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STEP: DRIVING A PATHWAY TO ACCELERATED FUSION DELIVERY

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Abstract

The STEP (Spherical Tokamak for Energy Production) programme aims to deliver a prototype fusion plant in the UK, targeting 2040, and to demonstrate a commercial pathway. UK Industrial Fusion Solutions (UKIFS) has been established to lead the delivery the STEP Prototype Plant (SPP) and, through this, drive the creation of a skilled fusion industry sector as a key outcome of the programme. The adopted approach is designed to demonstrate "fusion is now", delivering early societal and economic benefits, creating new high quality jobs and actively seeking spin-out opportunities of fusion technologies into adjacent sectors. UKIFS is supported by the Fusion Partner (UKAEA) and Construction Partner (to be selected from industry through a competitive process during 2025), who will work with UKIFS and key engineering companies (through competitive tendering) to design, build and operate test rigs at the West Burton site in Nottinghamshire, UK, which has been chosen for the SPP. This drives early benefits, supporting economic growth in parallel with establishing the fusion industry and addressing the remaining technical challenges facing the SPP design. The technical case for the spherical tokamak as an attractive pathway to fusion delivery is summarised, highlighting its potential but also describing some of the challenges associated with realising that potential. Addressing remaining science and technology questions while driving forward the design at pace informs the technical development pathway to SPP delivery, examples of which are briefly outlined.

1. INTRODUCTION

The urgency driven by the needs of climate change and the importance of energy security underpin an important research question – can we accelerate the commercialisation of fusion power, and identify a rigorous pathway to delivery on this accelerated timescale? The UK's STEP (Spherical Tokamak for Energy Production) programme has grappled with this question since its launch in 2019. STEP recently concluded its first 5-year funding Tranche [1], and is now transitioning to align with the requirements of the second, so it is timely to reflect on lessons learnt from this first phase, and look forward to the next stage of STEP's development.

STEP was launched as a publicly funded programme, initially led by the UK Atomic Energy Authority (UKAEA). It is strongly driven by national interests that extend beyond direct financial returns, such as supporting early economic growth and societal benefits through the development of a coherent national fusion environment and infrastructure. Specifically, the technical research and development (R&D) required to advance a fusion pilot plant design provides a vehicle to seed the fusion industry and associated supply chain, while also supporting skills growth through the further and higher education sectors. Integrating these three aspects – technical R&D, skills and industrial capability – into the STEP programme is essential for realising fusion energy but, just as important, it offers opportunities to realise early benefits through high quality jobs, skilling industry ready to be competitive on an international fusion stage, and actively seeking spin-out opportunities for advanced fusion technologies into adjacent sectors. This approach is establishing solid foundations for a fusion energy industrial sector in the UK, providing capacity and capability to realise STEP's ambitions while also positioning industry to support a wider range of fusion pathways being followed around the world.

The STEP mission is to "Deliver a UK prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion". This statement captures the above philosophy, emphasising our two key aims: (1) to deliver a prototype fusion energy plant in the UK that delivers net power (the STEP Prototype Plant, SPP), and (2) through this, foster the development of an industrial fusion sector, maximising near term economic benefits. These aims are closely coupled. First, it will be industry that builds the prototype and therefore aim (1) can only be delivered if aim (2) is successful. Second, our strategy to stimulate growth of a fusion energy sector is to integrate established companies (large and small) into the design, development and construction of the prototype plant from the start, fostering the transfer of knowledge and benefitting from a diversity of cultures through solid public-private partnerships. In parallel, skills are driven by contracting out some STEP research projects to universities, which then embeds faculty staff, post-docs and postgraduate students into the programme, benefitting from their technical expertise while at the same time strengthening fusion capability in the academic community which filters down into undergraduate teaching. This diversity of organisations involved in STEP supports the identification of spin-out opportunities of fusion technology into adjacent sectors, and stimulates the emergence and growth of new, specialised companies. Skills growth is further supported through apprenticeship programmes, which will meet many of the technical competences required to deliver a fusion plant, and these are also being coupled into the programme to ensure apprentices will learn through hands-on experience in the construction and operation of test rigs and, ultimately, the pilot plant itself.

STEP's approach to build the fusion industry capability alongside the STEP Prototype Plant (SPP) design has been enabled by public funding mechanisms. However, building a prototype fusion plant is costly and complex, requiring a commercial, delivery-focussed mindset to drive pace, as well as open up access to a range of other investment opportunities. To provide this flexibility, UK Industrial Fusion Solutions (UKIFS) was established in 2024 as a wholly-owned subsidiary of UKAEA to serve as the delivery body for the STEP programme. At this time, STEP remains fully funded by the UK Government, but as the programme matures and confidence in the pathway grows, a key objective of UKIFS is to attract additional investment for STEP. This adds another aspect of the UKIFS approach – to progressively add value to the programme to ensure it is an investible prospect.

We have introduced STEP as a very broad, yet coherent, programme that integrates multiple activities associated with the commercial realisation of fusion energy. These are succinctly captured in its highest level objectives [2]:

(a) Demonstrate power plant characteristics
(b) Create an information baseline
(c) Develop a fusion supply chain
(d) Deliver UK economic value
(e) Deliver UK social value
(f) Deliver safely
(g) Schedule
(h) Cost

In the following sections, we will explore different aspects of the UKIFS strategy to deliver on these objectives. Partnership is a critical element of this – STEP will not be delivered by UKIFS alone – and we consider that in the following section. In Section 3, we describe our rationale for the spherical tokamak (ST) pathway adopted for the SPP, and how we are tapping into the attractive features of this approach to fusion power. In Section 4, we provide examples of some key high priority technical research challenges that remain outstanding; we illustrate our strategy to manage the uncertainty associated with these while advancing the engineering design consistent with our 2040 SPP delivery timescale. We close in Section 5 with a summary of our programme's forward plan.

2. PARTNERSHIP

UKIFS leads the STEP programme, and owns the SPP design. However, partnership is crucial, with each partner bringing value and each realising significant benefits. UKAEA remains closely integrated into STEP as the Fusion Partner. They bring decades of fusion knowledge and experience across all key fusion areas, from fundamental plasma physics, materials science and computational science, through to engineering applications such as in fusion technology, plasma control and remote applications. Significant additional fusion expertise also sits within the academic sector, complementing that available at UKAEA and adding further value by providing pathways to deliver on our skills requirements and linking to research in related fields. The Fusion Partner provides access to a range of facilities which are key for informing the design of SPP. For example, MAST-U is presently the world's most advanced operating ST. While it is much smaller than the designs being considered for SPP, MAST-U nevertheless provides access to relevant plasma physics regimes for testing the models embedded in our simulation codes, giving greater confidence in their predictions for SPP to support the design work. Gaps remain, however, and we will return to this later. The Materials Research Facility provides access to a range of state of the art tools for analysing the properties of materials, including after irradiation (provided the activation levels of the samples are not too high). There are very few facilities for tritium science in the civil sector, and the new H3AT tritium loop facility – a partnership between UKAEA and the energy company ENI – will provide essential data for STEP's fuel cycle. Another UKAEA facility that is under construction at its Rotherham site is Chimera, which will provide non-nuclear thermo-mechanical testing of metre-scale components in (magnetic confinement) fusion-representative magnetic fields, highly relevant for testing elements of the SPP blanket. Finally, the LIBRTI facility is in an advanced stage of design at UKAEA, and will provide a modest fluence of 14MeV neutrons, sufficient to test aspects of tritium breeding and neutron transport science but insufficient for assessing the impact of neutron irradiation damage on materials. Working with UKAEA, we are bringing these facilities together with a validated high performance computing simulation capability to progressively reduce technical uncertainties associated with the SPP design. In addition, we have plans for new test rig facilities (e.g. for high power microwave development and high temperature superconducting magnets), which will be delivered largely through our Construction Partner and substantial contractual arrangements with other key engineering companies.

The Construction Partner (CP) is our second key partnership. While UKAEA was appointed as Fusion Partner from the outset of UKIFS in November 2024, the competition to identify the CP is ongoing, expected to conclude around the end of 2025. The CP will then be embedded into STEP, alongside UKIFS and Fusion Partner staff to deliver the programme – a single team operating across all three partners. This powerful combination of public and private organisations will grow to later include an Engineering Partner, learning together through the construction and operation of test rigs, site infrastructure and, ultimately, the SPP itself to demonstrate the commercial viability of fusion.

A number of fundamental R&D questions – common to multiple fusion pathways – remain to be addressed in parallel with advancing pilot plant designs, especially in plasma and materials science (structural and functional, such as high temperature superconducting magnets). These usually require substantial, international-class facilities, such as tokamaks and stellarators to advance plasma physics; irradiation facilities (e.g. test reactors) for materials development, and tier 0 supercomputers for advanced simulation capability. Not all of these can be provided by UKAEA, or indeed any single national programme, so international collaboration is key for maximising the benefits of these facilities, sharing cost and resource to bring the best minds to these major research challenges. This remains an important part of our strategy: playing a meaningful role in open collaborative international research to advance the fundamentals of fusion science for all. Of course, UKIFS has commercial ambitions, and managing intellectual property is key to optimally position UKIFS and STEP as an investible proposition. It is how we use the data and knowledge gained from collaborative research programmes that builds our commercial value. This is what guides the research areas we participate in, and this is where we protect our intellectual property closely.

3. THE STEP PROTOTYPE PLANT

The STEP Prototype Plant (SPP) is the key vehicle that drives the delivery of the STEP high level objectives listed in Section 1. As such, these objectives inform the requirements for SPP, which are [3]:

- *Net power output*: Deliver 100MW net fusion power to the grid for a representative period (measured in hours).
- *Fuel self-sufficiency*: Demonstrate fuel self-sufficiency through tritium breeding.
- *Safety and environment*: Demonstrate to the appropriate UK regulatory authorities (Environment Agency and Health & Safety Executive) that hazards and risks are As Low As Reasonably Possible (ALARP)
- *Availability*: Demonstrate maintenance interventions that will be required to enable commercially viable powerplant operations.
- *Development Flexibility*: Provide the flexibility to operate as a fusion technology development facility following its demonstration phase to optimise and accelerate the pathway to the commercial plant.
- *Schedule*: Meet the fusion demonstration goals as soon as possible, targeting operation in the 2040's.
- *Cost*: Deliver at lowest possible lifecycle cost.

The specific pathway that STEP is pursuing to meet these requirements builds on UK strength in ST physics, and the promising outcomes of early ST power plant design studies [4,5]. These point to a number of benefits:

- Compact radial build associated with tight aspect ratio.
- High plasma current carrying capacity for a given magnetic field provides access to high beta (ratio of thermal to magnetic pressure).
- Pathway to high bootstrap current fraction compatible with stable, steady state operation.
- Opportunities for novel, simplified maintenance procedures.

In the following, we will consider these benefits in a little more detail, some of the challenges in realising them and how we are addressing those challenges for the SPP.

Compact radial build: The tokamak is a magnetic confinement device that holds the plasma in a toroidal configuration (Fig. 1). Coils provide the toroidal component of the magnetic field (TF), while a current driven through the plasma provides the poloidal component (PF). A key geometrical parameter is the aspect ratio, A, which is the ratio of major to minor radii of the toroidal plasma. As $A\rightarrow 1$, the available space on the inboard side of the plasma (low major radius) to accommodate the TF coils is reduced, and the plasma appears spherical (like a cored apple). This then brings the outboard plasma edge to lower major radius, resulting in a more compact radial build, which is expected to result in lower capital cost for given fusion power.

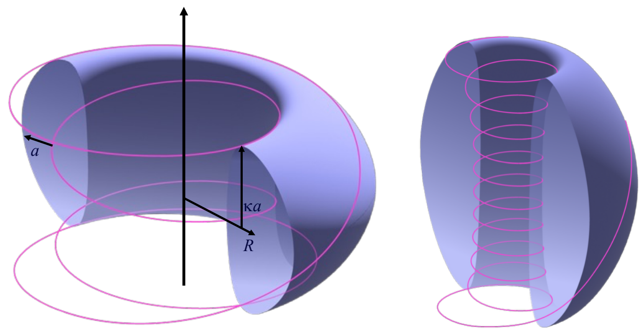

Figure 1: Plasma geometries from a conventional (left) and spherical (right) tokamak, showing a magnetic field line trajectory (pink line). The major, R, and minor, a, radii are shown, as well as elongation, κ.

The compact build creates design challenges, and here we highlight two: managing the plasma exhaust and designing the centre stack, which contains the TF conductor. MAST-U has pioneered the development of the Super-X divertor to manage the exhaust power in compact tokamaks (Fig 2). Experiments show that this reduces heat loads substantially (a factor ~5 in [6]), so this approach has been adopted for the SPP. Provided the magnetic equilibrium can be maintained up-down symmetric, the anticipated steady heat loads to divertor targets can be managed by radiating up to 70% of the power from the core using Xe pellets, and also relying on detachment enabled by introducing Ar gas into the divertor to radiate the remaining power while also buffering transients [7]. Turning to the centre stack, the radial build of this has a large influence on the overall radial build. It contains the high temperature superconducting (HTS) conductor at its centre, surrounded by a neutron shield material. The thickness of this shield is a significant size-driver, so quantifying the radiation tolerance of the HTS and optimising shielding materials are key research goals to drive down the radial build.

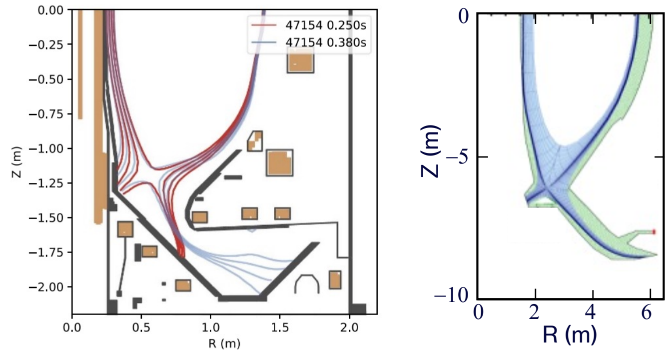

Figure 2: (Left) MAST-U super-X divertor magnetic geometry (blue lines) compared to the conventional divertor (red lines) in poloidal cross section. (Right) The divertor geometry for SPP from the CML5 design, showing Super-X outboard leg and X-divertor inboard leg.

Current carrying capacity: The higher plasma current carrying capacity of the spherical tokamak is also a result of geometry. A key plasma stability parameter is the safety factor, q, which is the number of toroidal turns a magnetic field line makes in performing one poloidal turn. For fixed geometry, $q \propto I_N^{-1}$, where the normalised plasma current $I_N = I_p/aB$, with I_p the plasma current, a the minor radius and B the magnetic field. Fig 1 illustrates how, on the inboard side of a ST plasma, a magnetic field line performs many toroidal revolutions while it migrates relatively slowly poloidally. This is because the toroidal component of the magnetic field ($\propto R^{-1}$) becomes very large there. The result is a higher value of q, for a given I_N; indeed $q \rightarrow \infty$ for $A \rightarrow 1$, independent of I_N. The plasma becomes unstable to ideal magnetohydrodynamic (MHD) instabilities when q at the plasma edge drops below about 2. This then implies a limit to I_N which, for an ST, is significantly higher than a conventional tokamak.

A high plasma current brings two benefits. First, confinement time is empirically observed to scale approximately proportionally to the plasma current. A high value of confinement time allows the fusion conditions to be achieved for lower heating power, which is important for two reasons: (1) it provides a pathway to net power production at lower fusion power (easing a range of technical challenges, and reducing capital cost), and (2) lower heating power lowers the exhaust power that needs to be handled, reducing the divertor and/or core radiation requirements.

High beta, β: The second benefit of high plasma current arises from considerations of the maximum plasma pressure, p, that can be confined for a given magnetic field. The ratio, β, of thermal (p) to magnetic ($B^2/2\mu_0$) energy is limited by ideal MHD instabilities to a value proportional to I_N. Thus higher I_N supports a higher β. This is important, because, as fusion power is proportional to the square of the plasma pressure, β provides a measure of how effectively we are using magnetic field to deliver fusion power. In short, a spherical tokamak makes optimal use of the confining magnetic field. However, operation at high β takes the SPP into new plasma turbulence regimes not accessed by conventional tokamaks, and this influences the confinement time. Today's spherical tokamaks (e.g. MAST-U and NSTX-U) can access such high β regimes, but typically using neutral beam heating which drives flows in the plasma that are not expected in SPP. Understanding this high β turbulence in low flow plasmas is a key area of uncertainty for SPP, and is a topic we return to in the following section.

Steady state operation: In its most basic operational mode, the plasma current in a tokamak is driven by a central solenoid, leading to pulsed operation. However, there is a natural steady current in the plasma driven by the plasma itself, called the bootstrap current. This can constitute the majority of the plasma current, and in SPP we target 90%, leaving in the region of 10% to be driven by non-inductive means which, for SPP, we choose to be via microwaves. The bootstrap current density is proportional to the pressure gradient, and is therefore maximised away from the magnetic axis. In a conventional tokamak, a high bootstrap current plasma scenario typically results in a non-monotonic q-profile that has a minimum away from the magnetic axis. While this can be beneficial for reducing thermal transport, the plasmas are prone to large-scale instabilities, requiring careful optimisation with (in a power plant) limited actuators. In a ST, because the safety factor rises so fast in the outer parts of the plasma, a lot of current density can be accommodated there while maintaining a monotonic safety factor profile. Indeed, pushing the current density out towards the plasma edge stabilises the plasma to vertical displacement events, allowing very highly elongated plasmas to be confined which, in turn, is a requirement for high bootstrap current. Such a broad current density profile helps to keep the values of q high in the plasma core, and in SPP we target q>2 everywhere. This is beneficial for pushing to higher β, accessing the so-called second stability window for ideal MHD ballooning modes. It is also beneficial for avoiding instabilities called neoclassical tearing modes, which are a concern for conventional tokamaks, such as ITER. This provides the ST with a self-consistent pathway to a steady state plasma scenario, able to deliver steady fusion power to the grid. Key to this is the ability to access high plasma elongation, κ, and in SPP we target κ=3 through a mixture of passive and active control coil designs. A recent success was the demonstration on the TCV tokamak that we can control the position of the X-points sufficiently accurately to avoid excessive transient heat loads to the inner divertor [8].

Let us return to providing the remaining ~10% plasma current by microwaves. This is very inefficient, requiring power in excess of 100MW to be injected into the plasma when using the conventional electromagnetic waves. This results in very high recirculating power which, in turn, pushes the required fusion power for net electric up. If we can drive the electron Bernstein wave (EBW) in the plasma, this is theoretically predicted to significantly enhance current drive efficiency. Two gyrotrons totalling 1.8MW are being installed on MAST-U to demonstrate this physics. In addition, we are advancing gyrotron and waveguide technology to improve the efficiency of microwave production. Both of these can significantly reduce the recirculating power fraction, allowing operation at lower fusion power which would bring a range of technical and cost benefits.

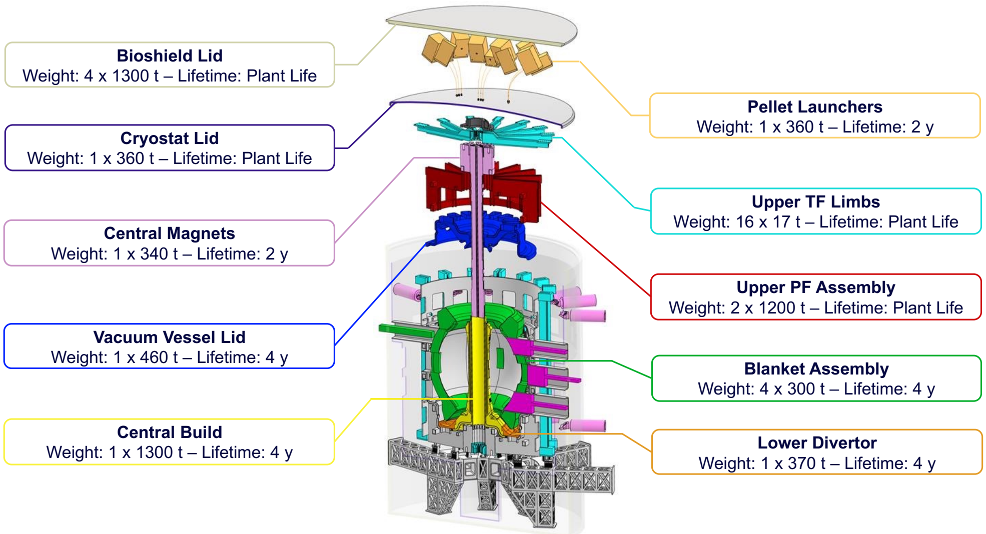

Figure 3: Maintenance scheme for an early design of SPP, showing the feasibility of a vertical lift, and how it provides ready access to multiple components in the tokamak core. [11]

Simplified maintenance opportunities: The first pilot plants will naturally carry uncertainty, and the ability to inspect and replace parts readily will be important for their availability. This is a significant design driver for SPP, which benefits from the ST approach through the ability to remove the central stack, which then provides ready access to vertical lift maintenance schemes [9,10,11]. This benefits from another feature of the ST: there is no need to breed tritium on the inboard side to achieve a tritium breeding ratio, TBR>1 (although one might choose to). Figure 3 provides an illustration of how a vertical lift maintenance capability provides ready access to multiple components deep inside the tokamak core [11]. A challenge for SPP is related to our choice of HTS magnetic coil conductor. At the start of STEP, there was no proven technology to break and re-make joints in HTS cable, and this is a key requirement in order to withdraw the central column. We have developed a design associated with interleaving threads of conductor originating from two arms of the TF coil that need to be separated as part of the maintenance procedure. This is now at an advanced stage of prototyping and testing, which so far has been successful, with encouraging performance and acceptable joint resistance [11].

In this section we have highlighted some of the key benefits of the ST approach; some of the design challenges associated with accessing those benefits, and how we are tackling them in our activities. In the following, we explore the origins of uncertainty and our approach to addressing it while maintaining programme pace.

4. MANAGING TECHNICAL UNCERTAINTY IN THE DESIGN OF SPP

Our design approach must accommodate uncertainty, and the associated technical risk, at two levels. First, an accelerated delivery timeline means that we must develop the integrated design before we have addressed all of the science and technology research questions. This is managed by making assumptions that are informed by the experience the international fusion community has gained from previous experiments and designing devices like ITER; these guide our physics understanding and help to (at least partially) validate the models and simulation codes that we employ in the design of the SPP. These simulations provide informed assumptions, of varying levels of confidence, which are passed to the design and prototype testing engineers to work with. In parallel, we have a science and technology R&D programme that advances understanding, prioritising those areas that carry most uncertainty such as plasma physics, materials science or novel approaches to advanced simulation. These progressively burn down technical risk, providing ever-improving confidence as the assumptions delivered to the design teams become increasingly constrained.

The second level is associated with the closely coupled nature of the design [12]. This means that even if we have identified an attractive solution for each subsystem, when multiple subsystems are brought together to build up the integrated design one can find that the interface requirements between them are not compatible, or are not optimal and a change in direction is required. Such integration uncertainties are managed through scenario and systems modelling that informs a nimble and adaptive design programme capable of rapid iteration. This approach creates opportunities for accelerated learning and refinement. With growing experience these iteration cycles are becoming less frequent, and their nature has evolved from the early stages of STEP where technical inconsistencies led to design iterations, to more recent iterations where the wider objectives are driving modifications, such as those related to improved safety, cost and schedule. The iteration cycles related to closing knowledge gaps, on the other hand, are on a much longer timescale, reflecting the nature of science and technology research which typically takes multiple years to draw conclusions. We now discuss some examples of each of these two classes of design uncertainty drivers, as an illustration of how they are being managed.

Starting with how integration can inform a design pivot, we describe our pathway towards an optimal breeder choice. In [13] a liquid lithium blanket was described, chosen because of the high tritium breeding ratio (TBR) that could be achieved. However, this raises a safety concern that arises when the interfaces with other systems are considered, for the following reason. As mentioned earlier, in a spherical tokamak, the radius of the central stack dictates the overall size of the tokamak core. This, in turn, is related to the thickness of the neutron shielding around the HTS magnets, which can be minimised by using water as the coolant. However, the presence of water and lithium raises a safety concern which (while introducing complexity) might be addressed through innovative design, but another option that we are now exploring is the viability of a solid breeder solution – highlighting a link between the magnet conductor and breeder material choices. Solid breeders come with known challenges, such as managing the degradation of the solid breeder due to neutron irradiation, and achieving sufficient TBR; we are exploring possible pathways to address these in order to broaden the design options available to us.

This leads us into the second category of uncertainty: that arising from gaps in our science understanding. These gaps typically arise because of the lack of a testing environment sufficiently representative of fusion conditions. For the breeding blanket, these conditions are extremely hostile, involving a combination of thermal, magnetic and irradiation loads. The latter arises due to the 14MeV neutrons that are produced in the DT fusion reactions, which are much more energetic than the neutrons formed in fission devices. There are two areas of concern that at present are not possible to test in a fully representative environment: (1) the damage caused by these neutrons to materials and the consequences for their properties, and (2) their ability to breed tritium through the reactions with lithium in the blanket, and recover it. To meet the requirements of the latter, UKAEA is building a new experimental test rig called LIBRTI (Lithium Breeding Tritium Innovation) which will be available for the international fusion community to explore the physics associated with tritium breeding and transport. The neutron flux will be many orders of magnitude less in LIBRTI than it will be in the blankets of SPP, so our challenge is how to optimally use LIBRTI to reduce the uncertainty in our predictions for tritium breeding in STEP. A science-based approach is key, relying on simulations to understand the effectiveness of a particular design. These simulations require accurate models for a number of different processes: the neutron transport; neutron reaction cross sections (noting that the neutron energy spectrum will be different in different parts of the blanket); the transport of tritium out of the breeder material, and what form it is in; the extraction of tritium out of the blanket. Each physics process carries uncertainty, and our task is to work with the UKAEA LIBRTI team to design experiments that reduce this uncertainty, giving us greater confidence in our simulation capability.

Turning to structural materials qualification for SPP, LIBRTI will not have sufficient neutron flux to provide useful information on this. A number of other experimental facilities can inform our understanding. Fission test reactors are a major workhorse, but their neutron energy spectrum differs from that in a fusion environment. Proton beams can be designed to represent features of high energy fusion neutrons, but their damage mechanisms have differences because of their electrical charge. Our approach is again a science-based one, such as employing micro-scale crystal plasticity models in simulation codes and using the experimental data from multiple sources (nuclear and non-nuclear) to inform parameters within those models, and to validate them – a programme we call Design by Fundamentals [14]. Additional data is used at progressively larger scales to ultimately develop a predictive capability for the performance of the SPP materials. These models will carry uncertainty until the first data comes out of SPP, but we will then rapidly refine them to provide an effective and efficient tool for optimised design of the commercial plant. This provides an example of the power of SPP beyond its key purpose as fusion pathway demonstrator. The data it provides will be fundamental to rapidly progressing to an optimal commercial fusion power plant. Because of the uncertainty anticipated to prevail until SPP operation, we restrict the use of our models to inform SPP asset protection, reliability and maintenance schedules, rather than be integral to our safety case. Our strategy there is to optimise the design so that any components that have a safety function are shielded from the high energy neutrons, thus removing this element of uncertainty from their performance.

Another area where there are gaps in our knowledge relates to the plasma. As mentioned in the previous section, there are uncertainties associated with the high β operation that underpins the SPP plasma design, and the associated thermal confinement. In low β plasmas, characteristic of conventional tokamaks, core turbulence is essentially electrostatic. Simulations show that at higher β, the turbulence involves both magnetic and electrostatic field fluctuations, which then opens up different drive and saturation mechanisms, and different thermal transport properties. Empirical data from conventional tokamaks therefore only provides a part of the story, and there remains significant uncertainty in the confinement properties of SPP. This has led to a substantial research activity to provide a first-principles calculation of the thermal transport in SPP, confirming the importance of electromagnetic fluctuations driven primarily by an instability called the (hybrid) kinetic ballooning mode (with micro-tearing modes also in play) [15,16]. Encouragingly, non-linear simulations of the plasma turbulence and associated transport provided evidence in support of the confinement requirements assumed for SPP giving a level of confidence in its design [17]. However, the simulations are extremely challenging, close to the limits of the capabilities of our supercomputers and, furthermore, they are not robust, often failing to converge. Recent theory, supported by further simulations, postulates that fluctuations in the magnetic field fundamentally alters the turbulence saturation mechanism and can, under certain conditions, result in extremely high transport [18]. Experimental data is crucial in order to validate and inform this modelling, but there is a challenge. The simulations show that strong flow shear suppresses the kinetic ballooning mode that we expect to influence turbulence in SPP. Because today's spherical tokamaks access SPP-like conditions with strong neutral beam injection that drives plasma flows it is likely that this suppresses the kinetic ballooning mode, masking the physics we wish to validate. We need to confirm this expectation through simulations of MAST-U and NSTX-U plasmas, for example, as well as to find plasma conditions in those tokamaks that most reflect the turbulence physics predicted for SPP. This is likely to involve heating schemes that do not impart momentum to the plasma, and we are exploring the feasibility of achieving this on MAST-U with a further upgrade to its microwave heating system.

There are several other research areas that are just as important as those discussed here, but there is insufficient space to cover all in this paper. These include disruptions, transients, start-up (and termination), tritium retention, HTS magnets, fast particles. The three examples described in this section exhibit key features of our approach to addressing these outstanding science and technology questions in parallel with advancing the SPP design. In each case, it is not possible to exactly reproduce the SPP plasma; in each case, we are using advanced, physics-based simulations to predict the performance and consequences for SPP design; in each case we are designing experiments to test (or inform) specific aspects of the physics models, to further improve our confidence in the predictions. As our confidence improves, the assumptions passed to the design team will be refined, progressively burning down the technical risk. The challenge (and the excitement) is to do this in time to deliver SPP on our 2040 timeline, which will require close coordination between the science and technology research teams and the design teams, each guiding the other's strategy and priorities.

5. SUMMARY

We conclude with a discussion of the timeline to delivery of the SPP. Three factors influence this: the scale of the technical challenge; establishing the supply chain, and creating the national infrastructure and skill base. The SPP cannot be realised unless all three are in place, and our strategy and timeline recognise this. Thus, during the current four years of Tranche 2a funding we will bring our partners together to develop the SPP engineering design and grow the site infrastructure, thus progressively establishing the skills base and industrial supply chain. In parallel we will seek additional investment pathways; add value to our organisation by progressively burning down technical uncertainty and risk, and build an IP portfolio while actively seeking technology spin out opportunities into adjacent sectors. Construction of the SPP will target operations from 2040, with a demonstration of net fusion power expected later that decade. We understand the magnitude of the challenge but we believe in our strategy and remain committed to delivering SPP as early as possible, remaining focused on 2040.

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