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Conceptual Design of a Cryo-Distribution System for STEP: Addressing Cooling Challenges and Enhancing Energy Efficiency

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Abstract. The STEP program is an ambitious initiative aimed at demonstrating, for the first time, a fusion energy prototype power plant capable of delivering net power to the electrical grid. Cryogenic users, such as fuel cycling, thermal shielding, current feeders, and superconducting (SC) magnets will require substantial cooling power, currently estimated at ~90 kW at 4.2 K. This work focuses on the design challenges of the cryogenic distribution system, including helium delivery at multiple temperatures, thermal transients, and buffer tank configurations. We present the conceptual design of the cryogenic distribution system. The optimised conceptual design features nearly 250 cryogenic feeds and multiple temperature requirements, resulting in 49 valve boxes distributed across three levels around the Tokamak. Unsteady cooling demands were calculated and present a challenge for power consumption, which can range from 37 MWe to 46 MWe. Finally, we compare two liquid helium buffer options for the 5–10 K temperature range. Results show a variation in heat exchanger effectiveness from 95% to 55% when the feed temperature set-point to the cryogenic users is adjusted from 5 K to 10 K, impacting overall system performance.

1. Introduction

The STEP program will demonstrate net power to the electrical grid (>~100 MWe) [1, 2], address maintainability of fusion powerplants, and provide a pathway to commercial viability of fusion. The delivery of the prototype powerplant will be in three phases: Phase 1 – develop concept design and select a site, Phase 2 – detailed engineering design and permissions and consents as well as pre-construction works by early 2030s, Phase 3 – manufacturing and construction – targeting operations around 2040. Currently STEP is transitioning to Phase 2. In line with STEP's engineering programme, which adopts a holistic approach encompassing all areas of development for the prototype power plant, the cryogenics group is structured into commercial/technical pillars and targeted actions aimed at advancing technological maturity and reducing risk (Figure 1). This approach ensures sustainable progress and a long-term increase in confidence levels. The current power budget for STEP power plant is presented in Figure 2. The power plant will be located in West Burton, Nottinghamshire, UK [3]. The Tokamak device will use high-temperature SC coils made from REBCO to confine plasma and maintain the magnetic field [4]. These SC magnets, which will be kept at around 20 K and cooled by supercritical helium, will require significant cryogenic cooling power. Other systems like the fuel cycle [5] and thermal shielding will also contribute to the estimated cooling power demand of ~90 kW, equivalent at 4.2 K [6].

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This places the STEP Cryogenic System among the largest in the world, comparable to ITER and CERN mega science

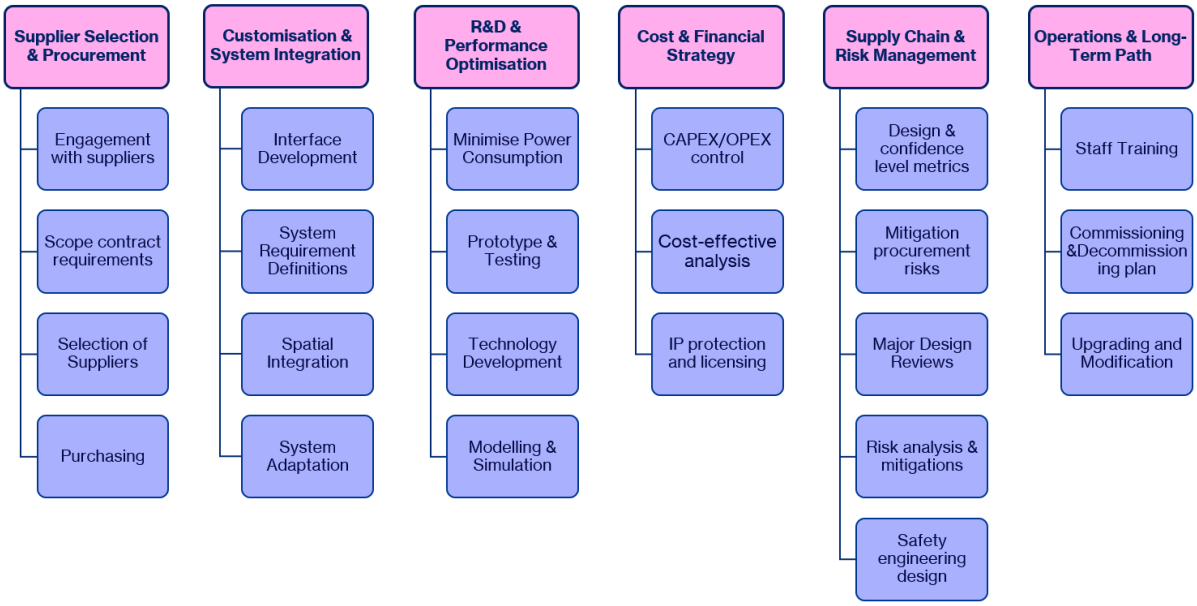

Figure 1. STEP Cryogenics pillars and actions to advance technological maturity and reduce risk.

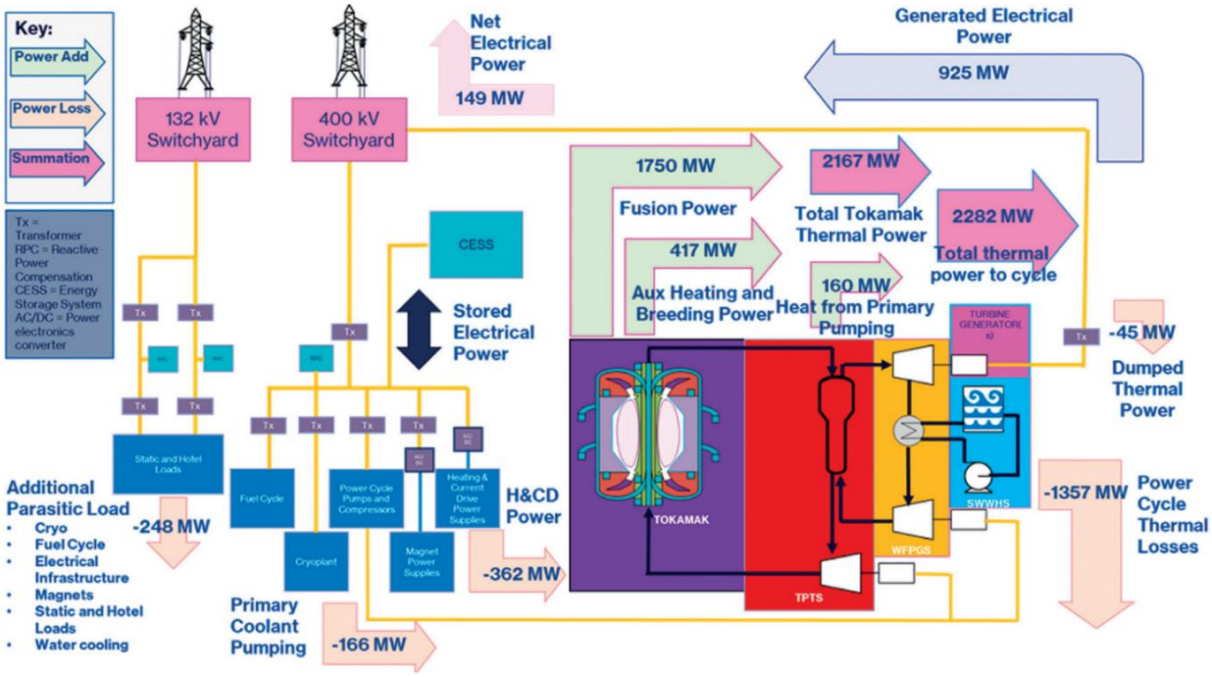

Figure 2. Current STEP power budget and electrical/cooling infrastructure [1].

projects. The STEP Cryogenic System is designed to provide cooling, thermal stability to the SC magnets, thermal shields, cryopumps, and fuel cycle equipment by managing and supplying the necessary cryogenic coolant to meet peak demands during various plasma stages. To make STEP

a commercially viable fusion power plant, a key challenge is achieving economic efficiency, which involves minimising parasitic electrical loads that reduce net power generation [7].

1.1 STEP Cryogenic System Requirements

Table 1 shows the estimated heat loads for the cryogenic plant. Currently, the STEP SC magnets, including the toroidal field (TF) and poloidal field (PF) coils, are intended to operate at an approximate temperature of 20 K. This same low-temperature environment is also applied to the central solenoid (CS) coil in order to minimise thermal stresses and limit both conductive and radiative heat loads on the SC components. To shield the SC magnets from ambient room temperature, thermal radiation barriers are cooled to around 80 K, serving as intermediate thermal intercepts.

Table 1. Estimated heat loads for the ~90 kW @ 4.2 K helium refrigeration plant. The heat load values are consolidated by temperature levels and users.

User @ T	Mass flow rate [kg/s]	Heat load @ T user [kW]
Thermal shields (~80 K users)	5	520
Magnets (~20 K users)	15	170
Fuel Cycle @ 5-10 K	2	30
Other users @ ~50 K	0.1	10

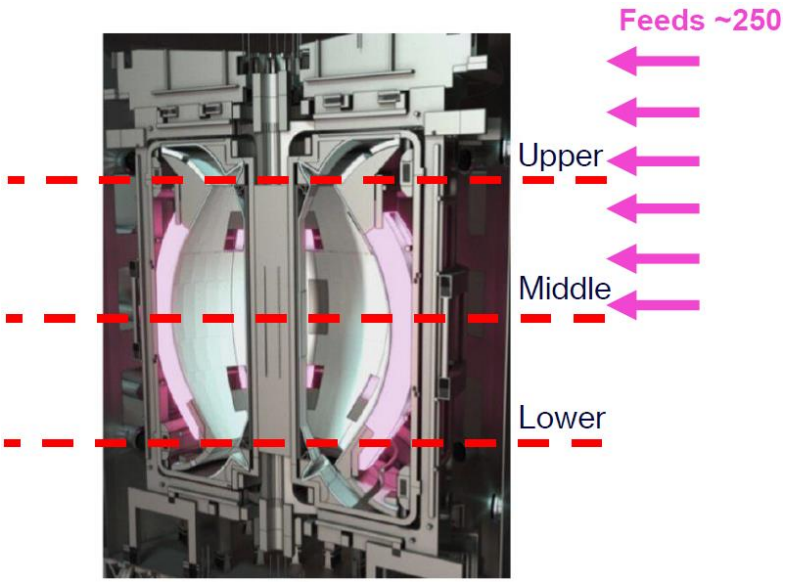

Figure 3. Main cryogenic feeds (250 approx.) location around STEP Tokamak machine. (The number of feeds may vary across Tokamak and cryogenic user design iterations).

Additionally, other systems that rely on cryogenics, such as cryopumps, current leads, fuel delivery systems, and cryogenic gas separation equipment, are also expected to function within a

temperature range of 15 K to 20 K. The cryogenic distribution system is conceptualised with three distinct levels. A lower, a middle and an upper level distributed along the vertical axis of the reactor is established to group the user feed locations for improved subsequent supply/return header definition. The levels are shown in Figure 3.

1.2 Cooling Challenges for STEP Cryodistribution System

1.2.1 Dynamic Heat Load During Operational Regimes

Figure 4 shows the variation in power consumption for the cryogenic plant. During operation, thermal loads fluctuate significantly due to plasma radiation impacting internal structures, current ramping through the magnets, cryopump regeneration, fuel recycling, and pellet injection processes and regeneration. Additionally, scenarios such as vacuum vessel baking impose high peak loads on the cryogenic plant. These unsteady cooling demands also present challenges for power consumption, which, according to recent estimates, can range from 37 MWe to 46 MWe (Figure 4). Ongoing efforts are focused on refining the cryogenic requirements, reducing uncertainties, and achieving an efficient and robust design. During a cooldown mode, the STEP cryogenic system supplies the cryogen needed to bring the Tokamak structures to operating temperatures at a controlled pace. The cooling strategy is designed to cool components individually, minimising thermal contractions and internal stresses at component boundaries to prevent structural and material damage. In this way, the cooled part can shrink freely without being held back. Once surrounding components reach a similar temperature, they connect fully and then contract together, which keeps relative movement small. The cryodistribution system contains buffers which absorb both small and large thermal transients during magnet ramping.

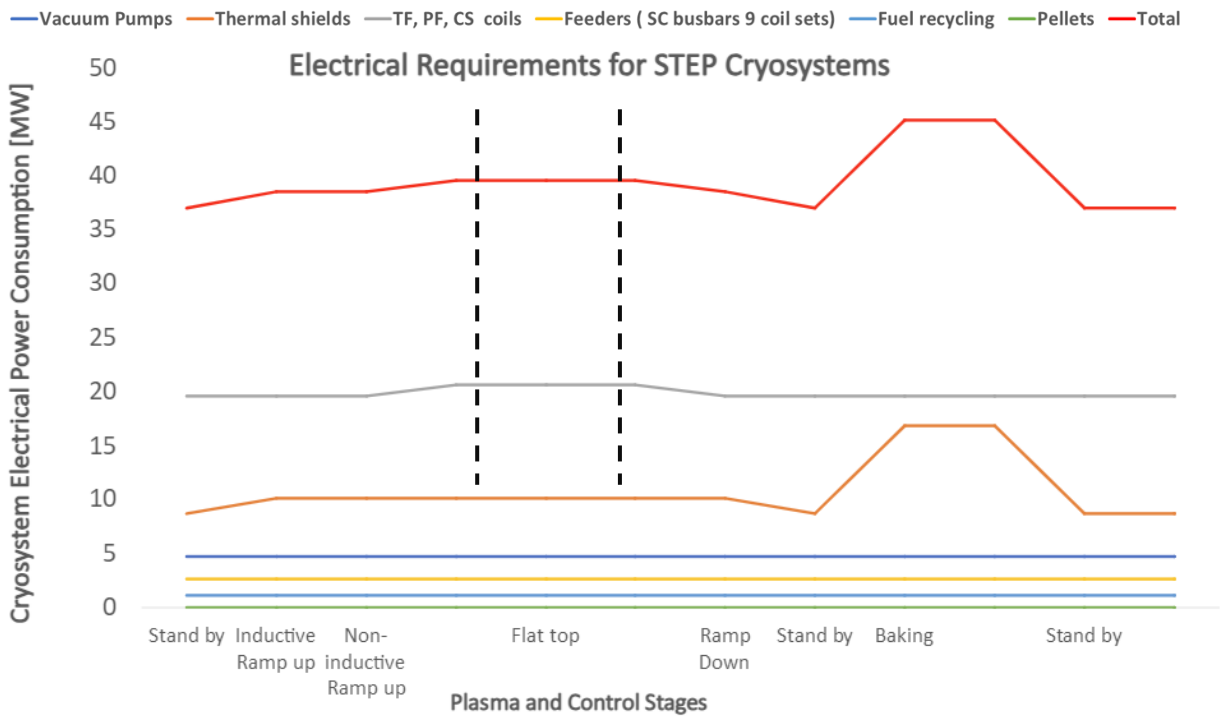

Figure 4. Power consumption to support maximum cooling rates of the cryogenic system during STEP Tokamak operation stages. This requirement may vary due to the use of cryogenic buffers that absorb peak heat loads. The precise timescales have yet to be defined.

The cryogenic buffer system (Figure 5) delivers cooling power from the distribution manifold to the user valve boxes. Moreover, the buffer system also acts as a reservoir, ensuring lung capacity in the event of a power outage or cryoplant failure. In such cases, plasma operation may be halted, but the cryogenic buffer keeps cooling the current leads, cryopumps and fuel cycle equipment. The buffer system also provides additional cooling to the CS magnet after the inductive plasma stage. In the event of a magnet quench, the cryogenic system is designed to safely release and recover the cryogen, protecting the integrity of the equipment and maintaining operational safety.

1.2.2 5-10 K Cryogenic Buffer Optioneering

Figure 5a illustrates a configuration in which a liquid helium (LHe) bath is used when the required temperature is near the LHe saturation point of 5 K. In this setup, temperature control is inherently limited, particularly when the required temperature varies between 5 K and 10 K, unless additional bypass streams are introduced. Moreover, heat transfer in this configuration relies on pool boiling at the surface of a submerged heat exchanger (HE), which is governed by the latent heat of helium. As a result, LHe consumption is directly tied to the heat load. This approach has the advantage of large nucleate boiling convection rates of 10,000-15,000 W/m^{2}K. The suitability of the submerged HE may be limited by tank volume constraints. An alternative configuration, shown in Figure 5b, employs an external HE that utilises the enthalpy of LHe in a controlled flow system. In this arrangement, a counterflow heat exchanger (CFHE) enables improved thermal performance and precise temperature regulation by adjusting the helium mass flow rate. This novel approach significantly mitigates the limitations of the bath-only design by decoupling temperature control from helium phase change. However, it introduces greater system complexity, including the need for flow control instrumentation and additional piping, which may increase design and operational challenges. To date, a buffer system of the type illustrated in Figure 5b has not been subjected to experimental validation.

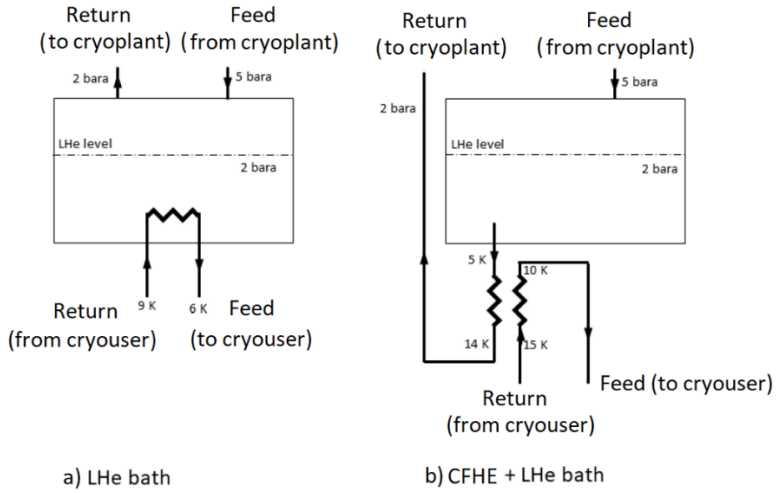

Figure 5. Diagrams for 10 K Cryogenic Buffer Optioneering. a) option with a LHe bath and submerged HE. b) option with a LHe bath and external CFHE. Pressure values are used only as a reference.

2. Conceptual Design of a Cryogenic Distribution System

Figure 6 shows the block diagram for the cryogenic distribution system. The scope of the study encompasses the key components of the Tokamak cryogenic distribution system. It includes the

main cryogenic multi transfer lines (MTLs) to various parts of the Tokamak complex. These serve as the primary conduits for helium flow from the cryogenic plant and form the backbone of the cryogenic infrastructure. These MTLs integrate multiple supply and return lines within a single vacuum jacket for spatial and economic efficiency. The interconnection box, located within the cryogenic plant building, interfaces the cryogenic plant with the main MTLs. Furthermore, the split box, located in the Tokamak complex, receives helium from the interconnection box and redistributes it to different floor levels via circuit separation boxes (CSBs). These are equipped with liquid buffer containers, temperature and flow regulation systems, and safety pressure relief devices. Finally, the cryogenic supply units (CSUs), distributed around the Tokamak, serve as the final link between the MTL ring and individual users. The CSUs regulate flow and control pressure to meet user-specific requirements, completing the cryogenic delivery architecture.

2.1 Technical Specifications and Manufacturing Challenges

The helium flows supplied by STEP cryogenic plant [6] are bundled in the interconnection box, a cylindrical vessel measuring several meters in diameter and height. This box serves as the interface between the cryoplant and the main MTLs that run between the cryoplant hall and the Tokamak complex. It houses isolation valves and safety relief valves for each process line, ensuring safe and flexible operation. The split box, which connects the interconnection box to the CSBs, consists of two cylindrical vessels. The main MTL extends several hundred meters in length. It incorporates process pipes housed within a single vacuum jacket, carrying helium flows at 5–10 K, 16–20 K, 50–80 K, and

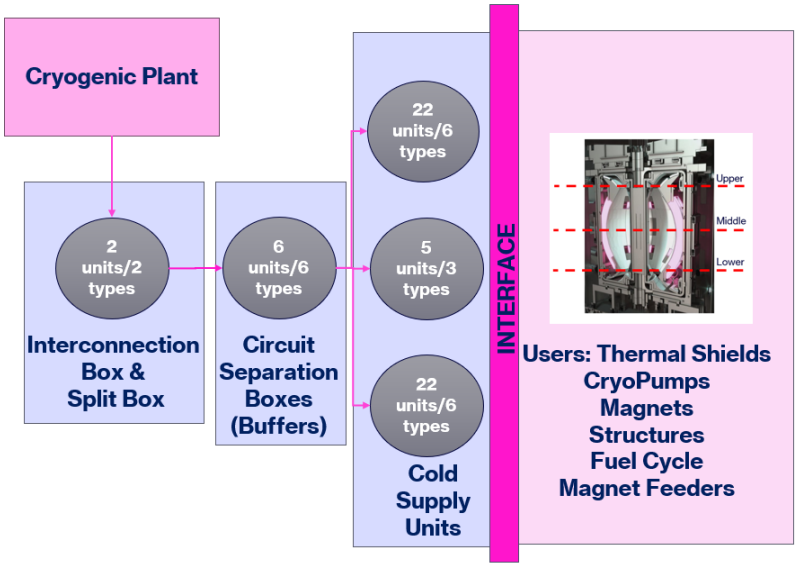

Figure 6. Block diagram of STEP cryogenic distribution system. This information could vary within design iterations of the Tokamak and systems.

100 K. Additionally, the MTL includes a thermal shield actively cooled by the 100 K return line. Overall, the system features more than 18 types of transfer lines, with wide outer diameters (up to 1 meter) and lengths reaching several hundred meters. In total, there are 49 CSUs distributed around the Tokamak, each measuring more than one meter in diameter and several meters height.

Manufacturing such an extensive and complex cryogenic distribution system will require several years and the coordinated effort of multiple manufacturing companies operating in parallel.

2.2 Simulation Study of 5–10 K Liquid Helium Buffer Options

A study of the LHe buffer options was conducted using two different modelling approaches. The objective was examine the impact on HE effectiveness of two different buffer concepts (Section 1.2.2) working under heat loads of interest for fusion. For the external HE configuration (Figure 7 (left)), simulations were performed using the design specification module of Aspen Plus v12.1. The thermodynamic and transport properties of helium were obtained using REFPROP. In contrast, the submerged HE option (Figure 7 (right)) was studied using a numerical model based on nucleate boiling equations, combined with a heat transfer model for a helical coil tube HE with fins. The physical properties of helium were obtained from the CoolProp, which is an open source thermophysical property package. Figure 7 (left) shows the results for a case study with a heat load of 1kW delivered to the external HE which is feed with 4.2 K LHe supplied by the buffer tank. The flowrate for the user helium line was set at 24 g/s. The results show the variation of 95% to 55% of the HE effectiveness when the set point for the feed temperature to the cryogenic user is changed from 5 K to 10 K. Control is achieved by regulating the buffer flow rate. Lower set-point temperatures require higher flow rates, which improves effectiveness. The best performance is achieved when the set point temperature is near the saturation temperature of the LHe buffer (4.2 K @ 1 bar). This indicates that an optimal performance is obtained with lower temperature difference between the temperature required from the user, and the liquid bath. Figure 7 (right) shows the results for the LHe buffer with submerged HE option. The flowrate through the helical HE pipe was set at 24 g/s, and the heat load from the user was varied from 0.6 kW to 1.2 kW. The results show a maximum HE effectiveness of 70%, for 0.6 kW and HE outlet temperature of 7.2 K. The performance drops progressively from 70% down to 54% while the heat load increases 1.2 kW. Since the mass flow is constant, the heat load increases the inlet temperature of the flow from 14 K to 17 K, and the outlet temperature towards the user rises from 7.2 K to 10.3 K. Similarly to the case study in Figure 7 (left), the effectiveness is influenced by the temperature difference between liquid bath vs. outlet flow temperature (working temperature or set point).

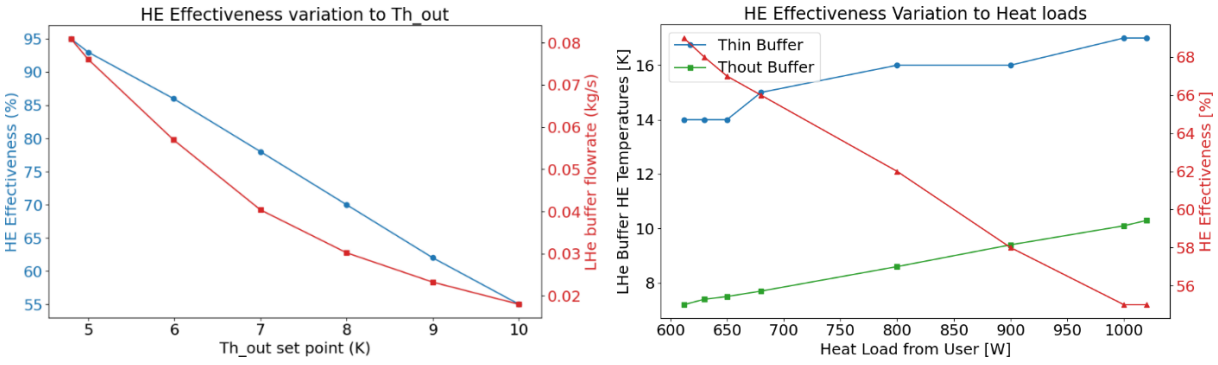

Figure 7. Impact on HE effectiveness of two different HE concepts. (left) Performance of the external HE LHe buffer configuration. The buffer is held at 4.2 K (at 1 bar), a constant heat load of 1 kW was set, and an inlet temperature to the LHe buffer is 17 K. The evaporation rate result is constant at 50 g/s. (right) Performance of the HE submerged in a LHe bath. The LHe buffer is held at 4.2 K, and the heat load from the user varied from 0.6 kW to 1.2 kW.

3. Conclusions

In this paper, we present the results of a conceptual design study for the STEP cryogenic distribution system. The system connects the cryogenic plant to the end-users within the Tokamak complex and comprises multiple transfer lines carrying helium at various temperatures, along with key components such as the interconnection box, split box, CSBs, and CSUs. Although this represents a preliminary design phase, several important conclusions and challenges can be drawn:

- A possible configuration and dimensional specification for the CSBs has been developed. A total of 49 CSBs were predesigned, measuring several meters in both diameter and height. The manufacturing and delivery of this system will involve a long lead time and will require the involvement of multiple cryogenics companies, along with significant engineering effort
- The CSBs of STEP cryogenic distribution system will have a large volume requirement of about 550 m^3. This information will contribute to predesign of the Tokamak building
- The transfer lines will span several hundred meters and accommodate multiple working temperatures within a shared vacuum jacket. The manufacturing of these lines is feasible and comparable in scale to those used in other large-scale scientific infrastructure projects
- The simulation study for the optioneering of LHe buffers working from 5-10 K show that the effectiveness of the HE drops from 95% to 55% when the temperature difference between liquid bath and set point temperature increases from 5 K to 10 K
- The external HE has an advantage to being able to fix the feed temperature of the cooling loop. However, this will require a method to drive the LHe flow, additional pipe work, and automatic control
- The cryogenic plant's power consumption ranges from 37 MWe to 46 MWe, primarily due to heat loads on the thermal shields during vacuum vessel baking. Additionally, the magnets are exposed to neutronic radiation during plasma breakdown and flat-top phases. These thermal transients can be mitigated using CSBs, which help stabilise the cryogenic plant’s power consumption. However, this approach increases the size and complexity of the cryogenic distribution system

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