

**WHITE PAPER**

**Heat Exchanger (HX/SG) System Description**  
**(Non-Proprietary)**

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# 1 INTRODUCTION

This white paper presents an overview of the Balance of Plant (BOP) design for the SOLO Micro Modular Reactor (SOLO RTR), the First Of A Kind (FOAK) non-power Research and Test Reactor (RTR) designed by Terra Innovatum (TINN). The SOLO RTR is a 5 MWth helium-cooled reactor with a thermal neutron spectrum, designed to deliver steady-state thermal energy. Thermal power generated in the core is extracted by the primary helium loop and transferred to a secondary water/steam Rankine cycle through a dedicated heat exchanger and superheater. The secondary side expands the superheated steam in a turbine for power generation, rejecting residual heat to the atmosphere through an air-cooled condenser.

The BOP described in this document encompasses the Reactor Gas System (primary helium loop) and the Secondary Loop (Rankine cycle), including the heat exchanger and superheater that couple the two sides. The majority of the BOP components are commercial-off-the-shelf (COTS) and are classified as non-safety related. The only safety-related components within the scope of this document are the isolation valves of the Reactor Gas System, which define the safety boundary of the primary loop.

## 1.1 PURPOSE

The primary purposes of this white paper are to:

- (1) provide the USNRC with an overview of the SOLO RTR Balance of Plant design, including the Reactor Gas System and the Secondary Loop, at a level of detail consistent with a Preliminary Safety Analysis Report (PSAR), and
- (2) provide a basis for discussion with the USNRC regarding the adequacy of the proposed BOP design information for inclusion in the PSAR, in alignment with NUREG-1537 guidelines.

## 1.2 SCOPE

This white paper addresses the following topics:

- The Reactor Gas System (primary helium loop), including the circulator, the primary side of the heat exchanger and superheater, piping, isolation valves, and instrumentation and control.
- The Secondary Loop (Rankine cycle), including the secondary side of the heat exchanger and superheater, piping, valves, feedwater pump, deaerator, turbine system, turbine bypass, air-cooled condenser, and condensate extraction pump.
- The classification of BOP components, identifying the safety-related and non-safety-related portions of the system, with the safety boundary defined by the isolation valves of the Reactor Gas System.

## 1.3 APPLICABLE REGULATIONS AND REGULATORY GUIDANCE

This section identifies the principal USNRC regulations and guidance documents applicable to the SOLO RTR BOP design information presented in this white paper. The content and level of detail provided herein are intended to be consistent with the guidance for non-power reactors.

Table 1 lists the USNRC regulations and guidance documents applicable to the SOLO RTR BOP design.

*Table 1: USNRC regulations and guidance applicable to the SOLO RTR BOP design*

Regulatory Document	Title
NUREG-1537	Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors
10 CFR §50	Title 10, Code of Federal Regulations, Part 50 - Domestic Licensing of Production and Utilization Facilities

## 1.4 REQUEST FOR NRC

The information contained in this white paper is intended to serve as the basis for licensing topic interactions with the USNRC staff. Terra Innovatum seeks the USNRC's feedback on the proposed BOP design overview and on whether the type, depth, and breadth of information presented are adequate for inclusion in the Preliminary Safety Analysis Report (PSAR) and consistent with NUREG-1537 guidelines. The following are specific areas where feedback on the SOLO RTR BOP design is being sought:

- Agreement that the type of information presented for the BOP systems is appropriate for the PSAR.
- Agreement that the level of depth and breadth of the BOP design information is adequate to support PSAR review.
- Agreement that the proposed safety classification approach, with the safety boundary limited to the Reactor Gas System isolation valves and the remaining BOP components classified as non-safety-related commercial-off-the-shelf equipment, is acceptable.
- Agreement that the overall BOP design presentation aligns with NUREG-1537 guidelines for non-power reactors.

Terra Innovatum requests that the USNRC provide its feedback on the above topics within a budget of 40 hours of NRC staff review time.

## 1.5 REPORT STRUCTURE

The present white paper is organized into two main chapters. Chapter 1 introduces the SOLO RTR and the purpose and scope of this document. Chapter 2 describes the Heat Exchanger System, organized into the Reactor Gas System (primary side) and the Secondary Loop, with each subsystem and its main components described in detail and accompanied by figures illustrating the key elements.

## 2 HEAT EXCHANGER SYSTEM

### 2.1 REACTOR GAS SYSTEM

The primary circuit is a closed-loop, pressurized helium system operating in forced convection. It is designed to provide reliable heat extraction and transport under all operating conditions.

Helium is circulated by the helium circulator and flows through the reactor core, where it removes the thermal power generated by the core itself. The heated helium then leaves the core and is routed through the hot leg to the heat exchangers, where heat is transferred to the secondary circuit, resulting in the cooling of the primary side. After heat rejection, the cooled helium returns to the core through the cold leg and is recirculated by the circulator, completing the loop.

Two pairs of isolation valves define the safety boundary of the system, limiting the safety-related classification to the components located between them. In fact, these isolation valves represent the only safety-related components within the loop described herein.

The main operating parameters are presented below (Table 2)

*Table 2: Reactor Gas System Main Operating Parameters*

Parameter	Value
Coolant material	Helium
Coolant flow rates	[[ ]]
Reactor core inlet temperature	[[ ]]
Reactor core outlet temperature	[[ ]]
Reactor core pressure	[[ ]]
Helium purity	>99.9999 %
Construction materials of components	Stainless Steel

The Reactor Gas System components are:

- S3.1.1 Circulator
- S3.1.2 Heat Exchanger (HX) (Primary Side)
- S3.1.3 Piping
- S3.1.4 Isolation Valves System
- S3.1.5 Reactor Gas System I&C

A conceptual diagram of SOLO Reactor Gas System is represented below (Figure 1)

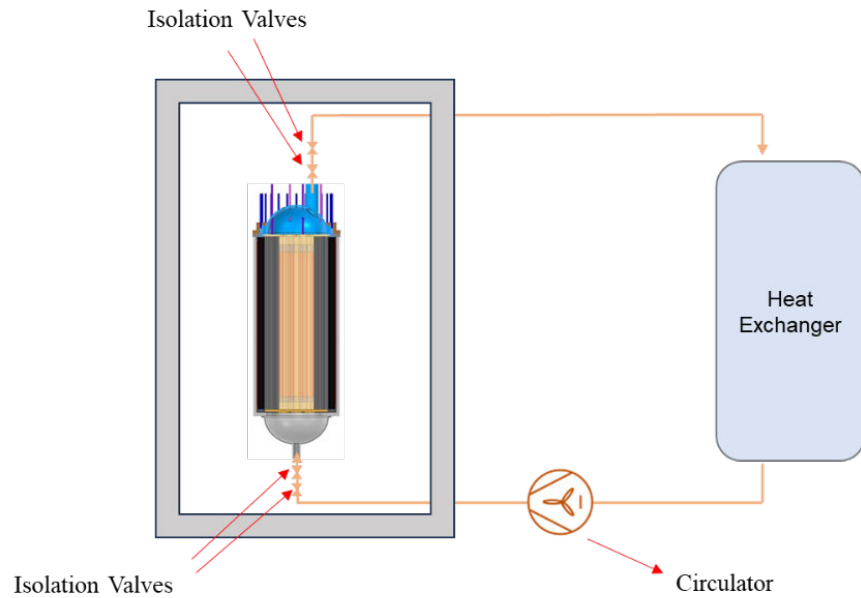


Figure 1: Reactor Gas System Simplified Diagram

### 2.1.1 Circulator

Helium circulation is ensured by a centrifugal fan, electrically driven, providing a pressure rise of up to 1 bar and featuring variable speed control through an inverter (Figure 2)

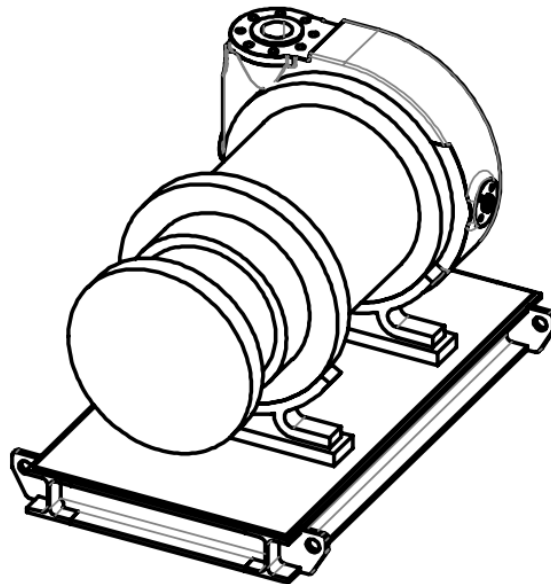


Figure 2: Helium Circulator

### 2.1.2 Heat Exchanger (HX) (Primary Side)

The system includes the main heat exchange components listed below:

- S3.1.2.1 Steam Generator

- S3.1.2.2 Superheater

The system is represented in Figure 3.

The primary side operates at a pressure of 80 bar, corresponding to a pressure margin of 15 bar above the secondary side.

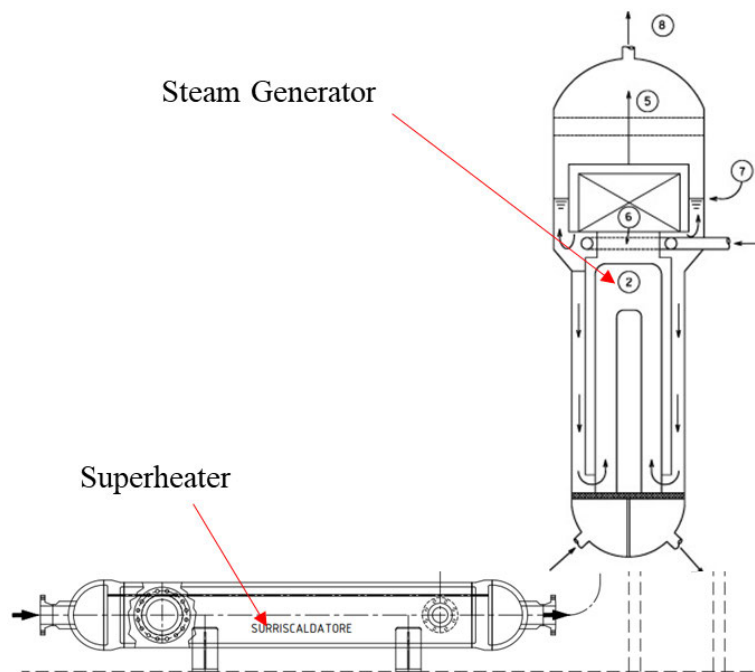


Figure 3: Heat Exchanger

### Steam Generator

The heat exchange between helium and the secondary water/steam system is performed through a helium-boiling water heat exchanger based on a U-tube configuration (Figure 4). This design is currently considered as the reference solution, while alternative configurations are also under evaluation to further enhance system controllability and operational flexibility.

Approximately 4 MW of thermal power are transferred in the steam generator, resulting in a reduction of the helium temperature down to [[     ]] K.

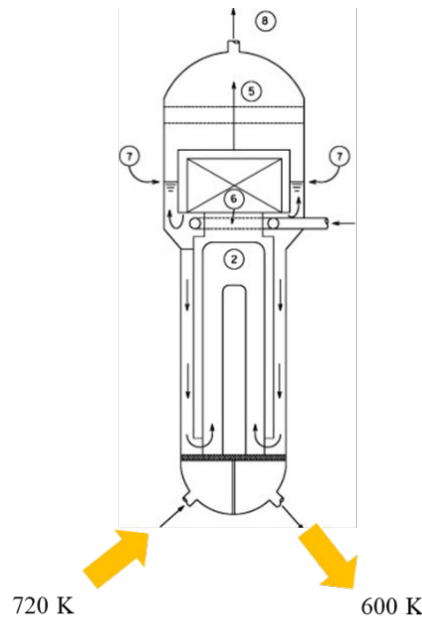


Figure 4: Steam Generator

### Superheater

The helium-superheated steam heat exchange is performed through a shell-and-tube heat exchanger with straight tubes. In this configuration, helium flows inside the tubes, while steam circulates on the shell side, ensuring effective thermal coupling between the two streams (Figure 5)

Approximately 1 MW of thermal power is transferred in the superheater, resulting in a further reduction of the helium temperature down to approximately [ ]K.

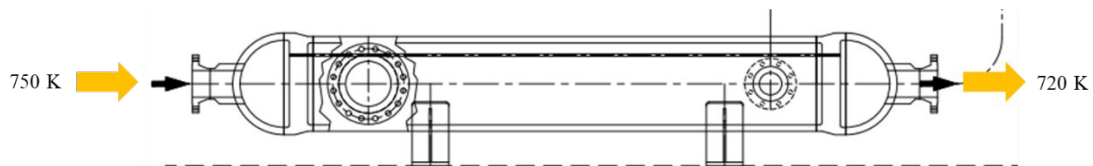


Figure 5: Superheater

### 2.1.3 Piping

The piping system includes the following main lines:

- S3.1.3.1 Hot Leg
- S3.1.3.2 Cold Leg

The Hot Leg (S3.1.3.1) connects the Pressure Tubes Coolant System upper plenum to the superheater. The line is specified as DN 200, Schedule 80S.

The Cold Leg (S3.1.3.2) connects the steam generator to the Pressure Tubes Coolant System lower plenum, crossing the circulator. The line is specified as DN 200, Schedule 80S.

#### **2.1.4 Isolation Valves System**

The isolation system consists of two pairs of isolation valves designed to isolate the reactor core by interrupting the helium flow both at the inlet and outlet. Their presence represents a key feature of the Reactor Gas System, as they provide a clear separation between safety-related and non-safety-related parts of the loop. In particular, safety classification is limited to the components located between the two pairs of isolation valves. Therefore, all other components in the circuit are not classified as safety-related, thanks to the segregation ensured by the isolation system.

#### **2.1.5 Reactor Gas System I&C**

Instrumentation is installed to ensure the correct operation of the system through continuous monitoring of the main operating parameters. These instruments are provided for monitoring purposes only and do not perform any direct control functions on the system.

All control functions are instead handled by the Reactor Control System, which is responsible for the active regulation of the plant operating conditions.

### 3 SECONDARY LOOP

The purpose of the secondary is to provide a continuous heat sink and to transform the heat into electricity.

The secondary coolant system is based on a superheated Rankine thermodynamic cycle operating in a closed loop. Thermal energy is transferred from the primary system through a steam generator and a super-heater where superheated steam is produced which is expanded in a steam turbine equipped with extraction stages. The exhaust steam is then condensed in an air-cooled condenser, and the condensate is routed through a condensate pump and a deaerator before being pressurized by the feedwater pump and returned to the steam generator, to close the cycle.

The system is designed to support continuous full-power reactor operation. In addition, it can operate in an island mode, (i.e., disconnected from external electrical loads), supplying power exclusively to internal loads and auxiliary systems.

The secondary loop includes the following main components:

- S3.2.1 Heat Exchanger (HX) (Secondary Side)
- S3.2.2 Secondary Loop I&C
- S3.2.3 Piping
- S3.2.4 Valves
- S3.2.5 Feedwater Pump
- S3.2.6 Deaerator
- S3.2.7 Turbine System
- S3.2.8 Turbine Bypass
- S3.2.9 Air Cooled Condenser (ACC)
- S3.2.10 Condensate Extraction Pump

Figure 6 shows the schematic flow diagram of the entire secondary side system while in Table 3 the main operating parameters are listed.

*Table 3: Secondary Loop Main Operating Parameters*

Parameter	Value
Coolant material	Water
Coolant flow rates	[[ ]]kg/s
Heat exchanger pressure	[[ ]]bar
Heat dissipation system	Air-Cooled Condenser
Heat dissipation system location	Outdoors

[[

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*Figure 6: Secondary Loop Simplified Diagram*

Hot Helium, transporting the primary side heat generated in the core, flows inside the tubes of the super-heater first and then of the steam generator. The shell side of the two components are filled with steam and a mix of water and steam, respectively. The steam generator is equipped with a safety valve aimed at limiting the overpressurization of both the super-heater and the steam generator.

The superheated steam is expanded into a two-stage turbine which is fed by the turbine control valve. After the first stage a certain mass flow of steam is diverted to the deaerator (FWT) to allow its degassing and to preheat the feedwater.

The steam exiting the second stage of the turbine is routed to the air condenser (ACC) to condensate it while dissipating the residual heat to the atmosphere. The condensate is extracted from the air condenser by a pump (ACC-pump) to move the water into the deaerator. The deaerator collects the condensate, eliminates the non-condensable eventually present in the water and provides a reservoir of pre-heated water.

The water is finally pumped into the shell side of the steam generator to be transformed again in steam.

The turbine bypass allows the partial or complete bypass of the turbine routing the steam directly to the condenser. Before entering into the condensation stage, the steam passes through the de-superheating system. The de-superheating system is a component in which condensate water is sucked and sprayed onto the steam to reduce the fluid enthalpy before moving into the condensation stage.

Isolation valves are installed before and after the main components to allow maintenance and repair processes. Other than the turbine control valve, the feedwater control valve is adopted to adjust the feedwater mass flow rate based on the water level measured inside the steam generator.

### 3.1 HEAT EXCHANGER (HX) (SECONDARY SIDE)

The heat exchanger system includes the following main components:

- S3.2.1.1 Steam Generator
- S3.2.1.2 Superheater

By removing heat from the primary coolant, the heat exchanger enables both the phase change of the secondary-side water and the subsequent superheating of the generated steam.

The secondary side operates at a pressure of [[ ]]bar, corresponding to a pressure level [[ ]]bar below that of the primary side.

#### 3.1.1 Steam Generator

The helium-boiling water heat exchange is performed in the steam generator through a U-tube heat exchanger configuration (Figure 7). The reference design adopts an external downcomer arrangement, while the phase change of the water takes place in the riser section. The recirculation flow rate can be regulated through a dedicated control valve, allowing adjustment of the thermal-hydraulic behavior of the system.

This configuration is currently considered as the reference solution, while alternative designs are also under evaluation to further improve controllability and operational flexibility.

Water enters the steam generator as a subcooled liquid at approximately [[ ]]K. As heat is transferred from the primary helium side, boiling occurs in the riser and the outlet flow reaches saturated steam conditions at [[ ]]K, corresponding to the saturation temperature at [[ ]] bar.

A mechanical separator is installed to ensure adequate steam quality at the outlet of the steam generator.

[[

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*Figure 7: Steam Generator, Secondary Side*

### 3.1.2 Superheater

The helium-superheated steam heat exchange is performed in the superheater through a shell-and-tube heat exchanger with straight tubes. In this configuration, helium flows inside the tubes, while steam circulates on the shell side, ensuring effective thermal coupling between the two streams (Figure 8).

Steam enters the shell side as saturated steam at [[     ]]K and exits as superheated steam at [[     ]]K, resulting in a total superheating of approximately [[     ]]K.

[[

]]

*Figure 8: Superheater, Secondary Side*

### 3.2 SECONDARY LOOP I&C

The Secondary Loop Instrumentation and Control (I&C) system ensures the correct operation of the system through continuous monitoring and control of the main operating parameters, guaranteeing stable and reliable performance under all operating conditions (Figure 9).

[[

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*Figure 9: Secondary Loop Instrumentation*

### 3.3 PIPING

The piping system ensures the circulation of water and steam throughout the secondary loop, providing the hydraulic connection between all major components and maintaining the continuity of the Rankine cycle.

It includes the following subcomponent:

- S3.2.3.1 Thermal Expansion Joints

The thermal expansion joints are designed to accommodate the thermal expansion of the piping system, ensuring structural integrity and reducing the mechanical stresses generated by temperature variations during operation (Figure 10).



*Figure 10: Thermal Expansion Joint*

### 3.4 VALVES

The valves system includes the following main components, as represented in Figure 11:

- S3.2.4.1 Safety Valves
- S3.2.4.2 Isolation Valves
- S3.2.4.3 Control Valves

The safety valves (circled in red on the figure) ensure that the system pressure remains below the maximum allowable limit, preventing overpressure conditions. Two sets of relief valves, operating at different setpoints, are provided to protect the integrity of all downstream components and piping.

The isolation valves (circled in yellow on the figure) are designed to isolate sections of the system in order to preserve component integrity and allow maintenance activities when required.

The control valves (circled in green on the figure) receive actuation commands from the PLC and perform the necessary adjustments to rapidly regulate the main process parameters and maintain stable operating conditions.

[[

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*Figure 11: Secondary Loop Valves*

### **3.5 FEEDWATER PUMP**

The feedwater pump (Figure 12) is a multistage pump designed to provide the large pressure rise required to ensure proper water circulation throughout the secondary loop. It is suitable for operation under medium-high temperature and high-pressure conditions, ensuring reliable performance in demanding service conditions.

The pump is driven by an AC motor and operates at fixed speed, while mass flow rate and pressure regulation are achieved through dedicated control valves installed in the system.

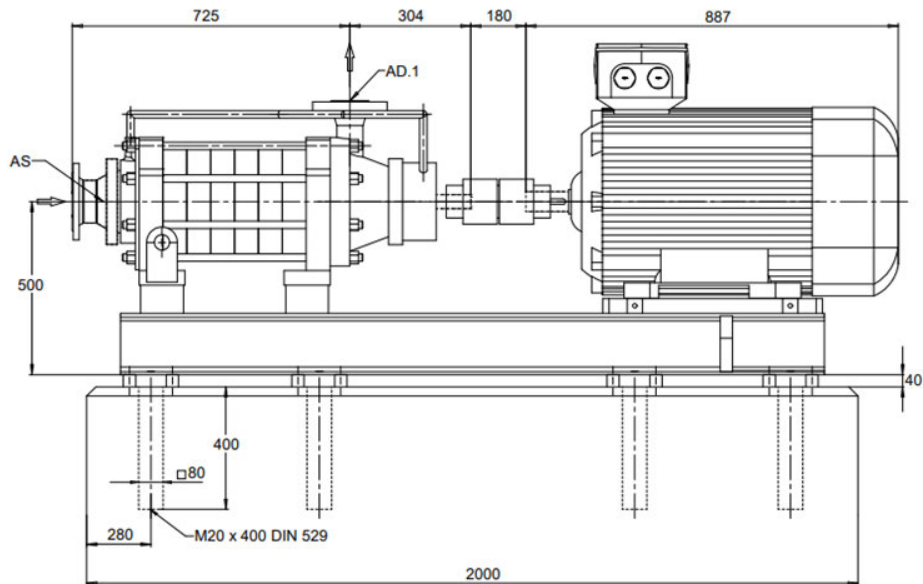


Figure 12: Feedwater Pump

### 3.6 DEAERATOR

The deaerator system includes the following main components (Figure 13):

- S3.2.6.1 Deaerating Column
- S3.2.6.2 Feedwater Tank

Under normal operating conditions, the deaerator performs two main functions: maintaining the dissolved oxygen concentration within acceptable limits and preheating the feedwater before it enters the steam generator. The removal of dissolved gases helps prevent corrosion and ensures reliable operation of the secondary loop.

Under certain conditions, the deaerator can also act as a temporary steam storage volume. Steam exiting the steam generator can be discharged into the feedwater tank to prevent overpressure conditions, avoiding direct venting and therefore preventing fluid losses from the secondary circuit.

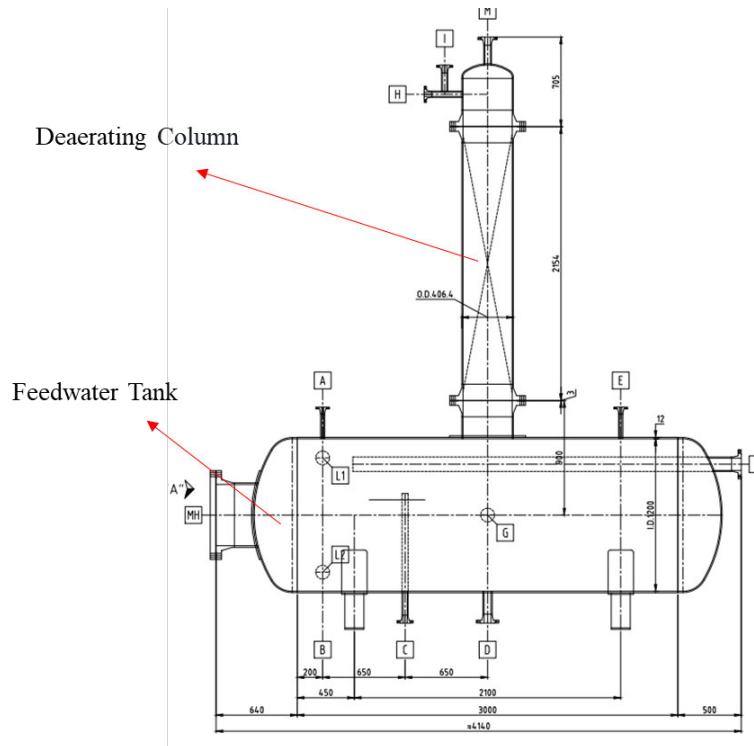


Figure 13: Deaerator

### 3.6.1 Deaerating Column

The deaerating column is a deaeration tower in which feedwater is sprayed from the top and flows downward across a series of trays. Steam is injected from the bottom of the column and rises counter-currently to the descending water (Figure 14).

During this process, the steam heats the water and promotes the removal of dissolved gases, particularly oxygen. The released air is carried upward and discharged through a dedicated vent, ensuring that the dissolved oxygen concentration is maintained within the required ppb range for safe and reliable system operation.

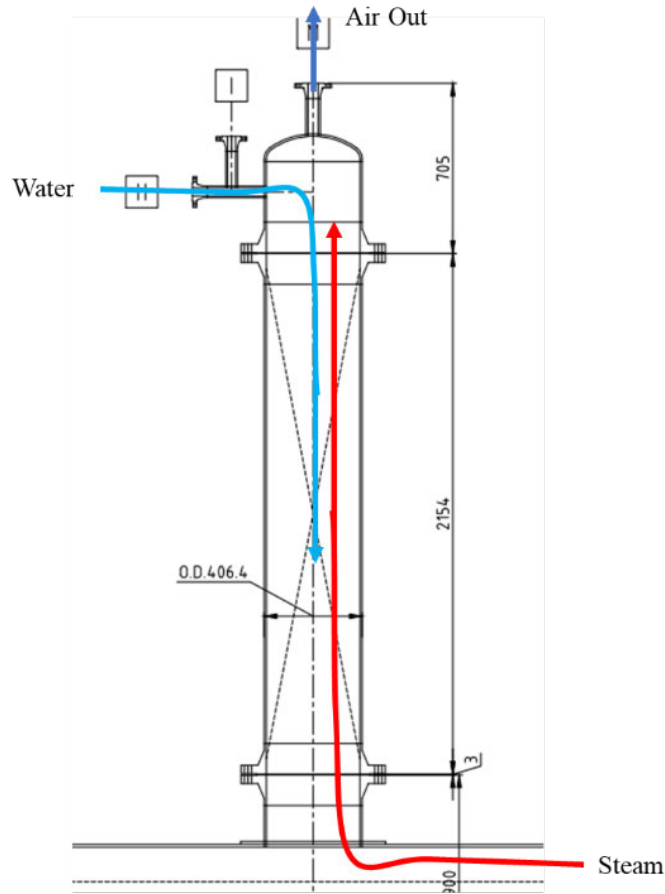


Figure 14: Deaerating Column

### 3.7 FEEDWATER TANK

The deaerated and preheated water from the deaerating column is collected in the feedwater tank, which acts as a storage volume for the secondary loop before the water is recirculated to the steam generator. The tank is sized to provide an operational buffer corresponding to approximately 10–20 minutes of autonomous operation, ensuring system stability during transient conditions.

### 3.8 TURBINE SYSTEM

The turbine system includes (Figure 15):

- S3.2.7.1 Turbine Inlet
- S3.2.7.2 Turbine

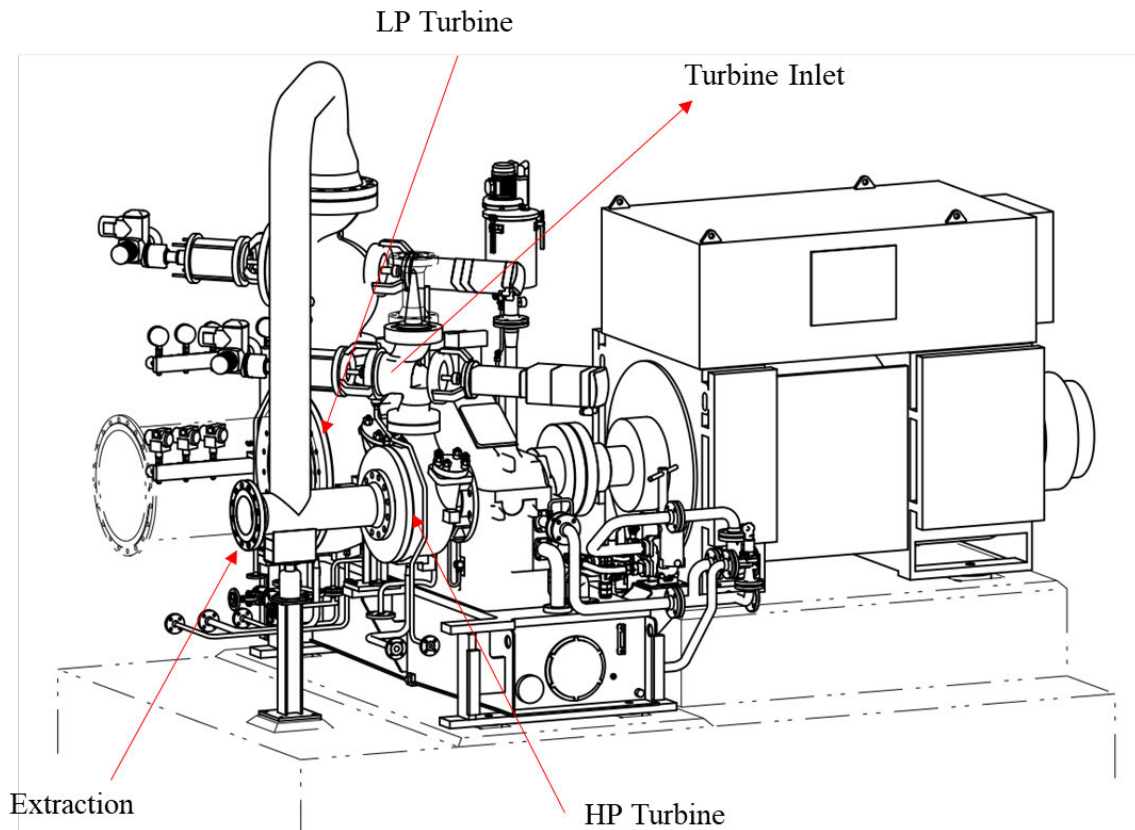


Figure 15: Turbine System

#### 3.8.1 Turbine Inlet

The turbine inlet mass flow rate is regulated by a turbine governor valve installed upstream of the turbine. This valve controls the amount of steam admitted to the turbine, allowing precise adjustment of the turbine load and ensuring stable operation under varying demand conditions.

The governor valve enables dispatch control by modulating the steam flow according to the required power output, providing operational flexibility and supporting grid-following strategies. In addition, it performs an isolation function, allowing the turbine to be separated from the rest of the secondary loop during shutdowns, maintenance activities, or abnormal operating conditions.

#### 3.8.2 Turbine

The turbine system consists of a two-wheel single-stage turbine arrangement. Steam first expands through the first turbine stage, reaching an intermediate pressure level.

A portion of the outlet steam from the first stage is extracted and directed to the deaerator tower as controlled extraction steam, while the remaining flow continues to the second turbine stage to complete the expansion.

process. The extraction mass flow rate and pressure are regulated by a dedicated extraction valve, ensuring the proper operating conditions for the deaerator and the overall balance of the secondary loop.

Both turbine stages are mechanically connected through a gearbox to a single shaft, which drives the electric generator for power production.

### 3.9 TURBINE BYPASS

Turbine bypass line allows the system to operate under highly dynamic conditions by enabling load following operation while keeping the reactor thermal power constant. This is achieved by diverting part or the full mass flow away from the turbine, allowing rapid load changes on the secondary side without affecting the reactor core conditions. In addition, it supports island-mode operation, where the system can run independently by generating only the power required by the internal SOLO components, ensuring stable and flexible operation under variable demand conditions (Figure 16).

Includes:

- S3.2.8.1 Desuperheating Valve
- S3.2.8.2 Condensate Recirculation Loop

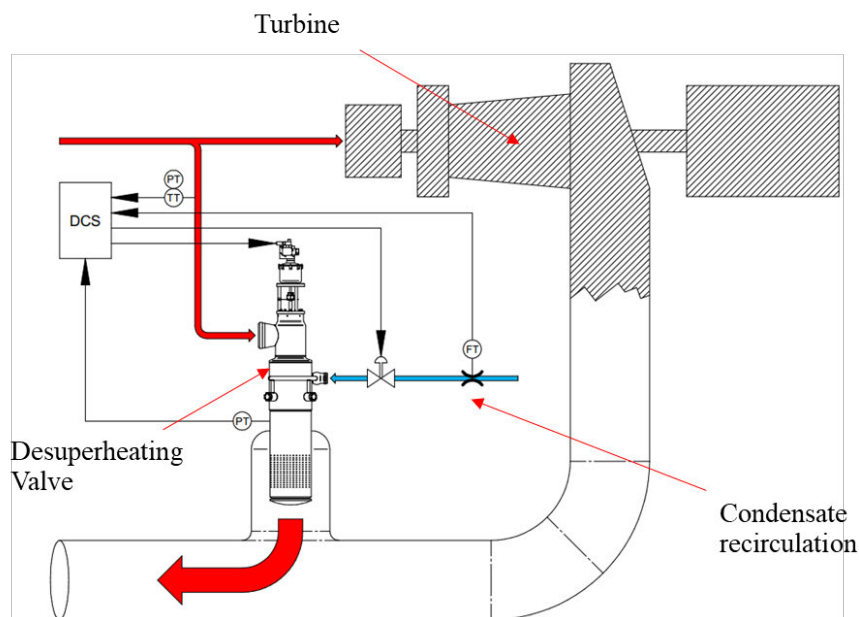


Figure 16: Turbine Bypass

#### 3.9.1 Desuperheating Valve

The desuperheater is a critical control valve designed to manage large temperature and pressure differences between its inlet and outlet conditions. It ensures that the steam discharged to the air-cooled condenser remains within acceptable temperature and pressure limits, protecting downstream components and ensuring stable operation (Figure 17).

The valve operates in two stages. In the first stage, depressurization is achieved through specially designed internal flow paths that generate a significant pressure drop. In the second stage, desuperheating is obtained by means of a water spray injection, where cold water mixes with the superheated steam, ensuring a controlled reduction of the steam temperature.

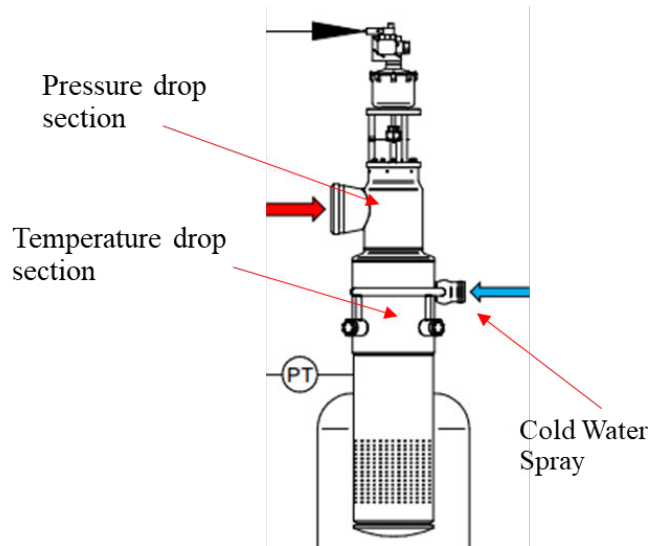


Figure 17: Desuperheating Valve

### 3.9.2 Condensate Recirculation Loop

The condensate recirculation loop transfers cold condensate from the condensate tank to the desuperheating valve, ensuring a continuous and controlled water supply for the steam temperature reduction process. A dedicated condensate recirculation pump increases the pressure of the fluid to a level compatible with the desuperheater spray injection system, enabling proper atomization and mixing with the superheated steam. Isolation valves are also included to allow safe access and maintenance of the system components without affecting overall plant operation (Figure 18).

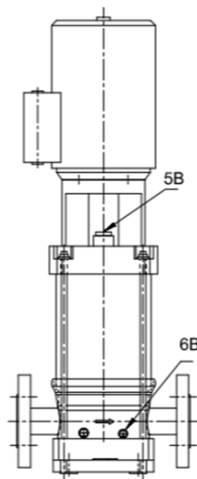


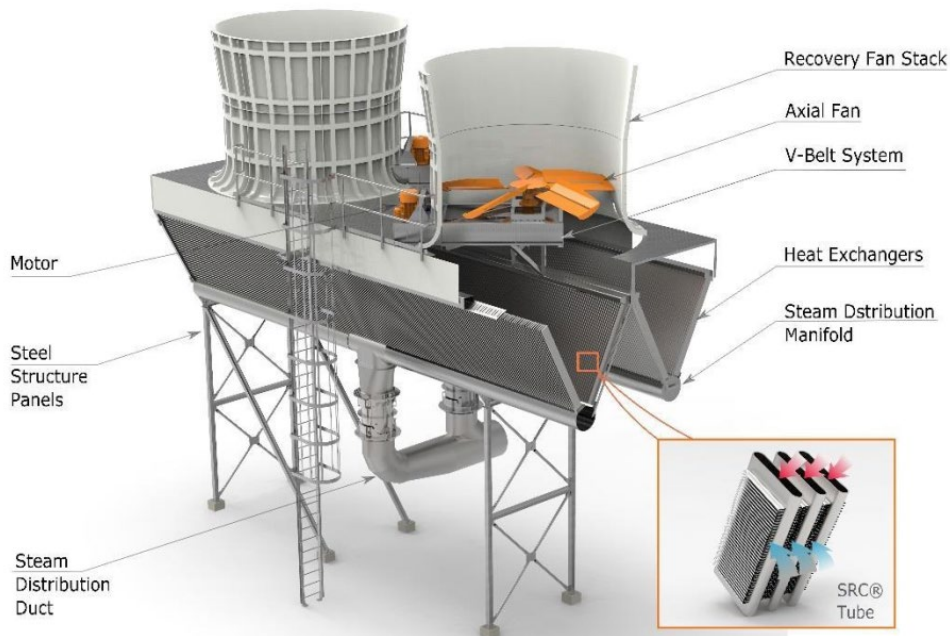
Figure 18: Condensate Recirculation Pump

### 3.10 AIR-COOLED CONDENSER

The air-cooled condenser is the system responsible for rejecting heat to the environment, specifically to the atmosphere. It operates as a steam-to-air heat exchanger, where incoming steam is condensed through heat transfer with ambient air, enabling a dry cooling solution without the need for external water resources. The system is installed outdoors and relies on forced ventilation to ensure effective heat rejection and stable condensation conditions, supporting reliable operation of the thermodynamic cycle (Figure 19).

Includes:

- S3.2.9.1 Tube Bundle
- S3.2.9.2 Forced Ventilation System
- S3.2.9.3 Condensate System
- S3.2.9.4 Air Evacuation System



*Figure 19: Air-Cooled Condenser*

### 3.10.1 Tube Bundle

The tube bundle consists of finned tubes arranged in a V-shaped configuration to maximize heat transfer surface and improve overall condensation efficiency. Within the tubes, saturated steam undergoes phase change to liquid water as heat is rejected to the surrounding air stream. This configuration enhances compactness and promotes uniform flow distribution, ensuring effective and stable condensation performance under varying operating conditions (Figure 20).



*Figure 20: Tube Bundle*

### 3.10.2 Forced Ventilation System

The forced ventilation system ensures controlled ambient air flow across the tube bundles through fans installed above the heat exchange surface (Figure 21). The fans are driven by electric motors equipped with inverters, enabling control of rotational speed. This variable-speed operation allows the system to adapt to changing ambient temperature conditions and to regulate the condensation pressure, which directly determines the turbine backpressure.

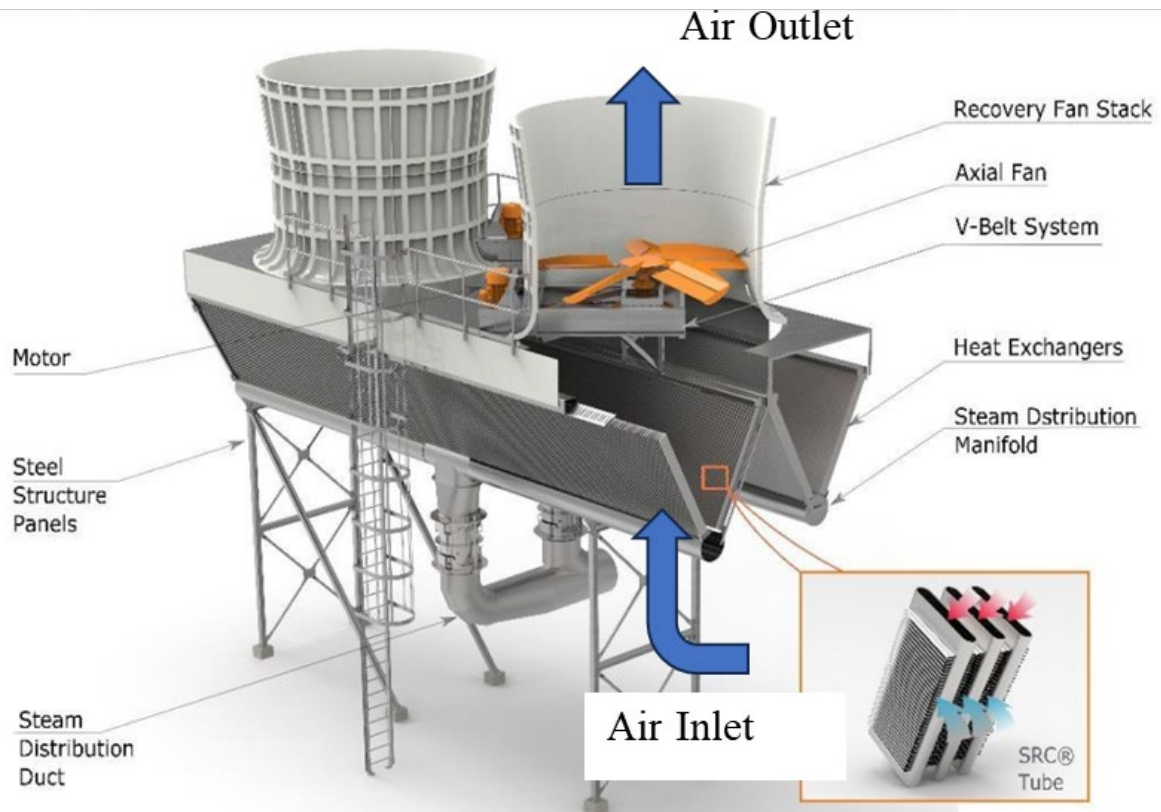


Figure 21: Forced Ventilation System



### 3.10.4 Air Evacuation System

The air evacuation system ensures that the air-cooled condenser operates under vacuum conditions by removing non-condensable gases from the loop. This is achieved through ejectors, which maintain the required low-pressure environment to support efficient steam condensation. A portion of the steam entrained with the extracted air is recovered within the system, where it is condensed and subsequently directed to the condensate tank, contributing to overall condensate management and cycle efficiency (Figure 23).

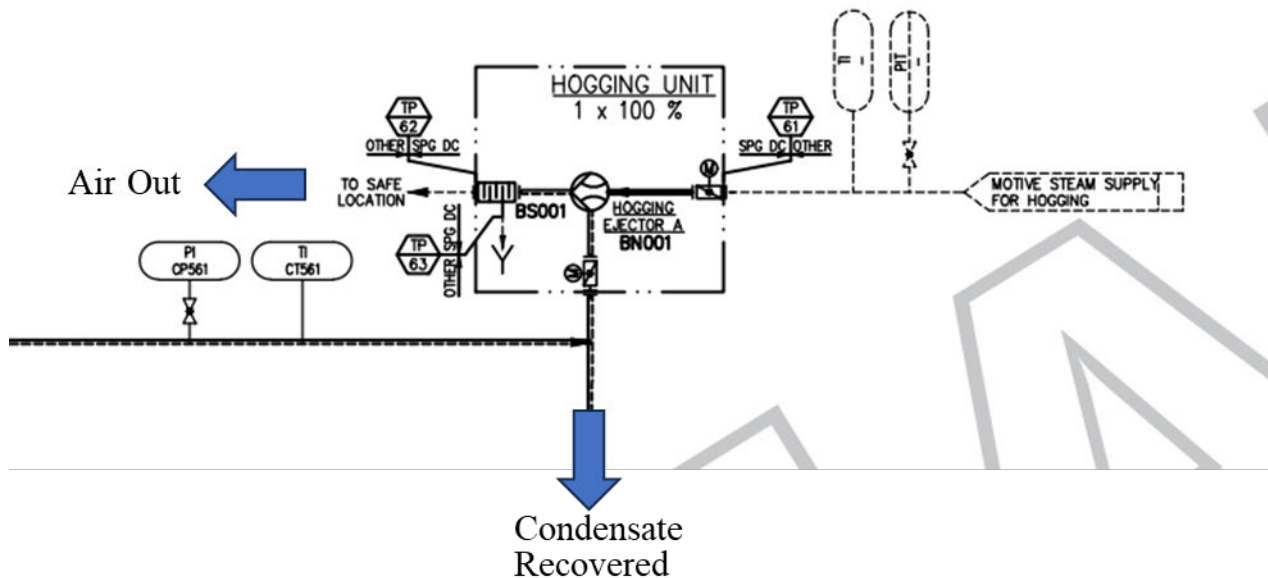
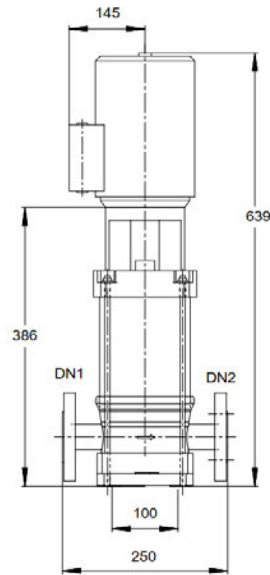


Figure 23: Air Evacuation System

### 3.11 CONDENSATE EXTRACTION PUMP

The condensate extraction pump transfers condensate from the condensate tank to the deaerator, ensuring a continuous and controlled feed to the next stage of the cycle. The pump is installed at a suitable elevation below the condensate tank in order to guarantee adequate NPSH, relying on the static head provided by the water column. This configuration is particularly important given that the condensate is maintained close to saturation conditions, where cavitation risk is significant and must be carefully controlled to ensure reliable operation (Figure 24).



*Figure 24: Condensate Extraction Pump*