Developing a technology roadmap for STEP's sCO2 Technology

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ABSTRACT

Fusion energy has the potential to revolutionise the energy landscape providing safe and clean power for generations to come. The Spherical Tokamak for Energy Production (STEP) is a multi decade project, led by the UK Industrial Fusion Solutions, seeking to establish fusion by developing a prototype powerplant, which in turn will produce 100MWe net power to the grid [1].

STEP has selected a unique and novel transcritical CO_2 cycle, a variant of the recompressed Brayton cycle [2] as its preferred power cycle. This power cycle will convert thermal energy stemming from the tokamak machine, into electrical power. STEP has selected this cycle on the merits of the overall efficiency, dynamic response, ability to integrate multiple grades of heat, and benefits of scale. STEP will also seek to use supercritical CO_2 for some of the in-vessel component cooling.

This is a careful trade that has been made weighing the benefits of sCO2 vs the added risks of using such a novel technology in what is already a highly ambitious programme. It is for these reasons a technology development programme has been developed. In this paper the novel STEP Hybrid Operations sCO2 Cycle (SHOCC) cycle shall be presented, highlighting key aspects which help address the unique requirements of a tokamak based powerplant. The proposed sCO_2 primary loop will also be discussed. Building on this, the key technological risks of the proposed sCO_2 solutions will be discussed. Finally, a technology development programme will be presented which highlights an overarching roadmap seeking to address

these risks and scale up the technology for the STEP application. As part of this rigs and test facilities at different scales will be discussed – including a proof-of-concept test rig which is intended to be described in detail within a separate paper also presented at this conference.

Introduction

Fusion offers a generational promise to simultaneously address clean energy and energy security global challenges. The UKIFS STEP project seeks to develop a first of a kind prototype energy powerplant, targeting operations in the 2040s. This novel powerplant, will have unique challenges in generating power, due to the unique aspects of its power source: the Spherical Tokamak. The power & cooling systems will seek how to extract thermal energy from the tokamak, generate electrical power from this energy, and manage this power across the site – ultimately ensuring STEP's primary objective: to generate 100 MWe net power to the national grid.

Notably, in the power & cooling system design, efficiencies and dynamic performance must be simultaneously addressed – among other challenges. This paper will introduce fusion and the STEP project, as well as the Power & Cooling system more broadly. Following this, the paper will summarise how supercritical CO2 technologies (including the novel sCO2 power cycle: SHOCC) can be used within the power & cooling systems to address these challenges across the powerplant. In turn, the technological gap to implement these sCO2 solutions will be discussed, before finally presenting a technology roadmap addressing how the STEP project plans to address these gaps for fusion powerplant relevance.

Fusion and the Spherical Tokamak for Energy Production (STEP)

Fusion, often hailed as the holy grail of energy, is regarded as a highly promising sustainable energy source, seeking to play a pivotal role in the global energy transition. Fusion offers clear advantages vs incumbent technology as it is:

- Clean – fusion is an emissions free reaction and fusion power generation is low carbon
- Sustainable – fusion is the most power dense process known, and Fusion fuel is potentially abundant in our seas and the Earth's crust
- Reliable - fusion energy will be baseload and does not depend on seasonal variation, the sun, or the wind
- Inherently safe – the fusion process is readily and safely controllable

The Spherical Tokamak for Energy Production project is a UK government led multi decadal programme seeking to build the first prototype fusion powerplant that will deliver net power to the grid. Through this prototype STEP will build a pathway to commercial fusion. The UK Industrial Fusion Solutions (UKIFS), a subsidiary of the UK Atomic Energy Authority, is targeting 2040s for STEP operations. UKIFS will deliver STEP at the selected West Burton site, together with industrial partners, developing socio-economic value for the UK.

STEP, will use a Spherical Tokamak, rather than a Conventional Tokamak. The Spherical Tokamak offer tangible benefits, notably:

- A more compact fusion device – which will improve the viability of future commercial plants
- The ability to run continuously. A conventional tokamak is based on an inductive plasma, which requires a central solenoid to keep driving the current of the plasma. This solenoid must be recharged on a regular basis, in turn this requires a pulsed mode of operations which adds complexity to the connected systems. Conversely, Spherical Tokamaks, operate with a non-inductive plasma due to a higher bootstrap current fraction [3] – hence do not require a central solenoid for steady state (so called “flat top”) operations, and can run continuously.

Despite the ability to run continuously, it is still expected that early operations of the STEP prototype powerplant will resemble pulsed operations through commissioning and early operational learning phases. This will ensure key learnings and testing before longer scale pulses are attempted, ultimately demonstrating powerplant readiness and commercial viability.

STEP Power & Cooling

STEP’s objective, among others, is to ensure 100 MWe or more net power export to the UK national grid. The Power & Cooling systems will enable this by providing the following functions

Cooling the tokamak: cooling the tokamak while also extracting useful thermal energy. This is achieved, primarily, within the Thermal Power Transfer Sub System (TPTS) – colloquially known as the primary loop(s).

Generating power: conversion of thermal energy to electrical energy (power generation). This is achieved within the Working Fluid Power Generation Sub System (WFPGS) - colloquially known as the power cycle. The power cycle receives heat from the primary loops, as the powerplant architecture is that of an indirect power cycle.

Managing energy: management of the site-wide distribution, storage and energy export – this will be managed by the Electrical Infrastructure system.

Power & Cooling need for efficiency

As with many other magnetically confined devices [4], there will be significant recirculating power to meet the load of the notoriously high recirculating power – as illustrated in the following figure:

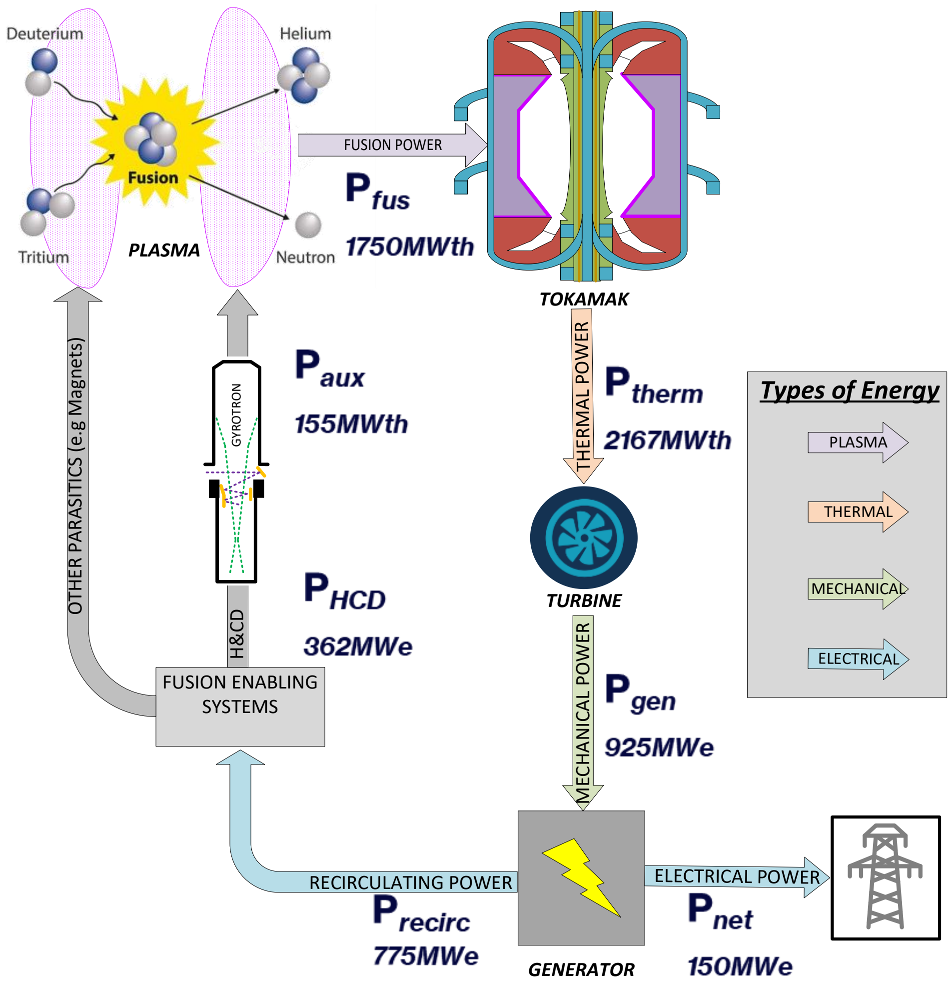

Figure 1: STEP Prototype Powerplant Power Balance [1] [10]

Figure 1 indicates how significant power is recirculated within the powerplant. This is *largely* to meet unique fusion loads such as the heating and current drive system shown in the diagram as 362MWe. Another major load is the coolant pumping power, this is because significant pressure losses occur over the plasma facing components due to large heat fluxes. Other important loads are the cryoplant, fuel cycle, magnets [1].

As such STEP needs supporting power & cooling systems which will enable high efficiencies throughout to maximise confidence in generating 100 MWe power or higher, to the grid.

Power & Cooling need for dynamic performance

Simultaneously STEP must ensure such power & cooling systems are able to match the operations of the tokamak and plasma – notably the power & cooling systems must enable the very rapid operations of the plasma.

During the plasma ramp up two key aspects must be considered:

- Significant electrical power is required before any thermal power is generated from fusion reactions (P_{fus} in Figure 1), to ramp the plasma current in the first place. This means another power source is required (which is likely to be the national grid).
- The ramp of fusion power (P_{Fus}) is very rapid, over minutes timescale [5].

From these two aspects one can logically conclude that a power cycle which would enable a rapid implementation of the thermal power from the tokamak, would be significantly more viable. That is to say a power cycle which can be rapidly ramped is significantly beneficial as it avoids additional infrastructure required to manage the sudden heat rise from the tokamak. Such a power cycle would also be able to generate power faster and displace the grid dependency sooner.

Tokamak Interface

Heat is generated primarily through the fusion reaction within the tokamak. Heat from fusion is deposited via neutrons and radiatively into the major in-vessel components. Heat is removed by cooling these components individually, each component has a unique cooling requirement, therefore multiple cooling loops at different conditions are needed. The heat extracted from each of the primary loops (within the TPTS) must, in turn, be integrated into the WFPGS (i.e. the power cycle).

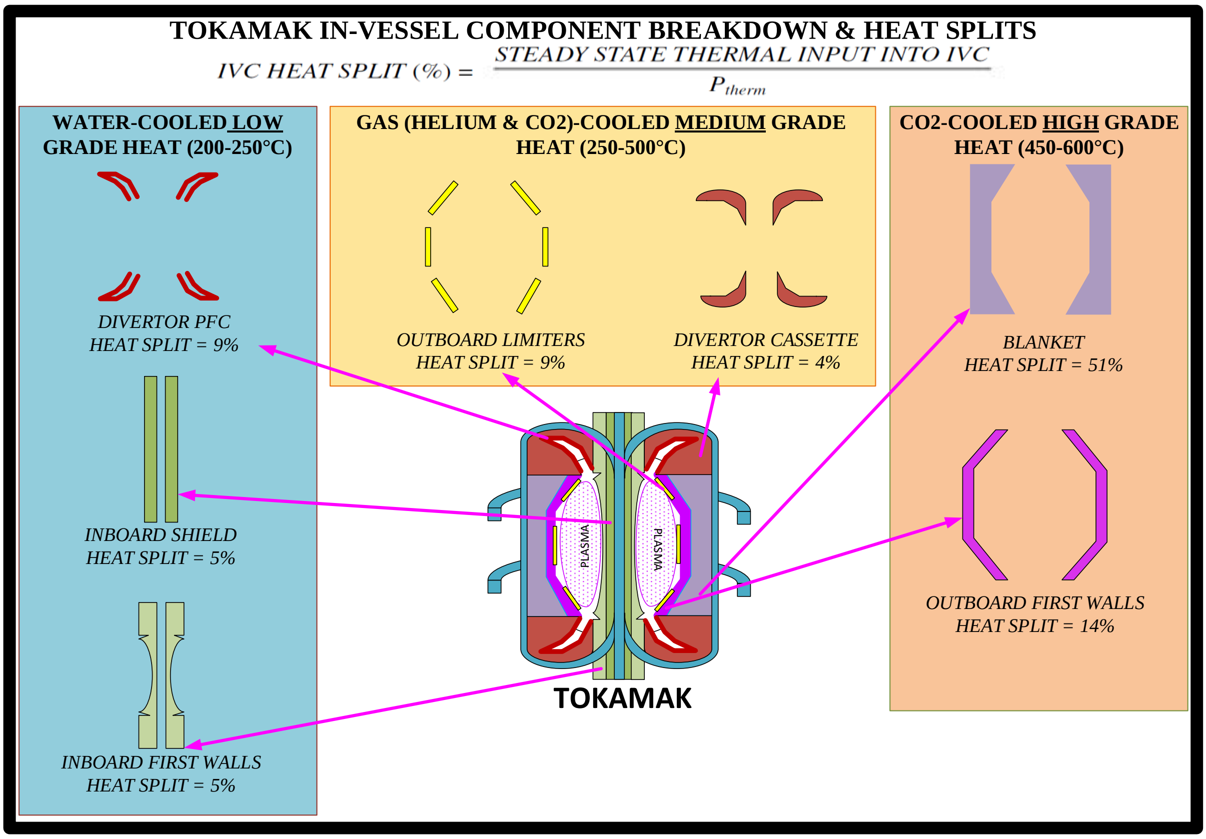

Figure 2: Tokamak In-Vessel Component Breakdown [1]

The inboard first wall and shield must provide a moderating effect to protect the centre column of the tokamak from neutronic damage, these are therefore water cooled.

The divertors see intense heat fluxes up to 10 MW/m^2 [6], hence the primary Plasma Facing Component (PFC) is water cooled; however the "cassette" component behind the divertor may be gas cooled to extract a higher grade of heat.

The Blanket and Outboard First Wall (OFW) must be somewhat neutron transparent to enable breeding and are therefore CO2 cooled, this is further discussed in this paper. The Blanket and OFW will be in series within a single coolant loop.

These coolants are broadly split into three categories according to the temperatures:

- ***High grade heat:*** 450-600°C
- ***Medium grad heat:*** 250-500°C
- ***Low grade heat:*** 200-250°C

The WFPGS (power cycle) architecture must consider how to integrate these various grades of heat, maximising both efficiency and dynamic performance.

Power and Cooling system breakdown and technology selection

The power & cooling systems have been carefully developed. The power & cooling systems are broken down into two major sub systems:

- The Power Cycle and Cooling system: which encompasses the Thermal Power Transfer System (TPTS) responsible for cooling the tokamak, and the Working Fluid and Power Generations System (WFPGS)
- The Electrical Infrastructure System that will manage all electrical power on site

The following diagram shows the breakdown of these two major systems and their connection to the tokamak:

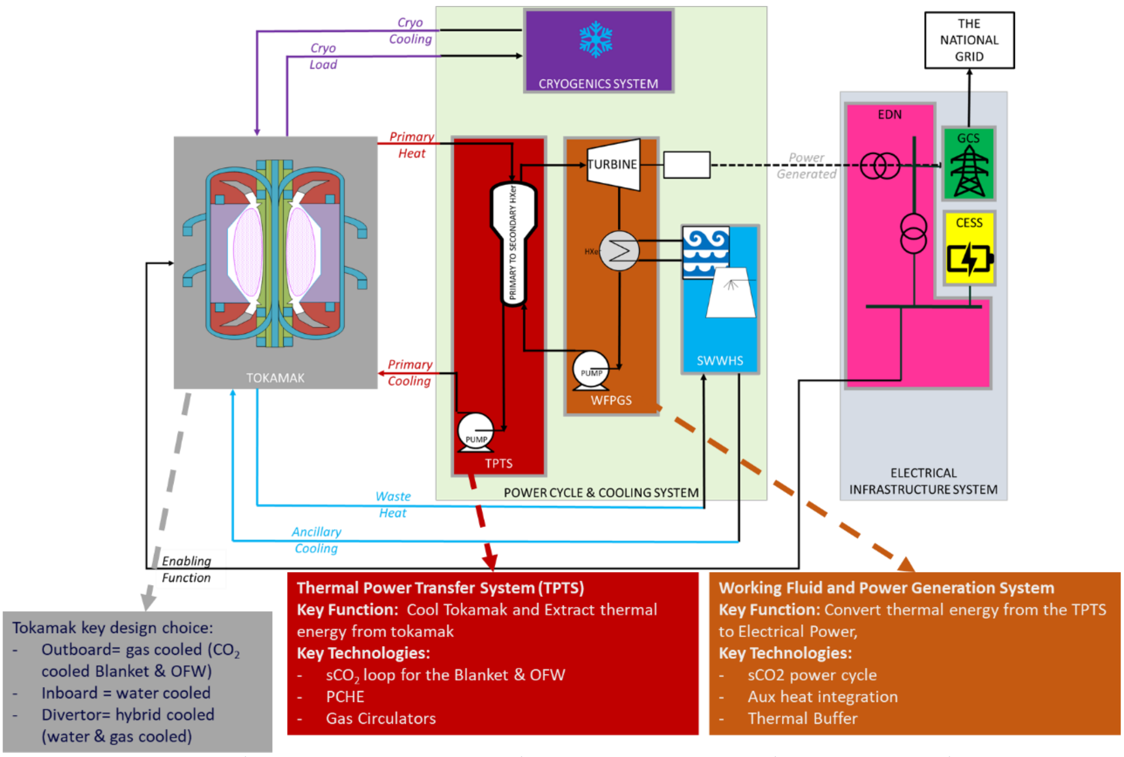

Figure 3: STEP Power & Cooling System breakdown with key technologies

Figure 3 also illustrates the key technologies required for the systems of interest within this paper. Notably the TPTS (primary loops) and WFPGS (power cycle) where sCO2 technology is preferred. The next section will discuss why.

sCO2 at the heart of the STEP Prototype Powerplant – why CO2 in primary and secondary loops

tCO2 power cycle: SHOCC

An sCO2 power cycle, is preferred for the STEP powerplant due to its efficiency and dynamic capability. Another considerations of note is the ability to integrate multiple grades of heat from the tokamak. The SHOC cycle has been developed as a variant of the recompressed Brayton cycle which is illustrated in the following diagram:

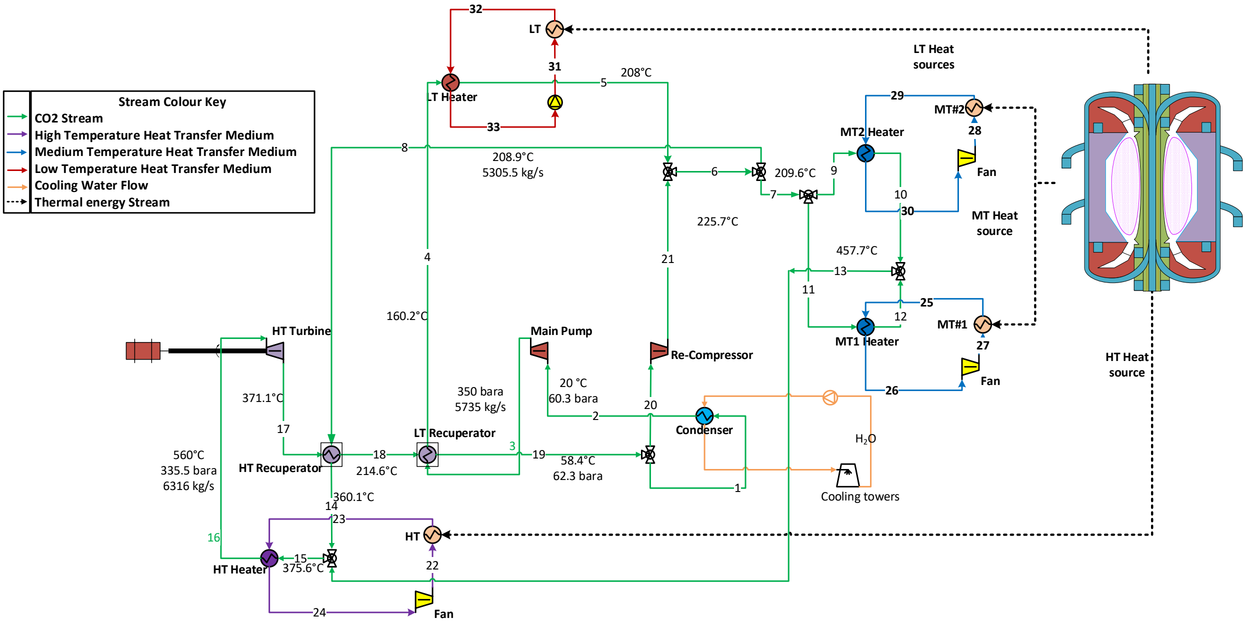

Figure 4: STEP Transcritical sCO2 power cycle (no blends): SHOCC [2]

Figure 4 shows in detail how the different grades of heat (High, Medium and Low identified in Figure 2) from the tokamak are integrated into the SHOC cycle, through the different TPTS primary cooling loops

As shown in Figure 4, the cycle is actually a transcritical cycle, this aspect was evaluated together with the potential for dopants [2]. Other cycles have also been evaluated [7] [8] .

As per Figure 3 (but not shown in Figure 4), there is a desire to integrate a Fusion Independent Heat Source (FIHS or Auxiliary Heat). This FIHS forms an integral element to the SHOC cycle, and this is why it is a “Hybrid Operations” CO2 cycle, as it is a cycle that can use both auxiliary heat (from the FIHS) and fusion heat. This FIHS will be needed to support the highly dynamic and pulsed operations ensuring the ability to pre-heat and manage power cycle operations (even at low loading) when the tokamak is not producing heat. In this manner the SHOC power cycle, can always use auxiliary heat and be ready to receive fusion heat – this has distinct operational advantages, especially when the fusion heat is prototypic in nature and inherently unreliable in its early stage of operations. This ability to switch between a “Fusion mode of operations” and an “Auxiliary heating mode of operations” is a key aspect of the SHOC cycle which will need dynamic development and demonstration.

The FIHS is currently undefined, but could be based on: thermal storage, electrical heaters, or various fuels.

Further details on the SHOCC design can also be found in the *Proof-of-Concept Demonstration of a Closed-Loop CO_2 Power Cycle for Spherical Tokamak Fusion Power Plant* paper of the 2026 sCO2 symposium.

<u>Why use a tCO2 power cycle</u>

At the chosen maximum temperatures, limited benefit can be gained in terms of efficiency vs incumbent technology (notably a steam Rankine cycle [1]). Temperatures of the in-vessel components, which are the heat sources of the tokamak, are shown in Figure 2. These temperatures are highly limited by the materials chosen inside the tokamak and features of the plasma within the tokamak, which incur significantly high heat fluxes [6]. Materials are in turn also limited by these heat fluxes, as well as the neutronic environment of the tokamak – careful material selection must therefore be considered which often trades performance (e.g. operating temperatures) for operational feasibility.

However, future advances in materials may enable higher temperatures to be unlocked, where the efficiency promise of sCO2 cycle may be realised. This potential for future commercial viability further promotes STEP's position on the technology.

The sCO_2 cycle dynamic performance is a significant advantage over the incumbent technology, largely due to improved dynamic performance of the turbomachinery (and to an extent low thermal inertia heat exchangers) previously modelled and discussed [5]. Initial modelling of the CO_2 cycle indicates promise for achieving rapid ramp rates due to compact turbomachinery and low-thermal-inertia heat exchangers with high heat transfer coefficients; however, this must be demonstrated at scale, accounting for component constraints and lifetime considerations.:

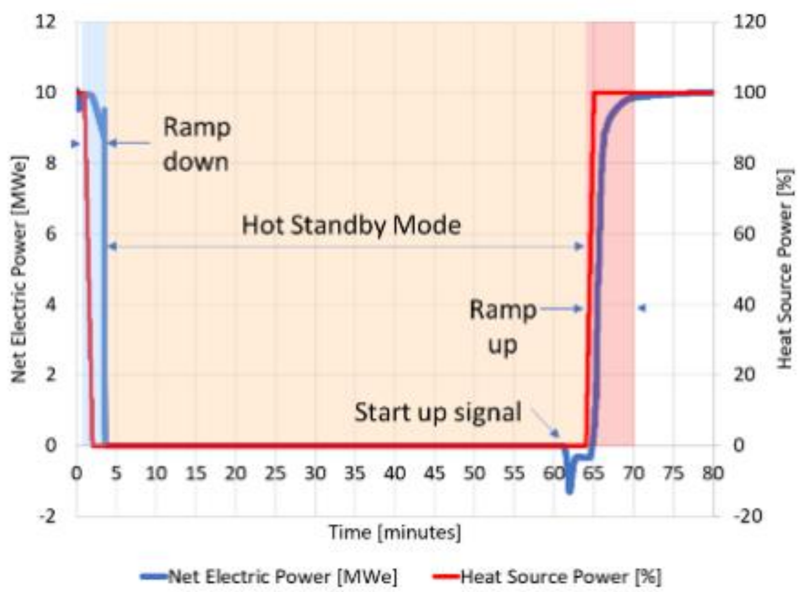

Figure 5: Rapid ramp rates of the STEPUSA sCO2 power cycle effectively support fusion plant operation [5]

A final consideration is that the sCO_2 power cycle technology also enables better FIHS integration due to its dynamic performance.

sCO2 as primary coolant

STEP has considered a multitude of primary coolants, which must meet unique requirements [1].

More recently STEP has favoured sCO_2 for the blanket and outboard first wall, over helium. The majority of the P_{Fus} thermal power is imparted onto the blanket and outboard first wall – the highest grade of heat is also achievable from the Blanket and OFW, as seen in Figure 2. For these reasons this loop is considered the most prominent and important. Nonetheless the Blanket and OFW are quite complex as they have multiple functions in the tokamak, notably the blanket must breed tritium.

For these reasons the Blanket and OFW coolant must, at a minimum:

- Enable tritium breeding by avoiding neutron moderation (dense fluids like water are not feasible).
- Manage high heat flux loads in the OFW (up to 1.4 MW/m^2 [6])
- Be compatible with selected in-vessel component materials, for example liquid metal or molten salt coolants can be corrosive

Gas coolants can meet these requirements, notably Helium and CO2. CO2 is preferred over Helium as, for the most part, it is readily available in bulk quantities (and more affordable) in an enduring manner which will enable a better pathway to commercial fusion. Moreover, a CO2 coolant, will leak less, which is of particular importance considering the need for re-mountable joints at the tokamak interface. These re-mountable joints are key to enabling a maintainable tokamak, one of the major objectives of STEP.

CO_2 is also, more generally, easier to circulate, and can have lower pumping demands in scenarios where pipework and coolant channels are significantly constrained. The CO_2 pressure will be circa 100 bar, this high pressure is to enable a sufficiently low compression ratio, as the pressure losses across the loop are significant – which is why the power demand is equally significant (100MWe+). The reason for such a significant pressure loss is due to the convoluted flow paths in the in-vessel components needed to meet functional requirements discussed.

To maximise efficiencies however careful considerations must be made on the total loop design, ensuring minimised losses in the pipework and, in particular, heat exchange to the thermodynamic power cycle. This is challenging consider the large amount of heat that must be exchanged, hence compact solutions such as Printed Circuit Heat Exchangers are preferred. Ultimately, compact nature of PCHEs balance pressure losses, footprint and heat exchanger efficiency in the right way to maximise STEP's confidence in net power. PCHEs are preferred over other compact heat exchanger technologies due to their relative technology maturity and the ability to operate in the relevant conditions. There is also a key opportunity to align technology development of the primary to secondary heat exchanger with the power cycle recuperators (which typically consider PCHEs in other industrial applications, such as in the STEP DEMO facility [9]) – as all fluids (cold and hot) are sCO_2.

It is worth noting that careful design of the primary CO_2 purification system will be required due to its exposure to a fusion specific neutron environment.

sCO_2 technology shortfalls and development needs

Both the primary sCO_2 loop and the tCO_2 power cycle rely on low maturity technologies. This has been a key consideration as part of the development of the design.

The overall strategy to manage this technology gap considers highly focussed maturity development which will run in parallel with industry led strides in this technology space. That is to say, STEP will seek to develop the technology adaptation for fusion and its specific STEP requirements but is still expecting wider industry to lead more generic (non-fusion specific) demonstrations, this is especially true for the power cycle. STEP's targeted technology development will be completed with chosen industrial partners.

The following technology development that will enable the STEP solution is identified:

<u>Turbomachinery</u>

STEP requires sCO_2 turbomachinery of significant scale, notably CO_2 turbines, pumps and compressors. The STEP power cycle will be split into four parallel trains, hence the turbomachinery scale needed will be equivalent to that of a power cycle of 200-250 MWe (the total capacity of the four trains will be ca. 1 GWe as per Figure 1). The parallel split is, in part, to enable a faster approach to the technology scale up, whilst also improving dynamics performance through the scale-out of multiple smaller units.

Turbines, at STEP relevant conditions, are developed and demonstrated up to 16 MW gross shaft power, at the STEP DEMO facility [9]. Further scale up to the multiple 100s MWe is therefore possible, with targeted risk reduction programmes and careful simulation through validated models. Nonetheless further testing for STEP specific operations at a similar scale (2-10MWe) is expected to be needed to test STEP's selected turbine architecture and design at a relevant scale.

sCO_2 compressors at STEP relevant scale (ca. 15-30 MWe needed for STEP recompressor per train) are reasonably well demonstrated technologies. However, the high pressure or high temperature conditions (for the primary loop) requires careful consideration, and dedicated technology development will be required. Similarly, it is not expected that an additional scale up step will be strictly required for both the primary loop and power cycle compressors – however demonstration at STEP relevant conditions and operations will be required – at a sensible, turbomachinery relevant (2-10 MWe) scale.

tCO2 pumps at the scale (ca. 40-60 MWe per train) and conditions of STEP for the power cycle will require more significant development, it is even possible multiple scale up steps will be needed to develop the confidence required. Demonstration is required of the NPSH demands and the capability of large-scale machines to operate under supercritical conditions during high ambient temperatures.

Seals testing throughout these programmes, is of particular interest to STEP, as managing leaks will be of vital importance. Furthermore, the long-term durability of seals, particularly under cyclic operating conditions, requires demonstration alongside validation of thermal management. It is recognised that this is an active area of research [10].

Heat Exchangers

Heat exchangers, compared to the turbomachinery requirements, are reasonably mature at scale, with highly pertinent demonstrations at the STEP DEMO facility and some reliability testing completed [11]. Furthermore, a modular approach will be taken for the STEP powerplant design, even within the dedicated trains. It is not expected that a single module will significantly exceed the current state of the art 50 MWth capacity [12] of compact heat exchangers – therefore no scale up programme of significance is planned in this space. Nonetheless, further demonstration is required to understand how the heat exchangers will manage rapid planned dynamic changes in operating conditions. It is not expected that this will necessarily be required at scale.

Dynamic system

In line with the heat exchanger shortfalls, there is a wider consideration on how the overall system may be operated in highly dynamic scenarios. This will consider many of the ancillary technologies (such as the Inventory management system, cooler/condenser, heat input stages, valve and valve actuation) as well as all the turbomachinery and heat exchanger components, connected together in one system. Evaluating how this system responds to rapid changes in heat input(s) representative of the tokamak operations will be key in the development of the overarching technology, but will also be important in validating models and demonstrating feasibility. Of particular interest will be testing how the SHOC cycle design responds to operating mode changes from the chosen FIHS to a pseudo Fusion Mode (e.g. using heaters to represent fusion heat input) and back again. Integrated testing is required here at the most relevant scale possible.

General sCO2 handling

General sCO2 handling must also be developed, this considers aspects such as safety, materials, and operations. While many learnings can be derived from previous experiments (notably STEP DEMO, USA), further considerations need to be made for the STEP relevant conditions. Scale up of key components may inherently enable key learnings in this respect, nonetheless handling capability should also be considered for the wider power cycle loop at relevant scales as well.

STEP's sCO2 roadmap

STEP's technology development will occur over the programme's "Tranche 2" (split into two: Tranche 2A and Tranche 2B), which spans into the early 2030s. With the technology gaps highlighted, STEP is considering a single technology development roadmap which is planning multiple key programmes:

- Proof of concept programme

Over the initial stages of the STEP design (T2A), a small scale proof of concept rig (ca. 200KWe) is planned to demonstrate key dynamic elements of the cycle and prove the operational ability of the design vs the planned plasma dynamics. It will also enable key learnings around sCO2 handling. This will be a full rig representative of SHOCC – ultimately creating design confidence, organisation capability and validating STEP's powerplant models and designs. This rig will also test the various modes of operations, namely the "fusion mode" and "auxiliary heating mode", using a FIHS and electric heaters (representative of fusion heat at different grades), as per Figure 6. In particular, the rig will test switching between the different modes of operations over STEP relevant timescales. Component demonstration for scale up purposes is not intended for the majority of the turbomachinery as the scale will be too small (e.g. only radial turbomachinery will be accessible, at small frame sizes, and the risks profile may not be relevant to SPP scale). Nonetheless some learnings are expected, especially on fundamentals. Sufficient learnings on heat exchanger dynamic performance is expected from this rig, however should further testing be required at a larger scale, a separate rig dedicated to larger scale heat exchanger testing may be subsequently developed as part of the scale-up programme.

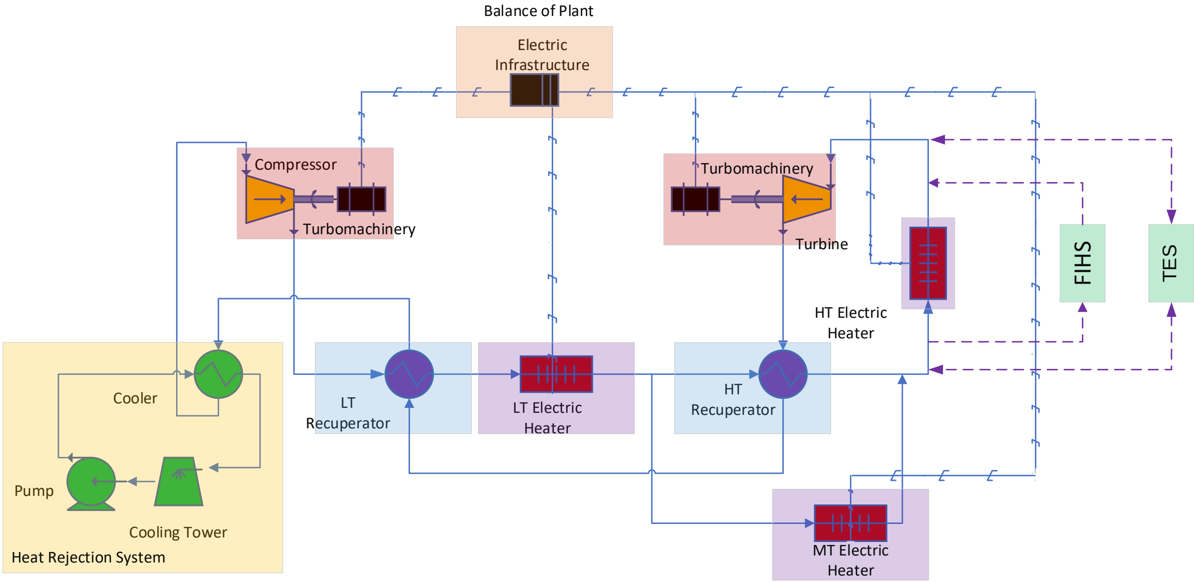

Figure 6: STEP's SHOCC proof of concept rig diagram

- <u>SHOCC Scale Up programme</u>

In the latter stages of the STEP design (T2B), after the proof of concept is complete, there will be a new "Scale Up Programme". It is intended that this programme will accomplish the full scale up of the turbomachinery at the relevant conditions and scale (2-10 MWe). Depending on industry advances this could be extensive and development of a full loop mimicking the full STEP power cycle may be the most logical approach. Such a facility would enable verification of transient performance under representative component limits, ultimately providing a suitable environment for endurance and life assessment under SPP relevant conditions. Particular attention to the scale up of the CO_2 pump will be required, testing the pump at multiple scales may be required to build sufficient confidence.

- <u>Primary Circulator Demo programme.</u>

Due to the, somewhat, unique conditions of the primary circulator and its environment a dedicated development and scale up rig is planned for the later phases of the STEP project.

The plan is to run this programme at the same time as the SHOCC scale up programme, incorporating knowledge gained from secondary cycle CO_2 turbomachinery design.

- <u>Early install of one of the trains vs added scale up stage</u>

The STEP CO2 power cycle is intended to be split into four parallel trains. Each train would deliver circa 200-250MWe, carrying the same risk profile as any FOAK plant. Such risks could be substantial and potentially unacceptable, particularly given that the tokamak is very low TRL itself. It can therefore be argued that testing of components, and potentially the cycle as well, at an intermediate scale of 50-100MWe would be needed, if the scale up programme will only deliver 2-10 MWe demonstrations. However, this demonstration facility would incur significant costs with little value beyond testing. Therefore, the current strategy considers the early install of one of the four trains which would have similar costs, by the late 30s. This would be scaled up based on tests done to date and industrial expertise already generated. Testing of train A would happen at the same time as the tokamak is being commissioned for plasma demonstration at low power levels – hence there is sufficient time to learn key operations from the testing of train A which will enable a full transition when all four trains are installed. There are indeed risks around the turbomachinery in such a scale up jump, but in an extreme scenario, this turbomachinery can always be replaced with the newer designs which will be shared among the four trains; this should not be overly onerous due to the small sizes of the turbomachinery, even at scale.

The above is summarised in the following roadmap:

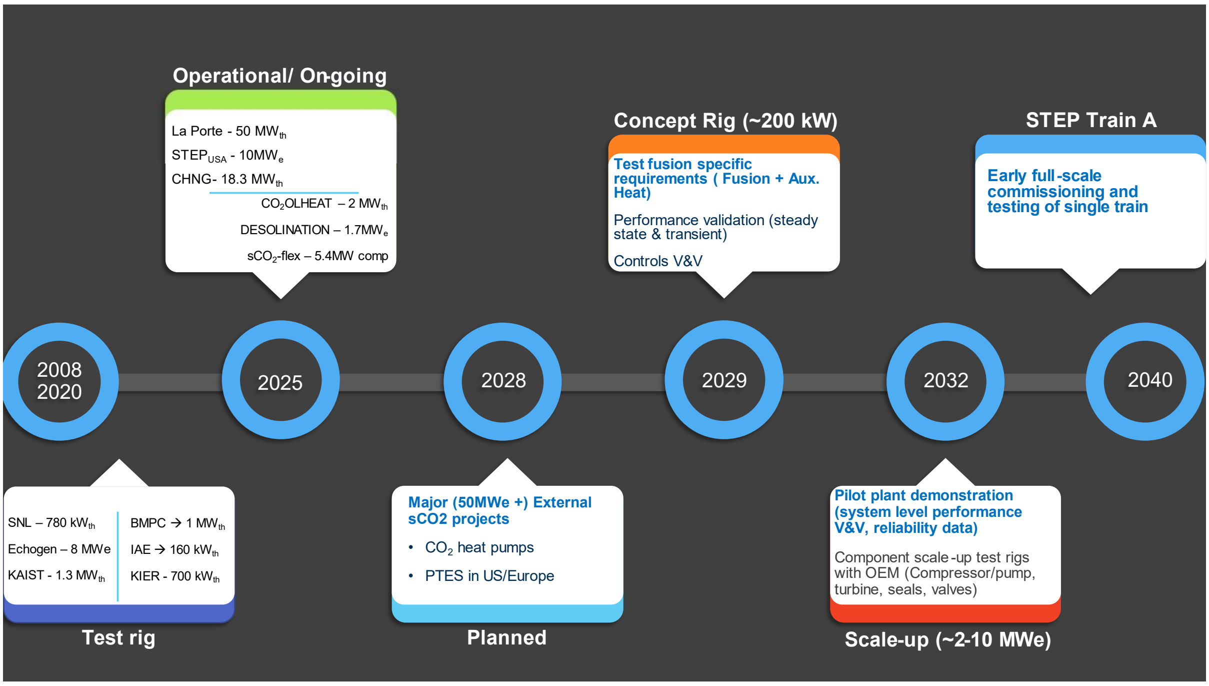

Figure 7: STEP's CO2 roadmap

Risks will be managed on an ongoing basis, and it is still possible that additional scale up tests will be required – especially if there is limited capability developed in industry. Equally it is possible that the need for certain tests are eliminated altogether due to the future sCO2 establishment in the market.

Conclusion

An overview of fusion and the UKIFS STEP project has been given, showing the crucial benefits of fusion and the unique aspects of the STEP project. The functions and key technologies of the power & cooling systems have been discussed, highlighting in particular where CO_2 technologies are being considered as preferred solutions. In particular the use of a tCO_2 cycle: SHOCC, and the use of sCO_2 as a primary coolant, have been discussed. The clear benefits of the CO2 technologies have been outlined, specifically around the dynamic performance of CO_2 power cycles, and the relative availability of CO_2 for the primary cooling loop – among many other advantages.

Due to this technology selection it is clear that there exists a technology gap in the deployment and implementation of the STEP power & cooling systems. As such a roadmap is presented highlighting what and when key testing steps must occur.

Further work is required to define these testing steps in more detail and ultimately deliver them – starting with the proof of concept rig. UKIFS is continuously seeking industrial support, potentially through dedicated partnerships, and will therefore invite the market as well as OEMs to support the efforts in demonstrating the CO_2 technologies, as appropriate. UKIFS and the STEP project as a whole will continue to evaluate the status of CO_2 technologies and their TRLs as new projects come online. Based on this, future adaptations to the programmes highlighted in the roadmap are likely.

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