STEP: DRIVING A PATHWAY TO ACCELERATED FUSION DELIVERY

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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? 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 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. While STEP is focused on a particular technical approach – the spherical tokamak – many of the programme's lessons are generic to multiple pathways being explored around the world, and here we focus on those.

The STEP mission embodies two key aims in its quest to establish the commercial viability of fusion energy: (1) to deliver a prototype fusion energy plant in the UK that delivers net power, and (2) through this, foster the development of an industrial fusion sector, maximising near term economic benefits. These are closely coupled through our strategy. First, it will be industry that builds the prototype and therefore aim (1) can only be delivered if aim (2) is successful. Second, the strategy to stimulate growth of a fusion energy sector is to integrate established companies 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.

Partnership is key, with each partner bringing value and each realising significant benefits. Much of the UK's fusion-specific technical capability sits within the public programme, and is led by UK Atomic Energy Authority (UKAEA) but with significant expertise also within the academic sector. Meanwhile industry brings broader expertise and a culture of commercialisation as well as opportunities for technology transfer to/from other more established sectors. A key benefit is the enormous commercial opportunity associated with delivering net fusion power to the grid and/or directly to industry. While the time to realise this is decadal, there are other benefits to society, industry and national economy that can be realised on much shorter timescales, enabled through the appropriate partnership arrangements embedded into the programme. A STEP delivery body called UK Industrial Fusion Solutions (UKIFS) was established as a limited company in 2024 to lead the development of the programme into its second Tranche and beyond. Three key partnerships have been designed to work with UKIFS to deliver STEP, which at this stage is a wholly public-funded programme. The Fusion Partner is UKAEA, bringing world-class expertise in fusion science and technology. The Engineering and Construction Partners bring industry know-how for design, construction and operations; following open competition, a final selection will be made in the coming year. A single team approach will see secondees from all three partners embedded with UKIFS in the "Programme Layer" with responsibility for the whole plant design management. Supporting that will be the "Project Layer", consisting of multi-functional "Integrated Project Teams" (IPT), each again staffed by all four partners working as a single team that integrates across cultures, expertise and disciplines. Each IPT will issue discrete packages of work to the whole plant partners, and then on to the wider supply chain.

The early site selection for STEP greatly enhances its opportunities for early benefit realisation, and a rigorous process identified West Burton in North Nottinghamshire as optimal from a number of regional bids. As well as meeting the technical requirements, a major factor in the final site decision was the opportunity for economic stimulus. Until it was closed in 2023, the West Burton site operated a coal-fired power station, while the wider region was a major contributor to the extensive UK coal mining industry before closure of the pits from the 1980's. STEP will drive the reconstruction of a modern industrial economy – regionally and nationally – supporting high quality jobs across a range of skill sets, with West Burton positioned as an international showcase for the early benefits associated with a transition from fossil to fusion energy.

Let us now turn to the technical challenge associated with aim (1), which is substantial. The Tranche 1 objectives included the delivery of an integrated concept design for the STEP Prototype Plant (SPP), which was reported in a series of publications [1], and will not be described in detail here. Two features characterise a fusion power plant design: (1) many of the subsystems remain at low technology readiness level (TRL), and (2) a fusion power plant is complex, with most subsystems coupled closely to most others. The former requires a strategy and team that can manage significant uncertainty in the technical programme, operating with parallel (and interacting) streams to advance the engineering design alongside the research and development required to drive technologies up the

TRLs. Early design iterations therefore carry substantial uncertainty and technical risk, but are key to highlight and focus the required research. This accompanying research progressively burns down the technical risk, or in some cases might invalidate an assumption, causing a re-think or iteration of the design. This is the phase that STEP is progressing into, requiring an agile approach to fail fast, learn and re-invent. An example, which also illustrates the closely coupled nature of the fusion pilot plant subsystems, is our strategy of working towards an optimal breeder choice. In [1] a liquid lithium blanket was described, chosen because of the high tritium breeding ratio that could be achieved. However, this raises a safety concern for the following reason. In a spherical tokamak, the radius of the central stack dictates the overall size of the tokamak core. This, in turn, is largely influenced by the need to shield the high temperature superconducting toroidal field coil (and the solenoid) – that shield thickness can be minimised by using water as the coolant, which is also effective for the divertor. The presence of water and lithium raises a safety concern which 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 tritium breeding ratio; we are exploring possible pathways to address these in order to broaden the design options available to us.

Part of our approach to manage uncertainty and complexity is to ensure a design that accommodates remote inspection, in-situ repair and/or component replacement at its heart. In addition, advanced simulations of the plasma and the engineered subsystems are being developed to (a) provide a rigorous basis for extrapolation from the conditions of an experimental test rig to those of SPP, and (b) to understand the interfaces and couplings between the different subsystems. Two coupled thrusts are being developed, as described in [1]. A pragmatic thrust that will provide an early capability is an engineering-based approach, in which we are developing a framework to efficiently integrate a suite of (largely) existing software modules for the different SPP subsystems. The second thrust will develop and employ high fidelity, multi-physics simulations to help validate those modules, informing uncertainty quantification and, where necessary, feeding into more advanced surrogate models that can provide the basis for new modules in the integrated framework. The emphasis on building first principles physics-based models gives greater confidence in extrapolations. Validation against physical data from test rigs remains important and will be integrated into the overall framework. One example is understanding the process of tritium breeding and transport in the blanket. An experimental test rig called LIBRTI (Lithium Breeding Tritium Innovation) is presently being designed by UKAEA for the wider community to test some aspects of this, but the neutron fluence will be orders of magnitude less than that in the real blanket of SPP. A virtual LIBRTI will provide an interpretation and extrapolation capability that will maximise the benefit of the experimental facility for STEP.

Commercial viability requires an investible concept, and this needs a rigorous approach to managing intellectual property (IP), both for the SPP itself and for potential spin-out technologies. However, fusion is difficult and has for a long time benefited from international collaboration. UKIFS recognises this, and sees mutually beneficial collaboration as a key part of its innovation strategy, consistent with the requirement to create and protect IP. Part of our organisational tool set for innovation and IP generation is a nimble expert team to explore Alternative Concepts (Alt-C). Alt-C works freely with minimal constraints to innovate, seeking new technical solutions to inform specific aspects of the STEP design, or indeed to explore radically new integrated solutions.

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 timeline recognises this. Thus, during the coming eight years of Tranche 2 we will first bring the whole plant partners together to develop the SPP engineering design and grow the site infrastructure, thus progressively establishing the skills base and industrial supply chain. Construction of the SPP will take a further eight years, so that SPP will start operating around 2040, with a demonstration of net fusion power expected later that decade.

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REFERENCES

[1] I.T. Chapman, S.C. Cowley and H.R. Wilson, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **382**, 20230416 (2024), and papers therein.