Conceptual Design and Industrial Challenges of a Cryogenic Plant for STEP Prototype Fusion Power Plant

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Abstract. The UK Government's Fusion Strategy has led to STEP (Spherical Tokamak for Energy Production) project. The programme will build a prototype fusion energy plant at West Burton in Nottinghamshire, targeting operations in the 2040s. This prototypic fusion power plant will also house a novel cryoplant to supply cooling power for its large refrigeration loads at various cryogenic temperatures, around 80 K, 50 K and 15 K. The refrigeration load is likely to be equivalent to around 100 kW at 4.5 K. In this work, we present an early cryoplant concept design developed in collaboration with CHART Industries, USA, and highlight some challenges facing the future cryogenics industry in the context of fusion energy.

Keywords: STEP, Cryogenics, Refrigeration, Fusion Energy, Tokamak Energy

1. Introduction

Fusion is one of the most promising options for producing clean energy. Recent milestones in fusion include the Joint European Torus (JET) located in Culham, UK, achieving a world record by generating 69 MJ of fusion energy over five seconds, using 2 mg of deuterium and tritium. This is enough to power 12,000 households for about the same period. Delivering fusion energy to the grid is a challenge of both physics and engineering, but achieving this commercially will also require significant industrial capability. The UKAEA (UK Atomic Energy Authority) aims to develop the STEP prototype fusion power plant demonstrating net power to the grid. Furthermore, STEP will demonstrate a path to commercial viability of fusion. Fig. 1 presents the road map towards STEP cryoplant

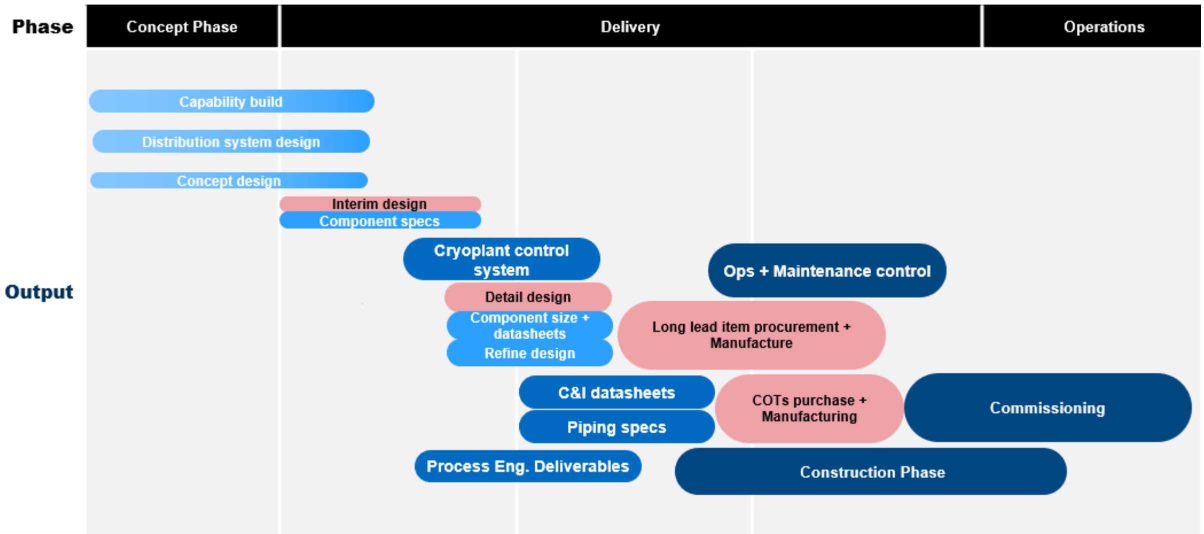

Figure 1:" Roadmap to STEP's cryoplant development".

development. The concept design stage is followed by an extended period of detailed design and procurement. Construction is scheduled to begin after the design phases are completed, followed by the plant's commissioning and operation. In this work we present the concept design for the cryogenic plant.

1.1 STEP Cryogenic Requirements

Cryogenics play a crucial role in tokamak fusion reactors in three primary areas. It cools the superconducting (SC) magnets necessary for plasma confinement, ensures the plasma vessel maintains the required vacuum level via cryogenic vacuum technology, and supports the fusion energy cycle by enabling matter injection and cryogenic separation of hydrogen isotopologues. At present, STEP's SC magnets (toroidal field (TF) and poloidal field (PF) coils) are designed to be maintained at 20 K approximately, with the central solenoid (CS) coils also kept at the same temperature to reduce thermal stresses, conduction and radiation heat loads onto the SC magnets (See Fig. 2). Two thermal radiation shields are maintained at 80 K to act as intercepts between the superconducting (SC) magnets and room temperature conditions. Other cryo-users such as cryogenic vacuum pumps, current leads, fuel injection and cryogenic separation units are assumed to operate at a 15-20 K temperature level.

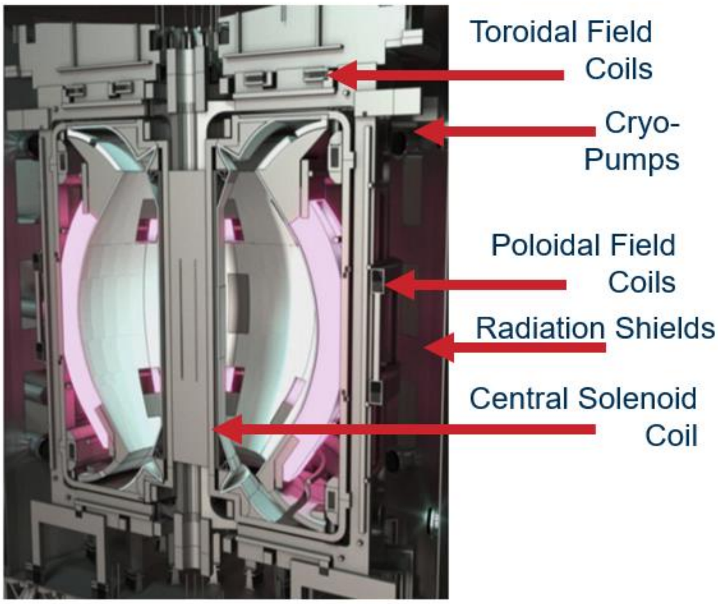

Figure 2: "Main users for cryogenics within STEP fusion reactor".

1.2 Industrial Challenges for STEP and Commercial Fusion Development

1.2.1 Large-Scale Efficient Cryogenic System

Ultimately, the economic impact of cryogenic systems is particularly significant in the early stages of commercial fusion, where energy gain, net power, and profit are limited by materials, techniques, and current production scales.

The estimated refrigeration capacity of the STEP prototype power plant cryogenic system matches that of LHC, presenting challenges for procurement, construction, supply chain, and manufacturing capabilities of providers. The requirements of the cryogenic systems are complex, involving intricate layouts, multiple cold boxes with connection points, and various cryogenic users with specific pressure and temperature requirements, as well as both transient and stationary operating states. The efficiency (relative to Carnot efficiency) is expected to be higher due to the increased size of the cryogenic plant. This is particularly important as the commercial viability of fusion is directly impacted by the energetic efficiency and cost of technologies. Efficiency improvements are primarily driven by helium compressors, which are the main consumers of electricity. These machines typically exhibit a relatively poor efficiency of 54% to 65%. The very high mass flow rates (10-20 kg/s or 216,000-433,000 Nm^3/hr) needed to cool large-scale fusion power plants, such as STEP, exceed the capacity of compressors available on the market, which are specified for up to 75,000 Nm^3/hr (unspecified for helium). Consequently, multiple compressors must be installed in parallel configurations to provide the necessary helium flow rate, significantly reducing the overall energy efficiency of the plant. Fusion power plant such as STEP will require top-tier cryogenic components, such as high-efficiency turboexpanders and heat exchangers (HE) designed with tight temperature approach specifications.

1.2.2 Helium Availability Outlook

Helium is a limited resource, and it is likely that in the long term (beyond 2100), supply constraints and geopolitical conflicts could result in a helium-scarce market [1]. Scaling up from research-oriented reactors such as W7-X, KSTAR, and JT60SA, which use less than 2.7 tons of helium [2], to power producing fusion power plants increases the demand for the coolant sharply. For example, early estimates for STEP's helium inventory range between 20 to 60 tons, with the upper limit being twice that of ITER [2]. Similarly, the DEMO tokamak has an estimated inventory of 72 tons. However, these estimated values are still a fraction of CERN's helium inventory, which is 150 tons, with the 8 sectors (3.3 km each) of the LHC holding 120 tons of helium [3]. In STEP's design, the transfer lines have an approximate extension of 7 km. This analysis demonstrates that the requirement from STEP and other first-of-a-kind (FOAK) fusion power plants will be a small fraction of the worlds production.

1.2.3 Scaled-Up Helium Cold Circulators

Cold circulators or cryo-fans [4] are crucial for maintaining the mass flow and working pressure of cryogenic fluids. They are essential for overcoming pressure drops and managing the dynamic heat loads on the cooling circuits within the tokamak. While fusion energy projects increase in size, the manufacturing and design of these components must meet the growing requirements [4]. Table 1 shows the pumping requirements for several fusion and cryogenics projects. Recent fusion projects, such as STEP and SPARC [5], are expected to require mass flow rates ten times higher than their predecessors. This is primarily due to the operation of novel tokamaks, which must evacuate large amounts of heat during the plasma pulse phase (MW in tens of seconds) [5]. Additionally, the pressure drops for STEP and SPARC are estimated to be higher than those in previous projects, owing to the complex geometric

Table 1. Reported specifications for cold circulators used in cryogenics and fusion projects [4].

Project	Year	Pressure [bar]	Temperature [K]	Mass flow rate [kg/s]	Pressure head [bar]
STEP (present work)	2024	3-6	15-50	10-20	1-5
SPARC	2021	9-30	12-20	10.5-190	1-2
ITER	2017	4.6	4.55	2.21	1.55
JT 60SA	2014	4.35	4.4	0.96	3.5

configurations of their large SC magnets and the extended cryogenic pipelines which will handle high mass flow rates.

2. Conceptual Design of a Helium-4 Cryogenic Plant

The conceptual design was performed through Aspen Plus simulations using REFPROP physical properties and SQP (sequential quadratic programming) optimisation. The cryogenic process consists of a reverse Brayton cycle with two turboexpanders and a recycle compressor within the helium plant. The cryogen is gaseous helium in temperature and pressure ranges of approximately 13 – 298 K and 2 – 23 bar respectively. Helium is work-expanded and split into multiple streams, providing refrigeration at three required temperature levels: 80 K, 50 K, and 15 K. Heat exchange occurs within multiple brazed aluminium HEs housed inside vacuum cold boxes.

2.1 Process Description

Referring to Fig. 3, the refrigeration cycle is pre-cooled to approximately 80 K by a standard LN2 plant. Within the helium plant, gaseous helium is compressed in a recycle compressor (REC), cooled, and work-expanded in turboexpanders T1 and T2 at different temperature levels to generate refrigeration (known as the reverse-Brayton cycle). Helium from the cold expander T2 provides cooling at 15 K. Gaseous helium refrigerant exchanges heat with helium from a secondary circuit in a brazed aluminium HE. The secondary circuit provides cooling to HE1. The secondary circuit uses a cold circulator (CC) to provide the necessary working pressure. A portion of helium from the warm expander T1 provides cooling at 50 K for HE2 in a similar manner. The low-pressure helium from the helium plant provides cooling at 80 K for HE3. The refrigerant return streams are combined in the helium plant and then enter the recycle compressor, completing the closed-loop refrigeration cycle.

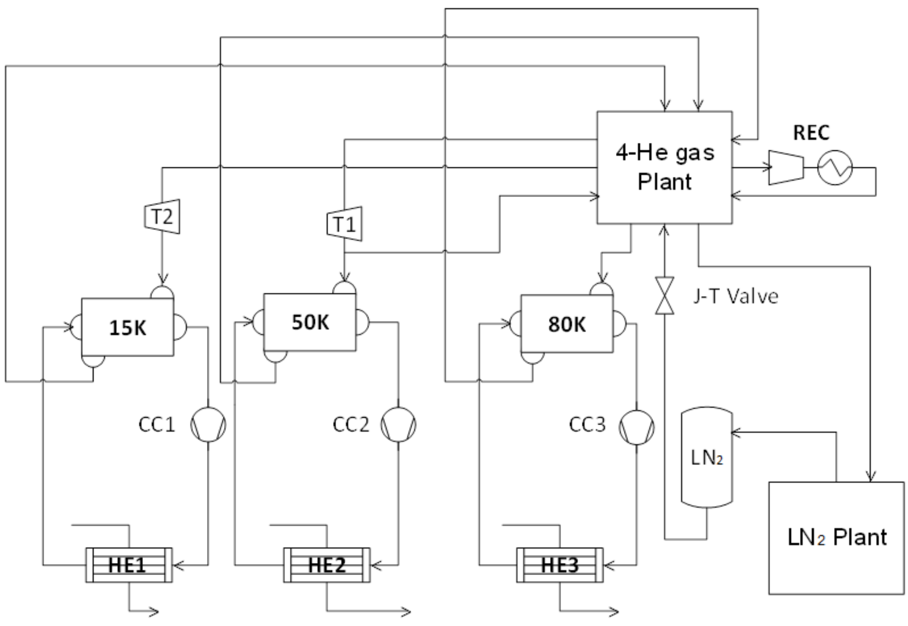

Figure 3: "Cryogenic plant for STEP".

2.2 Cryogenics Users

Table 2 shows the main variables for the HEs that supply cold to STEP cryo-users. The HE1 unit provides cooling at 15 K with a cooling duty of 214 kW and has the largest mass flow rate at 13.3 kg/s. HE1 also exhibits the lowest effectiveness due to differences in helium heat capacities.

Table 2. Cryogenic loads of the helium refrigeration plant.

Equipment @ T	Hot side- mass flow rate [kg/s]	Heat Flux [kW]	Effectiveness [%]
HE1 @ 15 K	13.3	214	60%
HE2 @ 50 K	0.21	277	98%
HE3 @ 80 K	2	209	90%

2.3 Plants Block Diagram

Fig. 4 shows the block flow diagram for the STEP cryo systems. At a conceptual design stage, the identified subsystems are the helium cryoplant with its liquid nitrogen liquefier precooler. The main heat exchangers and cooling loops distribute the cold through the Valve Boxes towards the cryo-users sub systems.

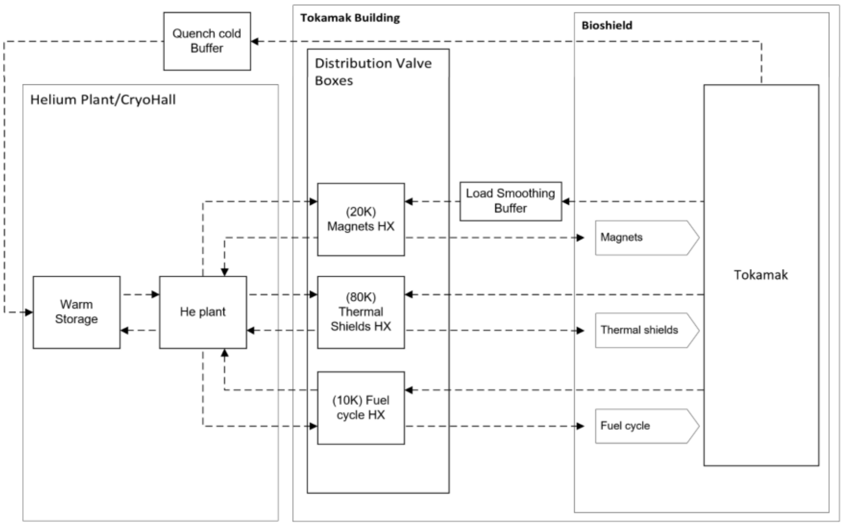

Figure 4:" Block diagram for STEP cryogenic system".

2.4 Key Performance Indicators

Table 3 shows the results for the conceptual design of the cryogenic plant for STEP. The inversed of the Coefficient of Performance (COPinv), defined as the ratio of power input to cooling power, and Figure of Merit (FOM) indicate an efficient design and within values expected for industrial high-temperature SC applications. The specific work of compression is 1.37 kWh/kg, which is a value eight-fold smaller than hydrogen liquefaction systems that also achieve around 20 K. The total compressor power is 53 MW, and the efficiency of compression is 46%. Here there is room for improvement in terms of helium compression technology since multiple compressors in parallel (6 in total) drops the energy efficiency

Table 3. Performance indicators for the helium cryogenic plant.

Indicator	Value [unit]
COPinv	76
FOM (vs. Carnot @ 20K)	1.37 kWh/kg
Spec. W. Compression	2
Compressor Power	53 MW
Compressor Efficiency	46%

3. Conclusions

In this paper we report the results of conceptual design of the helium cryogenic plant for STEP fusion project. The refrigeration system provides cooling power at three temperatures: 15 K, 50 K, and 80 K for SC magnets, thermal shielding, and other subsystems of the fusion plant. The conclusions of this work are as follows:

- The proposed helium refrigerator achieved 29% of Carnot efficiency, and a COP_{inv} of 76 which is competitive compared to other systems providing similar temperatures.
- The designed cryogenic system exhibits HE efficiencies between 60% to 98%. Further improvement can be done in the low temperature HE.

Some technological challenges for cryogenic technologies were also analysed. The findings are the following:

- There is a requirement for high-efficiency and large-scale helium compressors which must be led by cryogenic industry and fusion energy ventures.
- Helium circulators need to be scaled-up to manage the large requirements for fusion energy applications.
- Due to the uncertainty of helium availability, efforts must be made to explore alternatives using other types of refrigerants or to develop new technologies for helium acquisition.

4. References

[1] S. Mohr & J. Ward, Helium Production and Possible Projection, Minerals (2014) 4, 130-144.
[2] H. Vaghela, V. J. Lakhera, B. Sarkar (2021). Forced flow cryogenic cooling in fusion devices: A review. Heliyon, 7(1).
[3] M. Puarali (2017). Helium inventory management for LHC cryogenics (No. CERN-STUDENTS-Note-2017-119).
[4] J. Das, V. J. Lakhera, B. Sarkar (2021). Supercritical helium cold circulators for nuclear fusion machines: A comparative overview of different hydrodynamic design approaches. Fusion Engineering and Design, 169, 112537.
[5] B. Hamilton (2021). Analysis of Cryogenic Cooling of Toroidal Field Magnets for Nuclear Fusion Reactors (Doctoral dissertation, Massachusetts Institute of Technology).
[6] S. Entler, J. Horacek, T. Dlouhy, V. Dostal. (2018). Approximation of the economy of fusion energy. Energy, 152, 489-497.

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