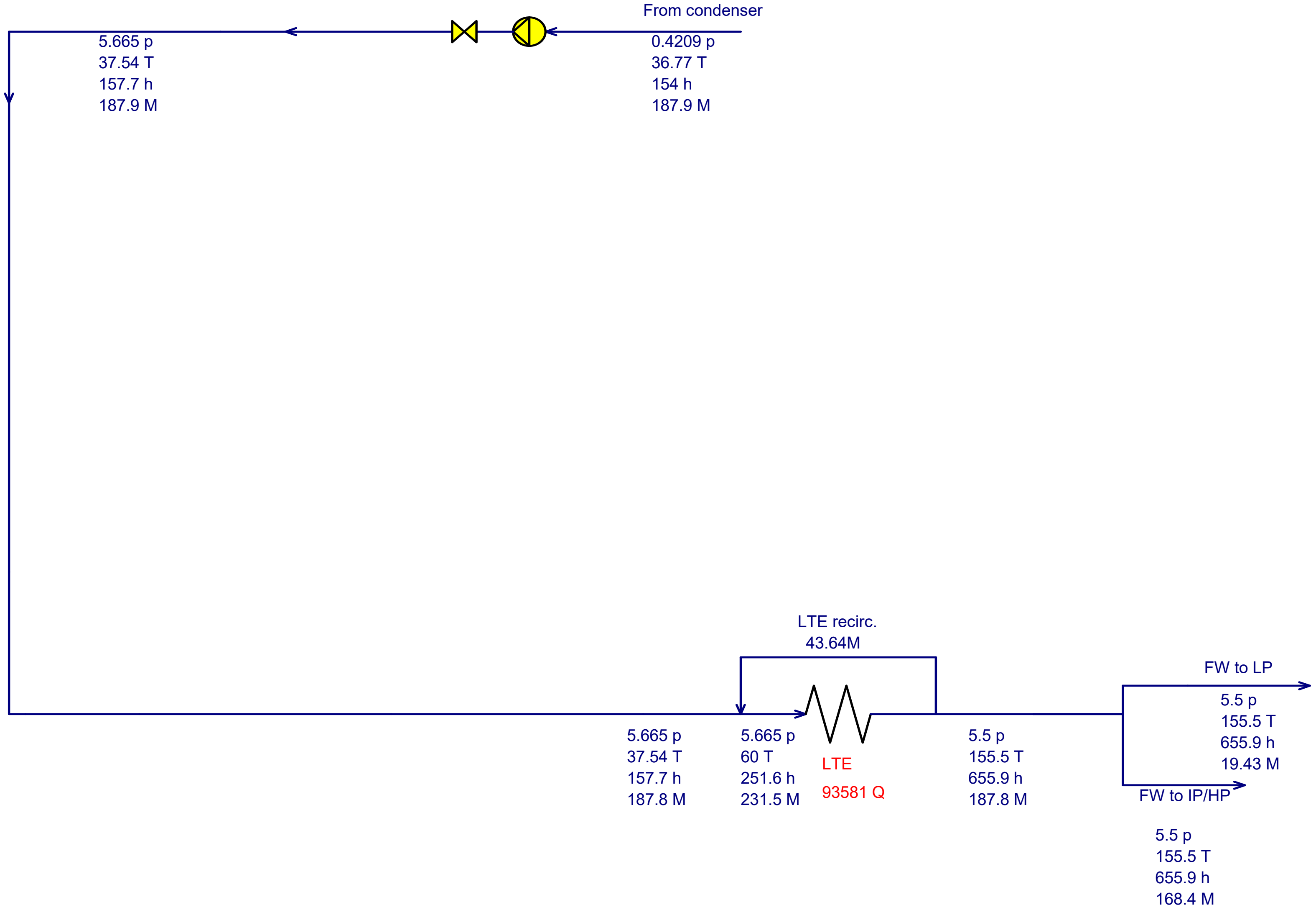


p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

1220 06-15-2020 14:40:07 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck.GTP

Feedwater Path



p[bar], T[C], h[kJ/kg], M[kg/s], Q[kW], Steam Properties: IAPWS-IF97

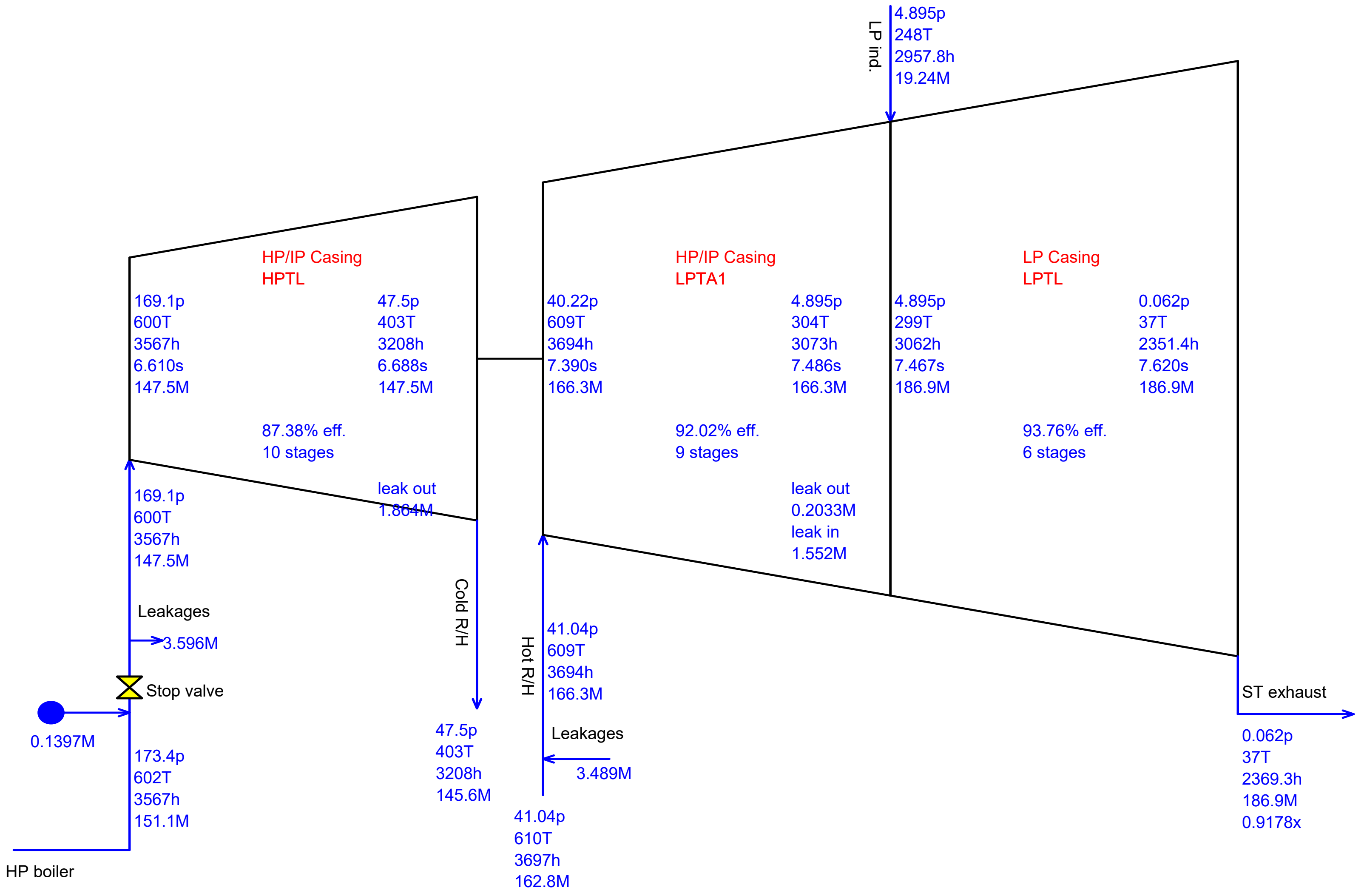
1220 06-15-2020 14:40:07 file=

Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck.GTP

GT PRO 29.0 AECOM

ST Expansion Power 285757 kW
ST Generator Output 281869 kW

Steam Turbine Group Data



p[bar], T[C], h[kJ/kg], s[kJ/kg-C], M[kg/s], Steam Properties: IAPWS-IF97

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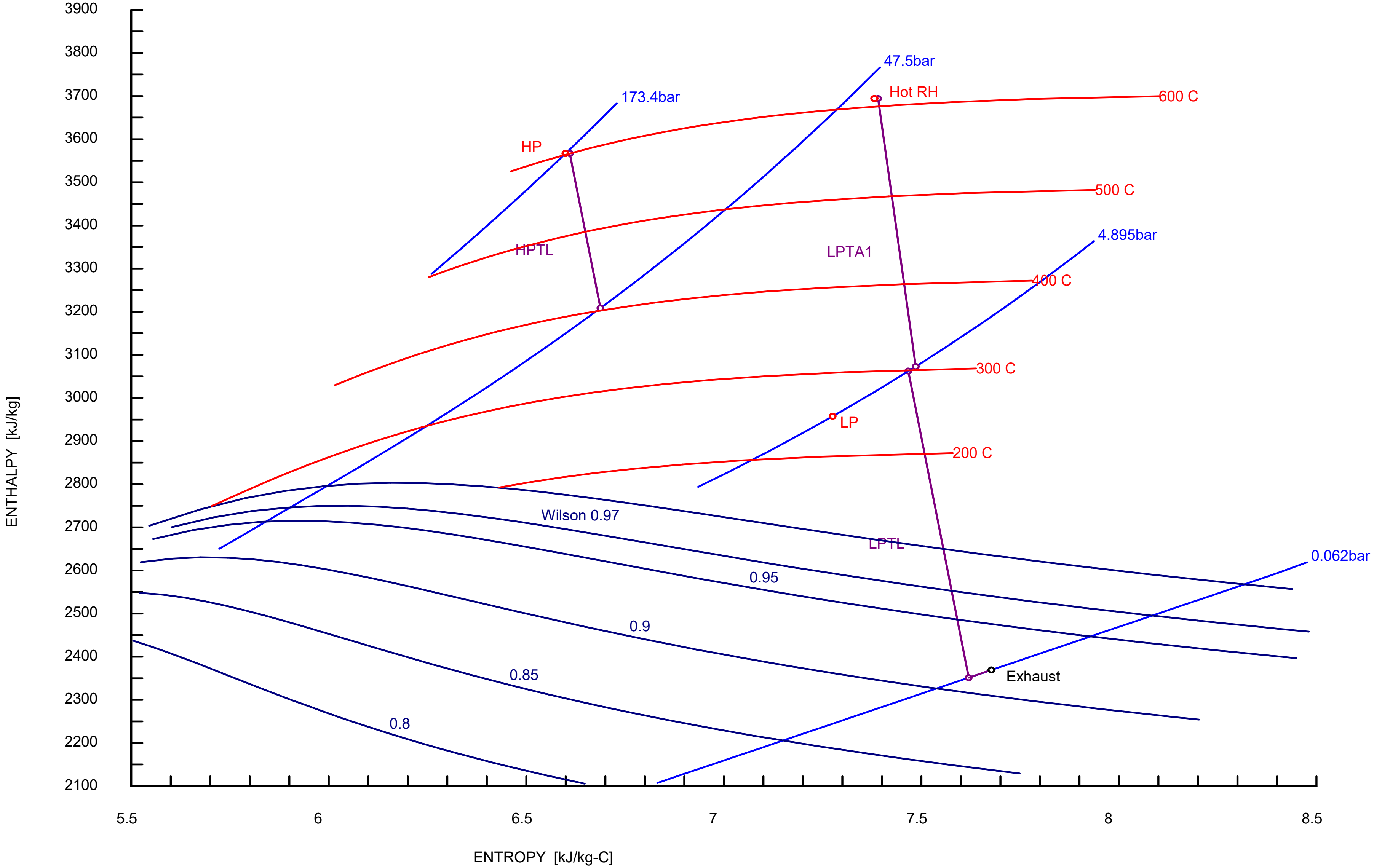
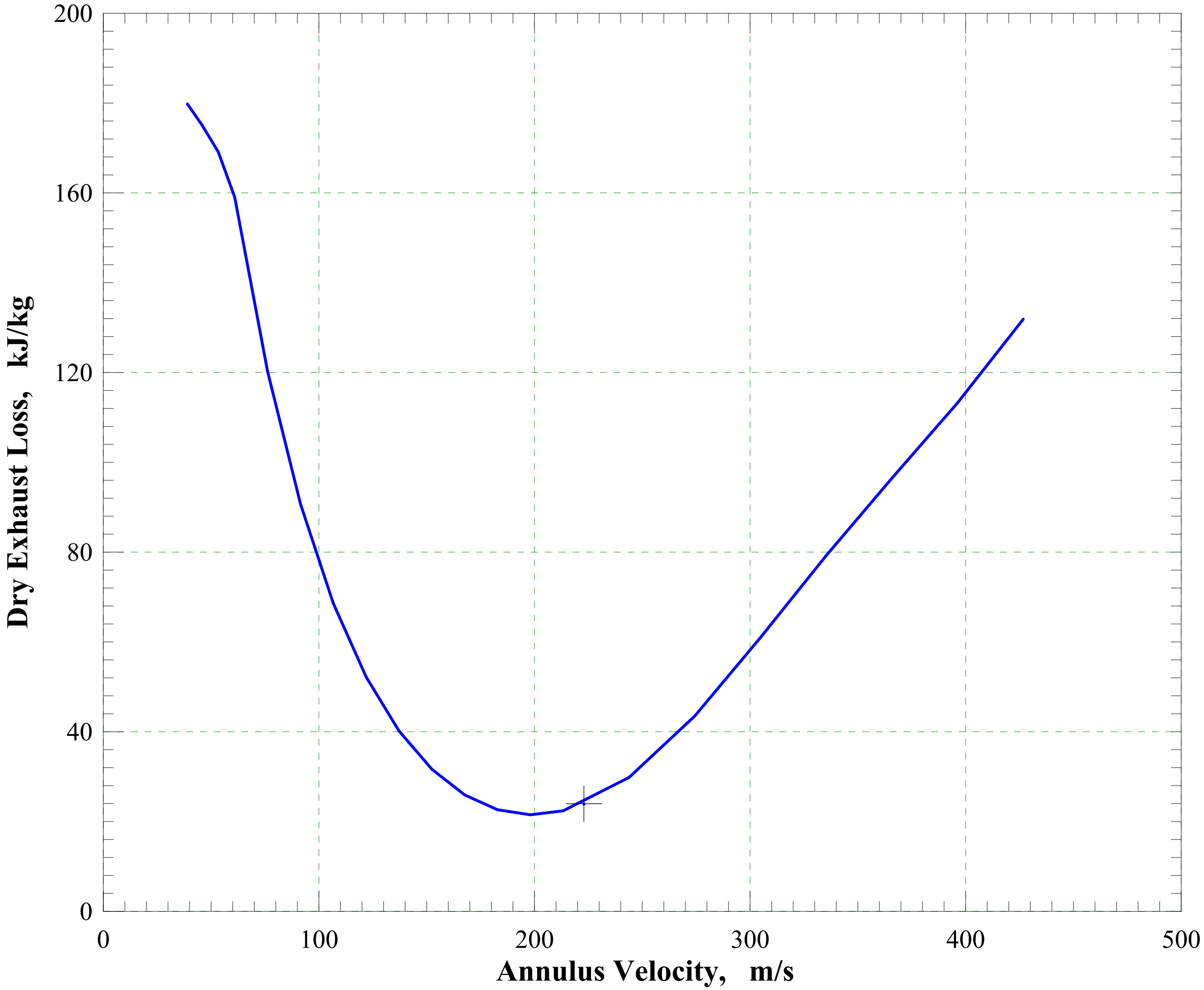
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck.GTP

ST Expansion Power 285757 kW
ST Generator Output 281869 kW

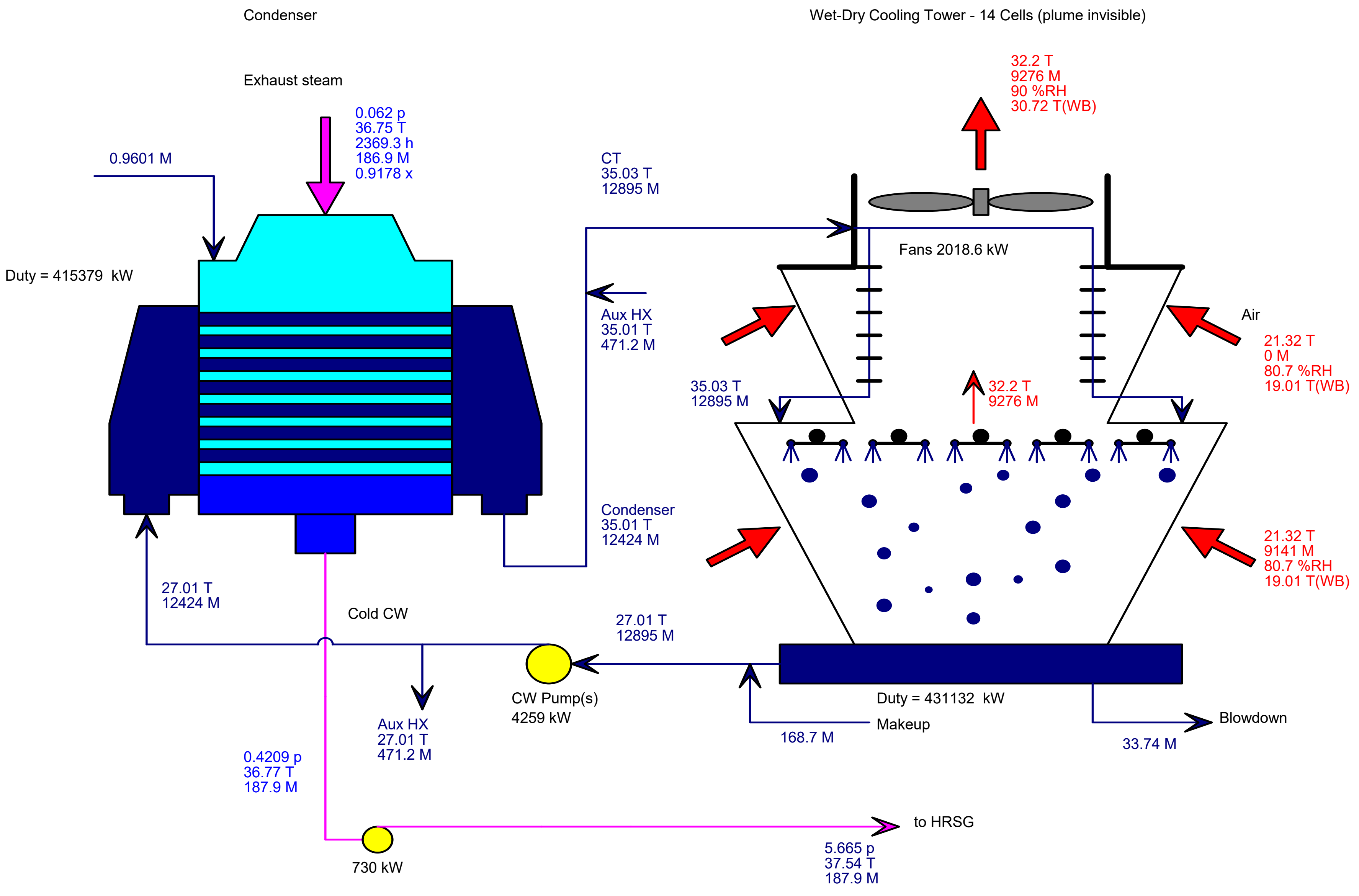
Steam Turbine Expansion Path



Steam Turbine Exhaust Loss



Cooling System



p[bar], T[C], M[kg/s], Steam Properties: IAPWS-IF97

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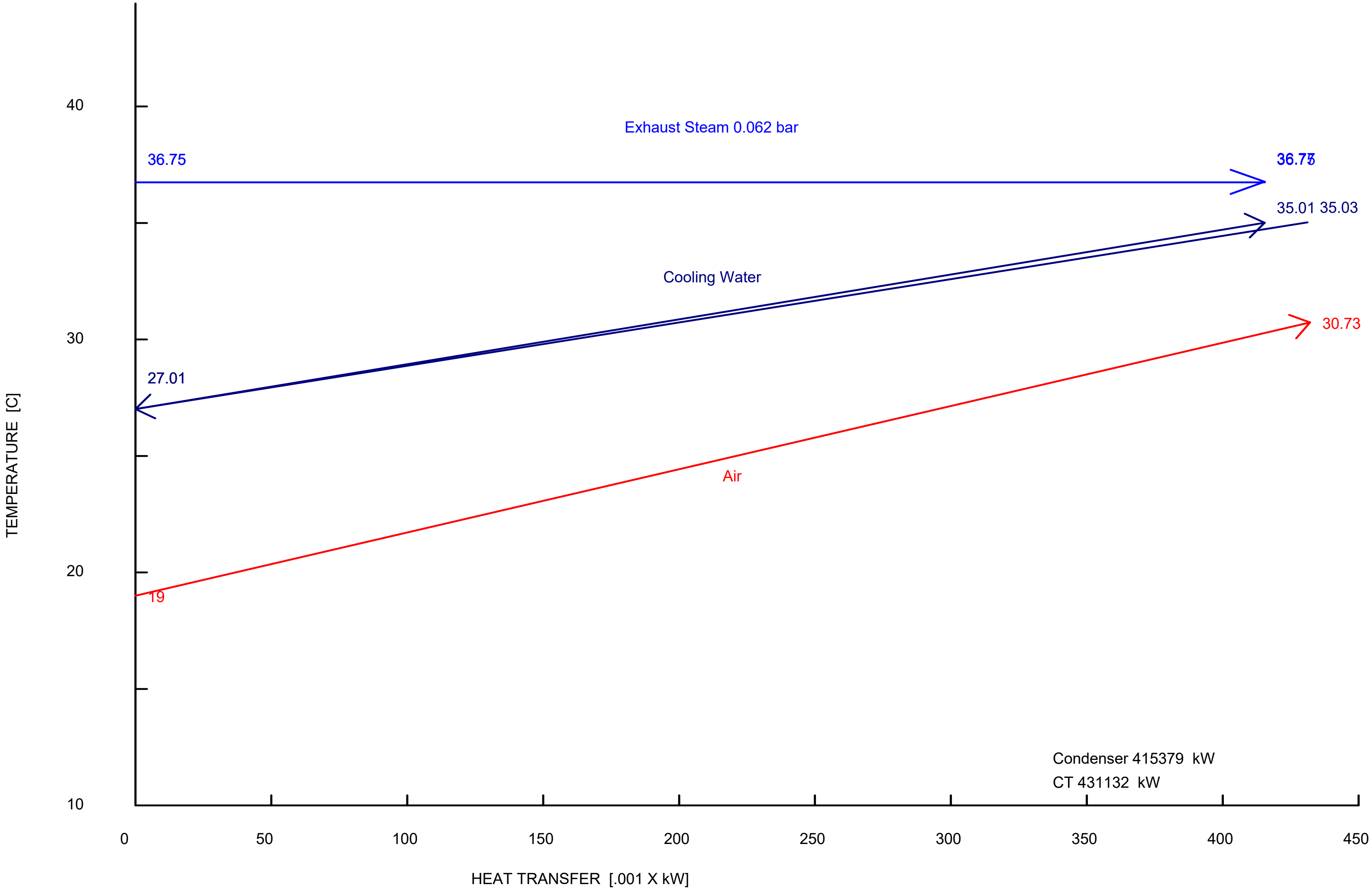
Power plant model rev 2 - 9000HL with 3pRH and 2019 cycle deck.GTP

Water Cooled Condenser and Wet-Dry Cooling Tower T-Q Diagram



AIR STATES:

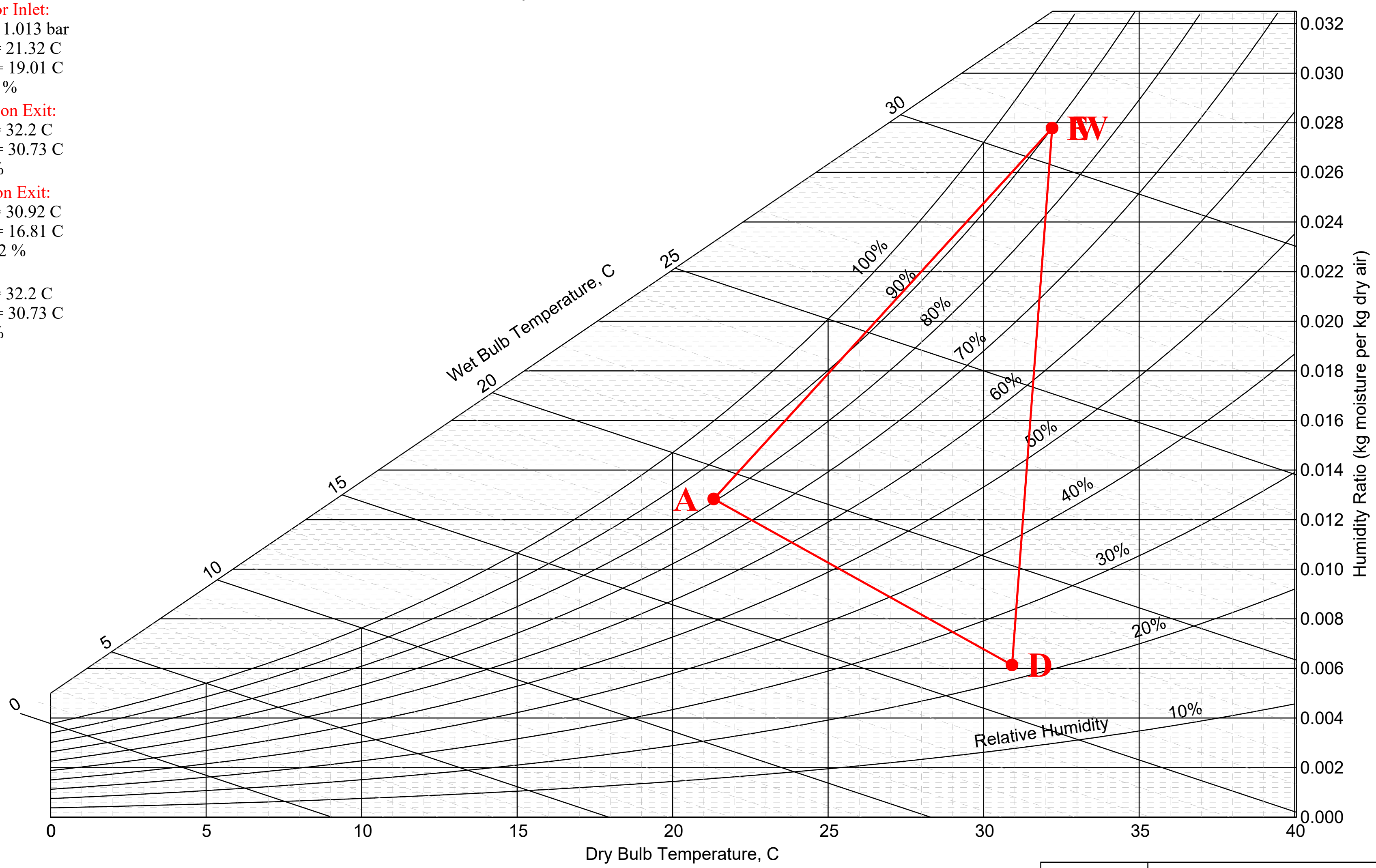
A) Ambient or Inlet:
Pressure = 1.013 bar
Dry bulb = 21.32 C
Wet bulb = 19.01 C
RH = 80.7 %

W) Wet Section Exit:
Dry bulb = 32.2 C
Wet bulb = 30.73 C
RH = 90 %

D) Dry Section Exit:
Dry bulb = 30.92 C
Wet bulb = 16.81 C
RH = 22.12 %

E) Air Exit:
Dry bulb = 32.2 C
Wet bulb = 30.73 C
RH = 90 %

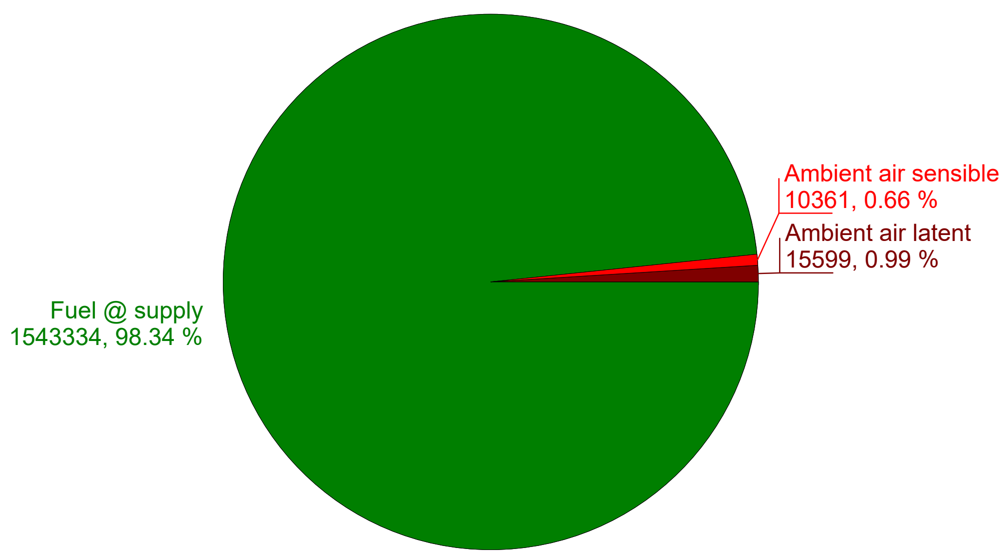
Psychrometric Chart



Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Cooling Tower
Date: 07/02/20	
Drawing No:	

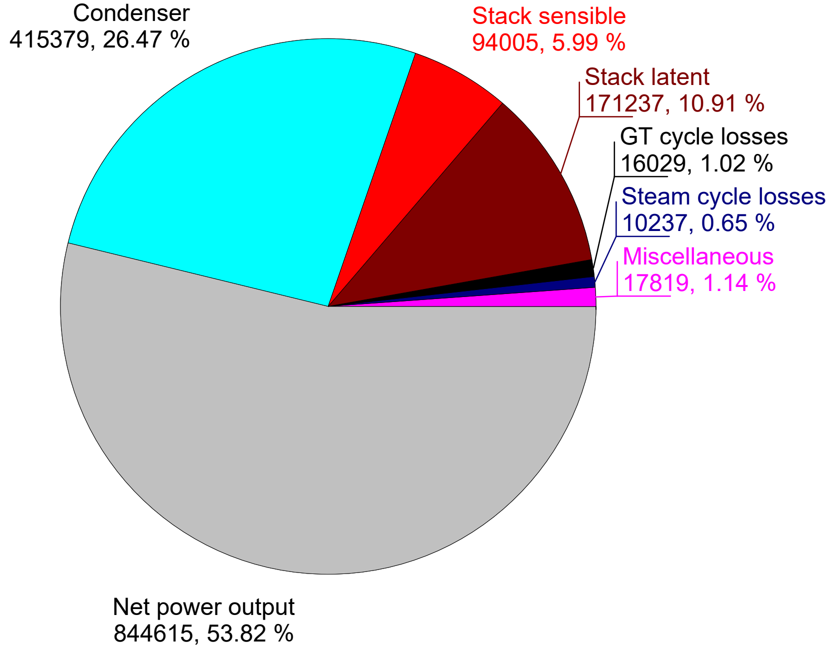
Plant Energy In [kW]

Plant energy in = 1569322 kW
Plant fuel chemical LHV input = 1386336 kW, HHV = 1538297 kW
Plant net LHV elec. eff. = 60.92 % (100% * 844615 / 1386336), Net HHV elec. eff. = 54.91 %



Plant Energy Out [kW]

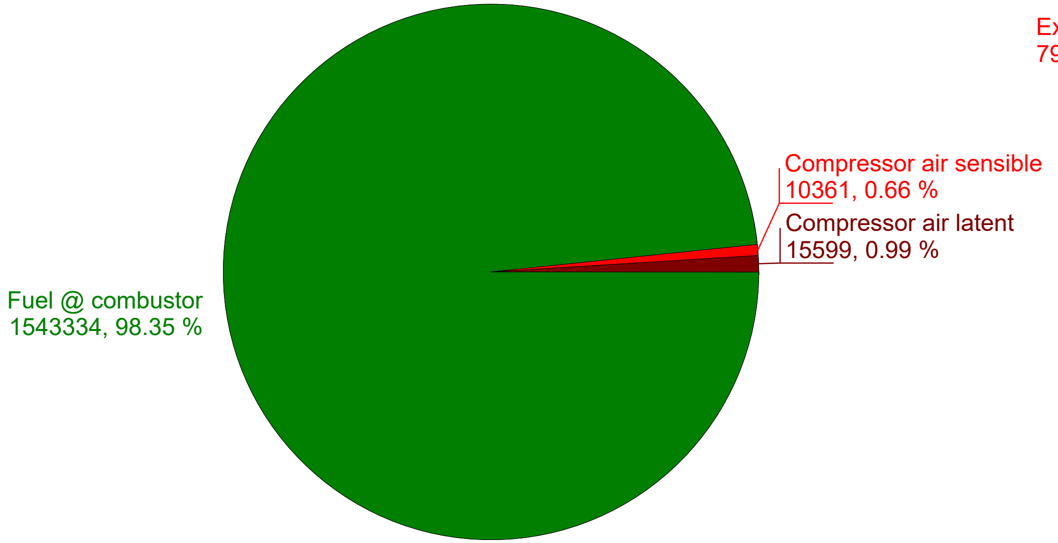
Plant energy out = 1569331 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

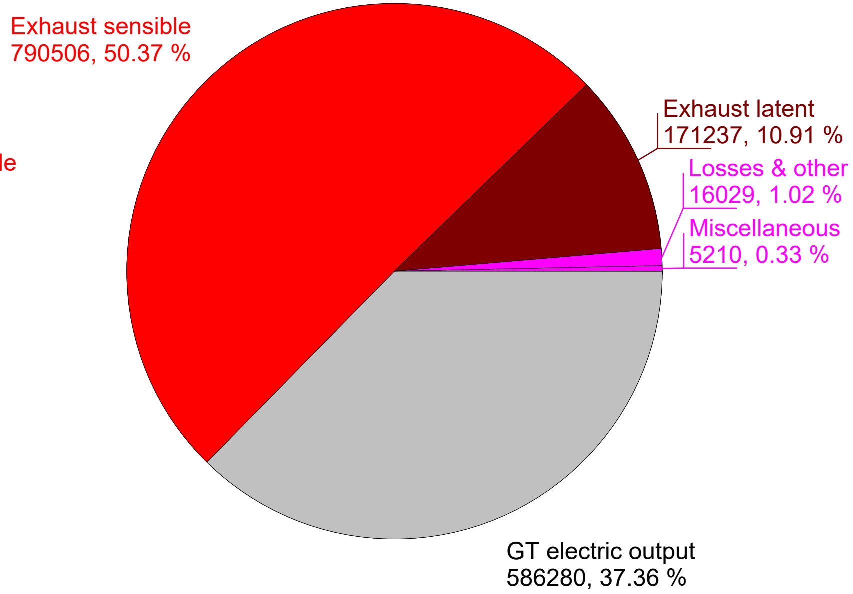
GT Cycle Energy In [kW]

GT cycle energy in = 1569295 kW
GT fuel chemical LHV input = 1386336 kW, HHV = 1538297 kW



GT Cycle Energy Out [kW]

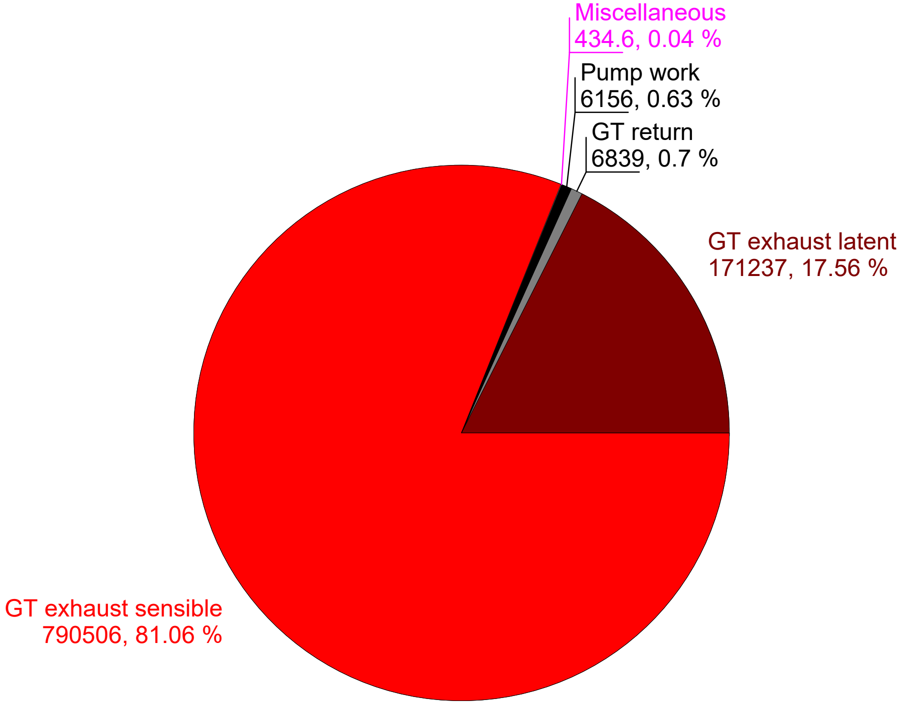
GT cycle energy out = 1569263 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

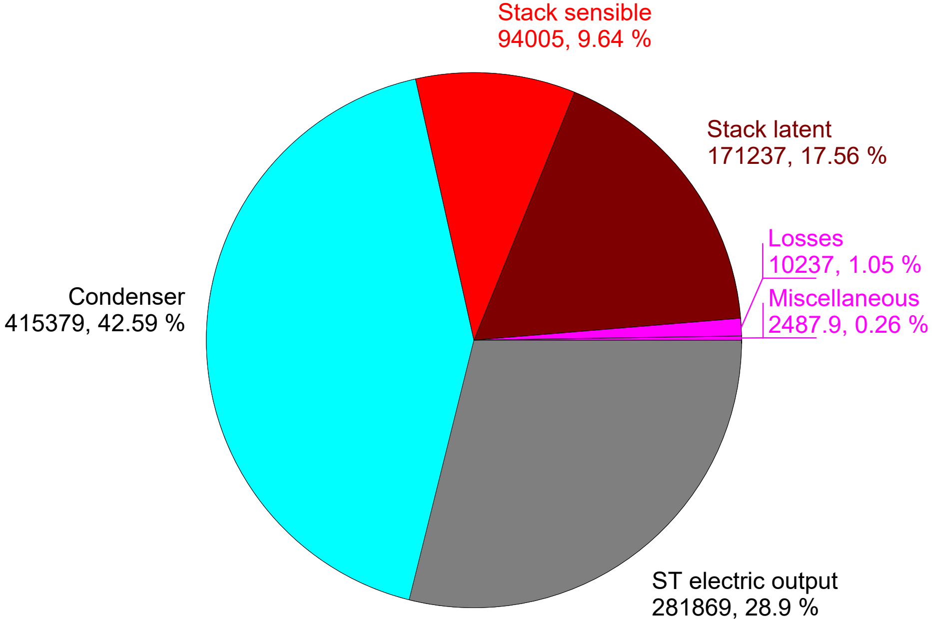
Steam Cycle Energy In [kW]

Steam cycle energy in = 975173 kW



Steam Cycle Energy Out [kW]

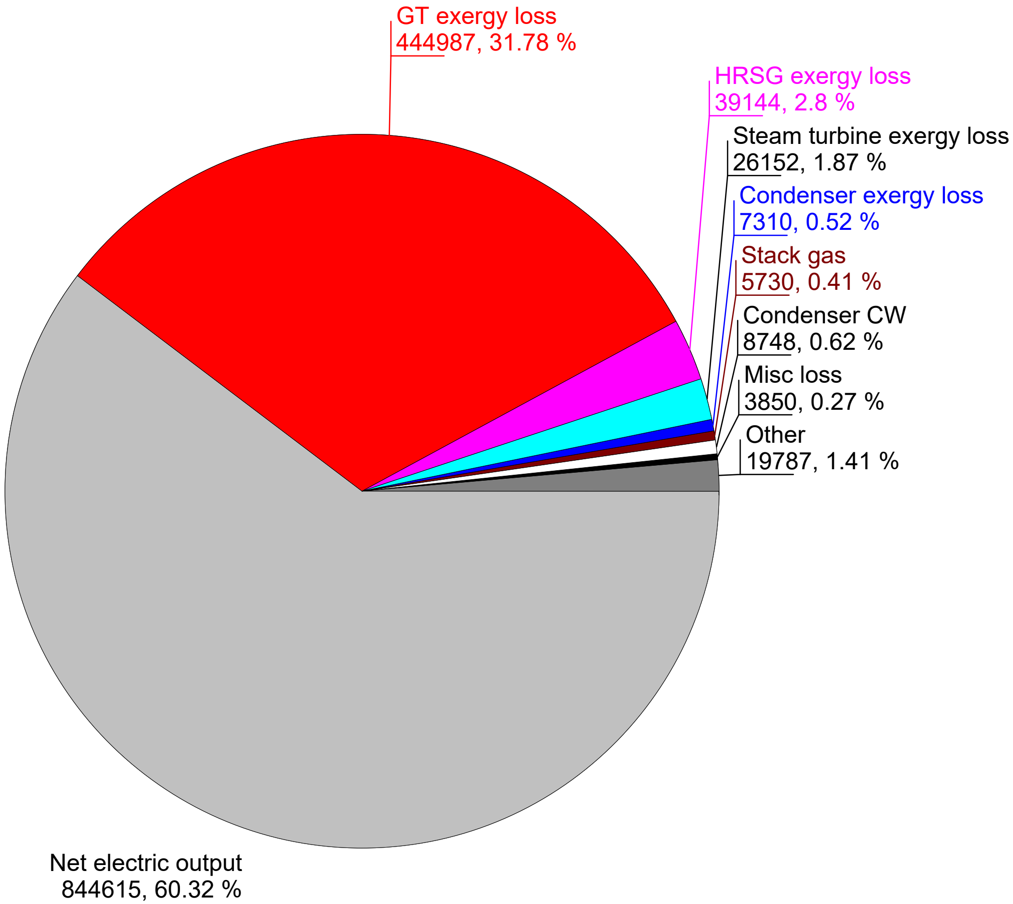
Steam cycle energy out = 975215 kW



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

Plant Exergy Analysis [kW]

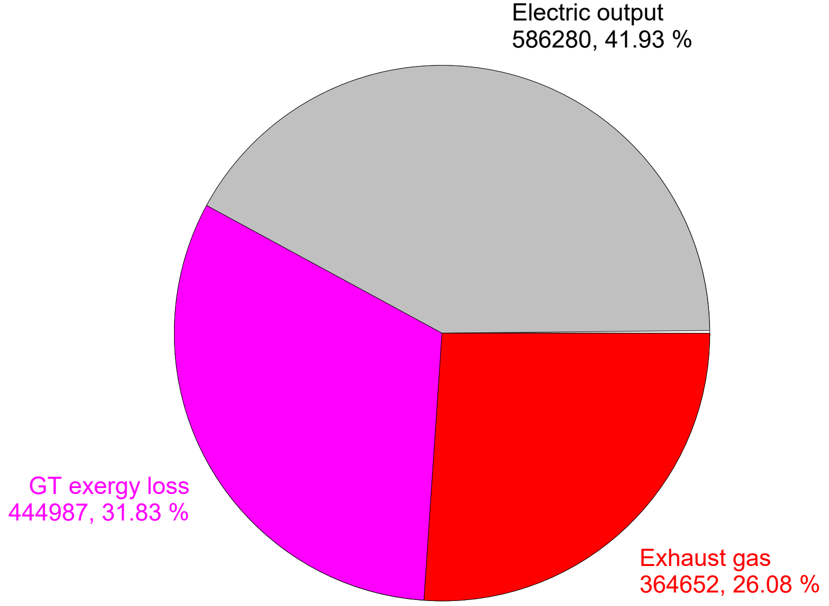
Plant exergy input = 1400322 kW
Fuel exergy input = 1399671 kW
Plant fuel chemical LHV input = 1386336 kW, HHV = 1538297 kW



Reference: 1.013 bar, 25 C, water as vapor.

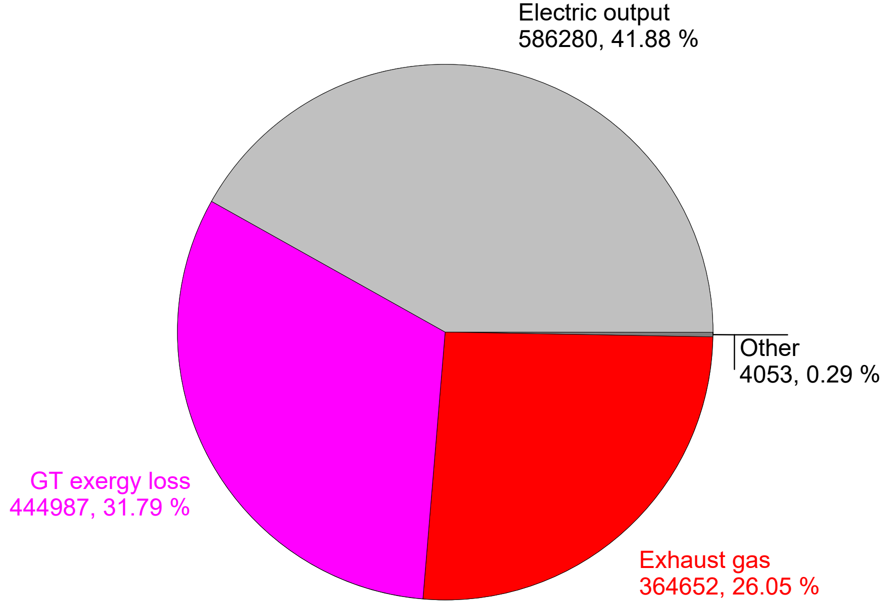
GT Exergy Analysis [kW]

GT exergy in = 1398145 kW



GT & Peripheral Exergy Analysis [kW]

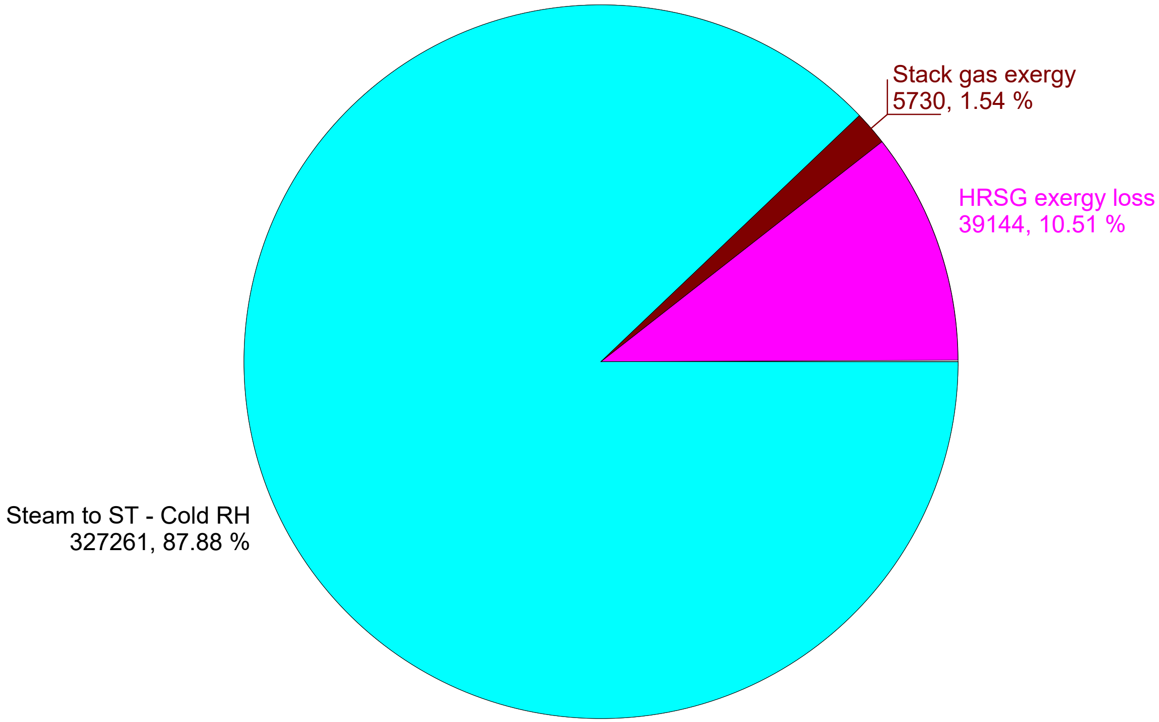
GT & peripheral exergy in = 1399972 kW



Reference: 1.013 bar, 25 C, water as vapor.

HRSG Exergy Analysis [kW]

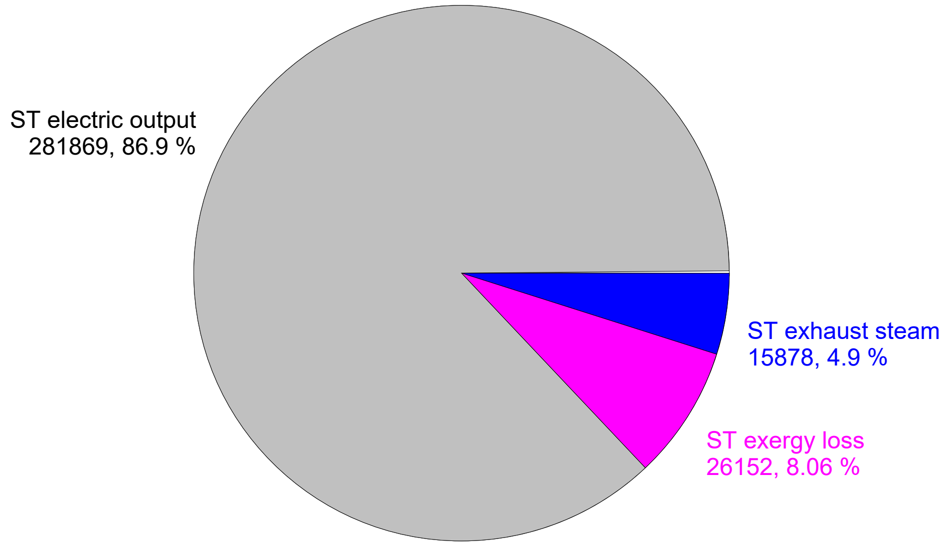
HRSG exergy in = 372382 kW



Reference: 1.013 bar, 25 C, water as vapor.

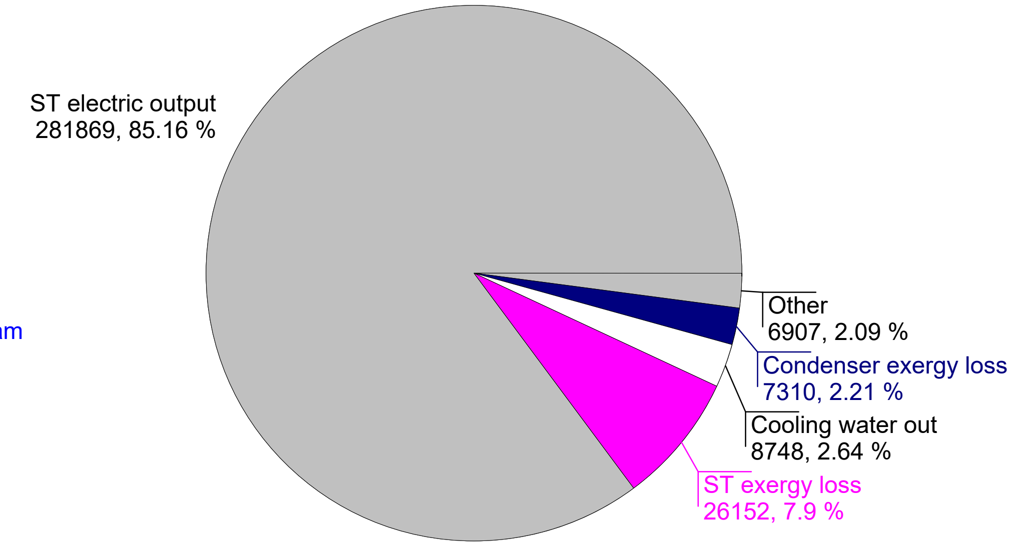
ST Exergy Analysis [kW]

ST exergy in = 324359 kW



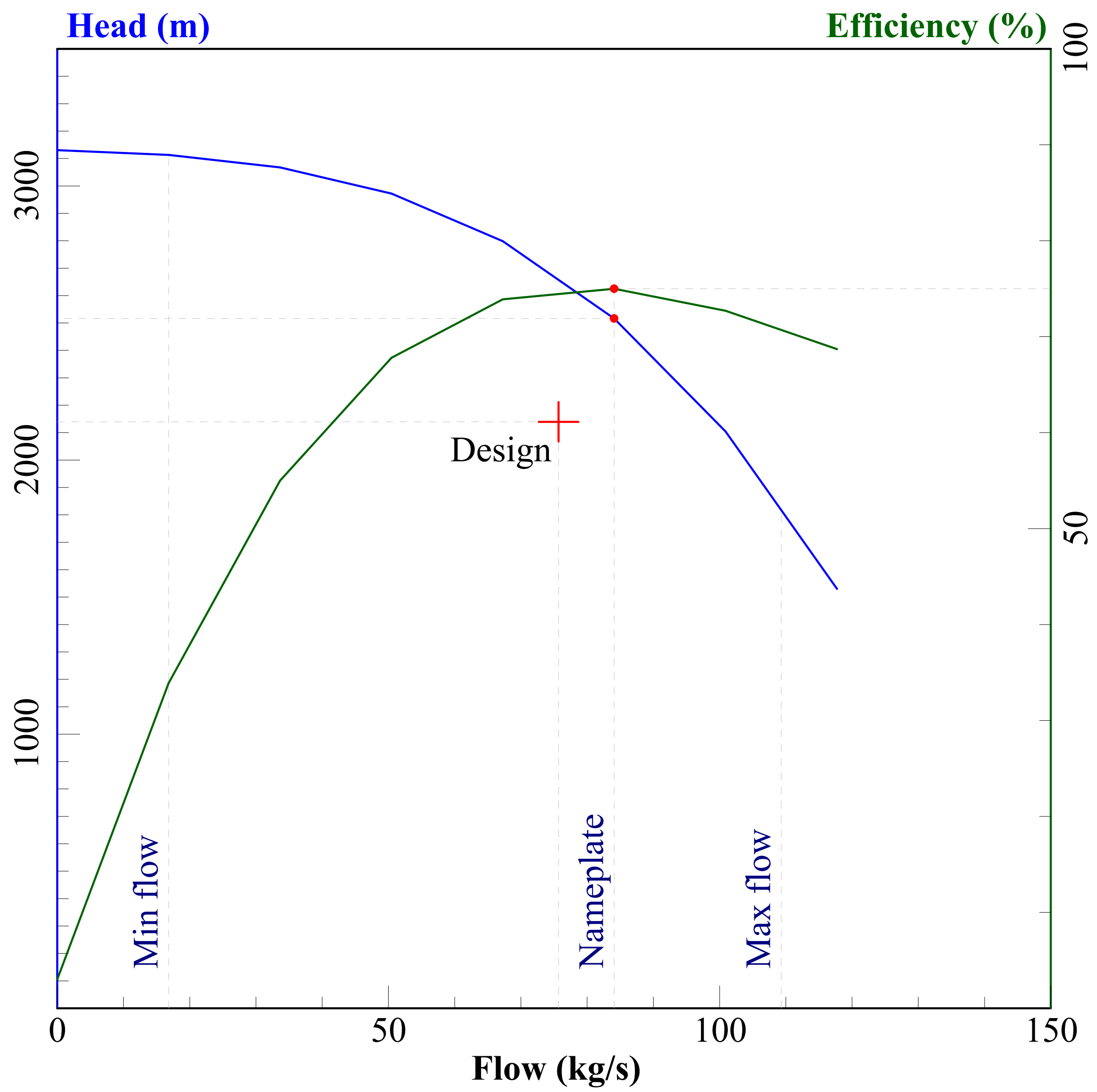
ST & Condenser Exergy Analysis [kW]

ST & condenser exergy in = 330986 kW



Reference: 1.013 bar, 25 C, water as vapor.

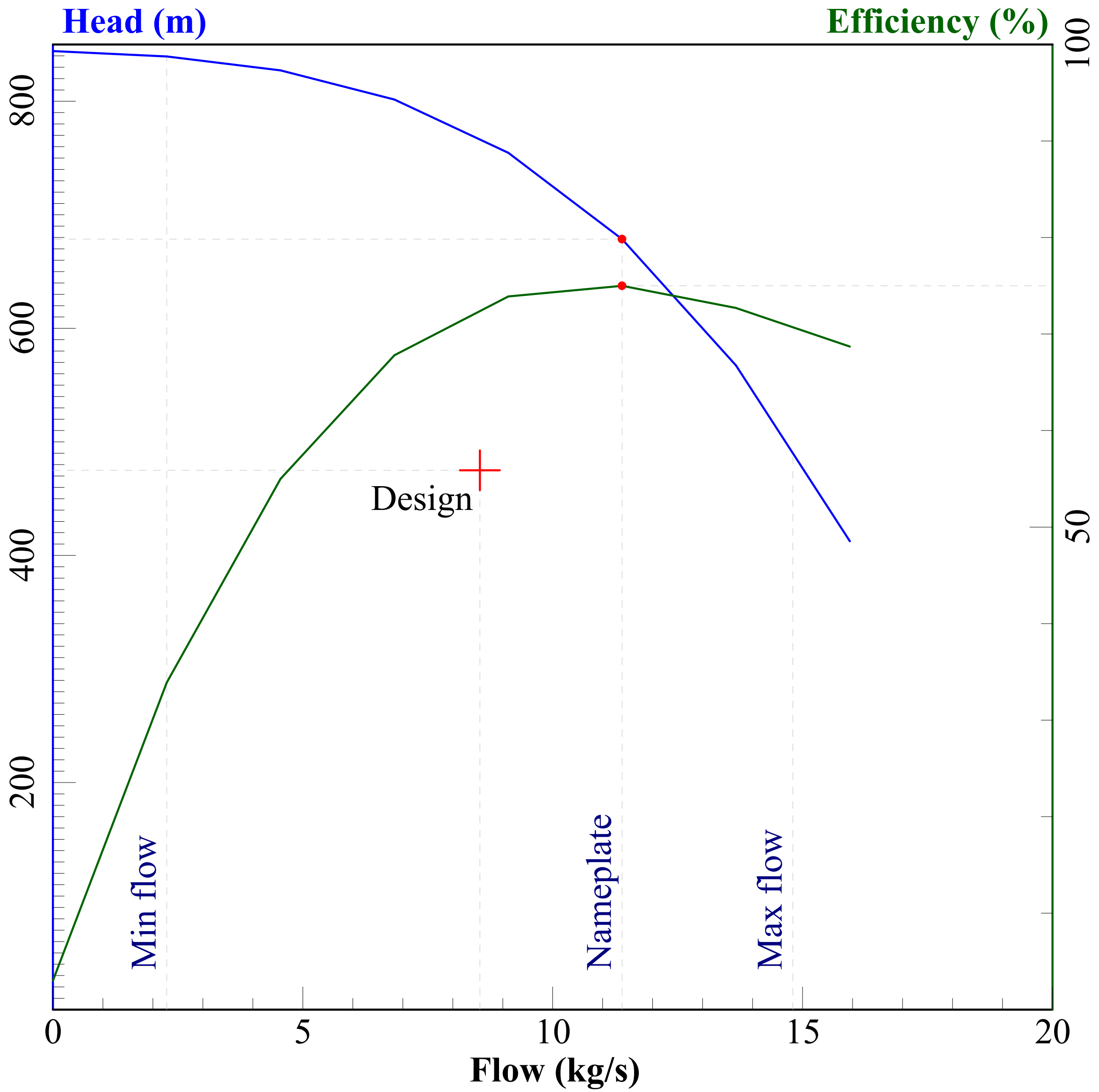
HP Feedwater Pump (P1)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	84.09 kg/s
Nameplate head	2516.5 m
Nameplate flow (nominal)	5678 lpm
Nameplate head (nominal)	2560.3 m
Nameplate RPM	3000
Design flow	75.68 kg/s
Design head	2139 m
Design RPM	3000
Minimum continuous flow	16.82 kg/s
Maximum continuous flow	109.3 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	HP Feedwater Pump (P1)
Date: 07/02/20	
Drawing No:	

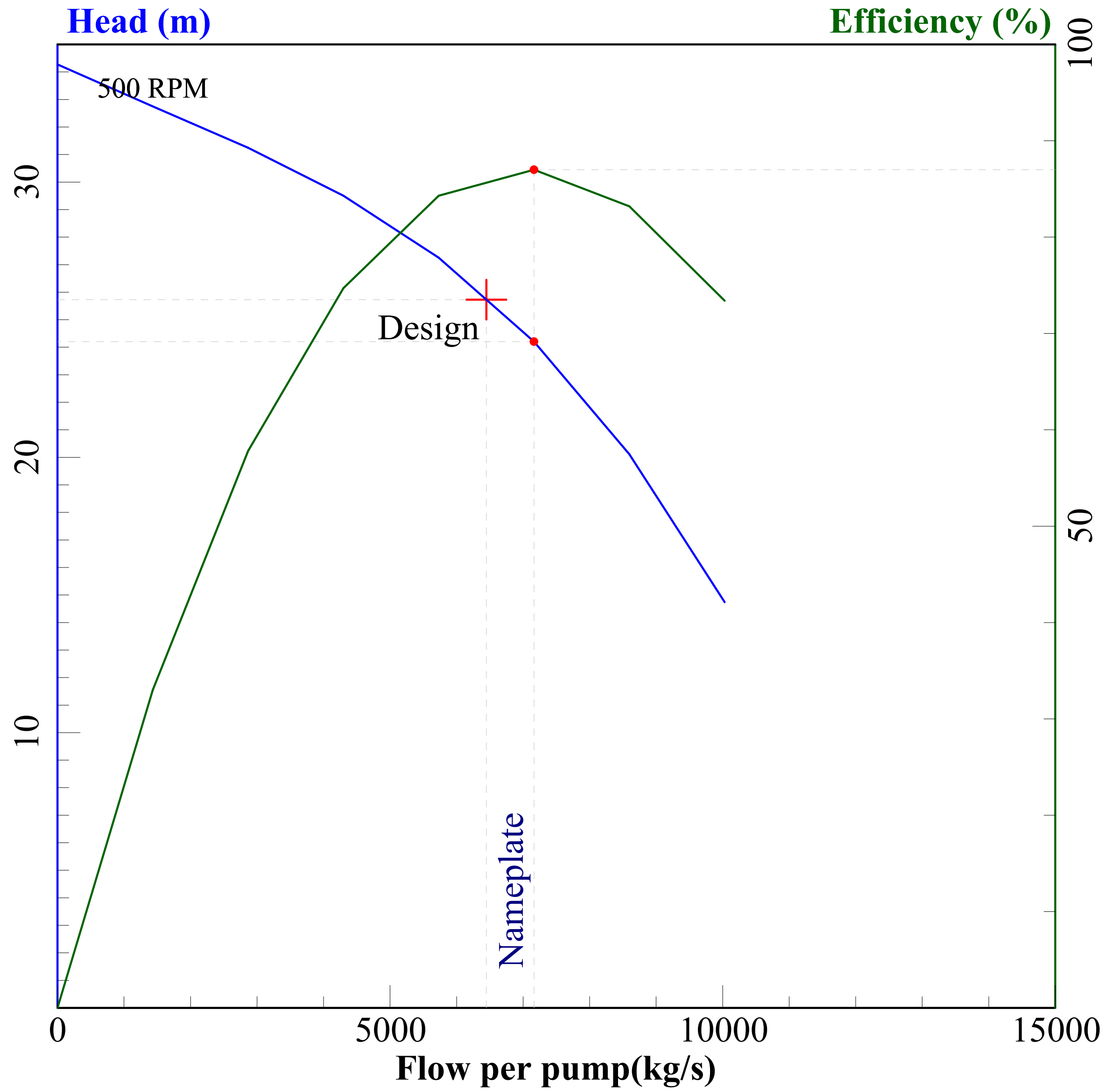
IP Feedwater Pump (P2)



No. per HRSG	3
No. operating per HRSG	2
Nameplate flow	11.39 kg/s
Nameplate head	678.6 m
Nameplate flow (nominal)	757.1 lpm
Nameplate head (nominal)	701 m
Nameplate RPM	3000
Design flow	8.542 kg/s
Design head	475 m
Design RPM	3000
Minimum continuous flow	2.278 kg/s
Maximum continuous flow	14.81 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	IP Feedwater Pump (P2)
Date: 07/02/20	
Drawing No:	

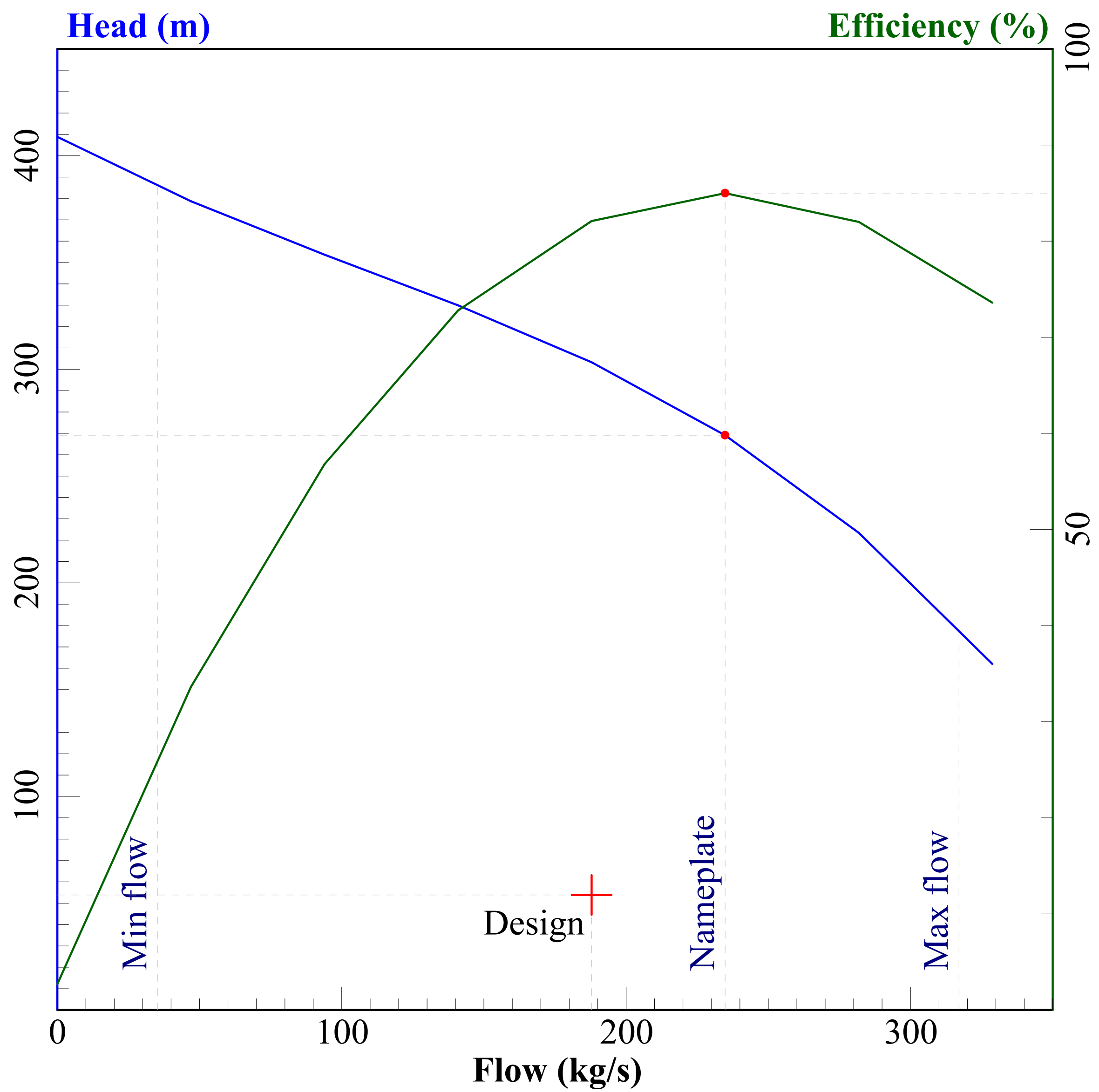
Condenser C.W. Pump (P4)



No. per Condenser	2
No. operating per Condenser	2
Nameplate flow	7164 kg/s
Nameplate head	24.2 m
Nameplate flow (nominal)	431537 lpm
Nameplate head (nominal)	24.38 m
Nameplate RPM	500
Design flow	6448 kg/s
Design head	25.73 m
Design RPM	500

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condenser C.W. Pump (P4)
Date: 07/02/20	
Drawing No:	

Condensate Forwarding Pump (P6)



No. per Condenser	2
No. operating per Condenser	1
Nameplate flow	234.8 kg/s
Nameplate head	269.2 m
Nameplate flow (nominal)	15142 lpm
Nameplate head (nominal)	274.3 m
Nameplate RPM	1500
Design flow	187.9 kg/s
Design head	53.83 m
Design RPM	1500
Minimum continuous flow	35.23 kg/s
Maximum continuous flow	317 kg/s

Thermoflow, Inc.	Company: AECOM Infrastructure & Environment UK Ltd.
	User: AECOM
	Condensate Forwarding Pump (P6)
Date: 07/02/20	
Drawing No:	