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The STEP design space is an intimidating and hostile arena to operate with extensive uncertainties in the pathway heightened by many moving parts, causality breakdown, and multiple significant decisions to be made. Many strongly interacting elements (tensions) of the requirements/constraints and the design within the physics, technology and engineering spheres and between them makes the pathway opaque. This paper outlines the development of an integrated concept for the STEP Prototype Powerplant (SPP) making use of the of the NASA developed Concept Maturity Levels (CML) to structure and pace the work.

The CMLs provide a structured progression, starting at forming an understanding of technology options. This is followed by trade space exploration where a range of concepts are developed to identify the major influences on the performance. Finally, down selecting and consolidation onto a single point design.

Choosing a singular design based on experience and iterating a design ignores potentially innovative design areas. Conversely exploring every possible combination of options leads to an impossibly large number of permutations. Two actions were taken to provide direction and enable development.

Firstly, the process to develop a powerplant concept was developed enabling multiple concepts to be developed quickly, with several stages representing the level of fidelity of assessments. Dependant on performance these could be further developed to greater fidelity, iterated to improve or parked.

Secondly the concept development process needed to have a clear focus on delivering understanding for major physics and technology defining decisions. A subset was selected as 'design family decisions' based on their impact on the plant design.

The concept development process was used to enable the design family decisions to be made, providing a clear basis for development of the SPP concept. Having followed this process, we now present the SPP design giving key technology options and major machine parameters.

Keywords: STEP, Integration, Powerplant design

1. Introduction

The Spherical Tokamak for Energy Production (STEP) is a programme that has been developed as part of the UK government's fusion strategy [1]. The heart of this strategy is the STEP mission: **to deliver a prototype fusion power plant targeting 2040 and a path to commercial viability of fusion**. The STEP Prototype Powerplant (SPP) will achieve this using a spherical tokamak design that provides an aggregated approach to technical risk, utilising margins and flexibility to accommodate for the uncertainties that remain in the key areas of powerplant performance. As a major national endeavour, employing public resources, the programme seeks to guarantee delivery of achievable technical goals despite the inherent technical challenges.

As a pathway to commercial fusion, the SPP must demonstrate that its design principles and operations can be scaled towards a commercially deployable powerplant. With a view to the commercial plant, the SPP must identify opportunities for the reduction of the commercial tokamak's size (and hence cost) and the increase in net electrical power output.

STEP is a magnetic confinement fusion machine, a tokamak, making use of a magnetic fields to hold the plasma inside the vacuum vessel providing the conditions to enable fusion. STEP has chosen a more compact spherical tokamak configuration as the basis of its design. Current tokamak programmes such as ITER [2] and EUROfusion's DEMO [3] are relatively large machines, and this size drives the overall capital cost. The spherical tokamak design seeks to use a high ratio of plasma to magnetic pressure (beta) and high plasma elongation to improve the performance and hence achieving a similar output for a smaller overall machine diameter. This is builds on understanding developed through development and operation of machines such as MAST-U [4] and NSTX-U [5] along with a range of studies on possible machine concepts such as FNSF [6]. The promise of the development of a more compact machine, benefitting from the use of high temperature superconducting coils are being explored by private enterprises, with Commonwealth Fusion Systems [7,8] and Tokamak Energy [9].

For STEP to deliver on its mission a set of key objectives have been identified:

- Safety and environment
- Net Power and Plasma Confidence
- Fuel Self-Sufficiency Confidence
- Maintainability
- Development Flexibility
- Schedule
- Cost

Safety and environmental sustainability are fundamental to any powerplant's design and they have been considered from the start of the SPP's design. For the SPP to successfully demonstrate a path to a commercial fusion powerplant, the design must be driven by creating confidence in the ability to generate and sustain a plasma that will produce a net power output of 100 MWe that can be fuelled sustainably. Maintainability and flexibility enables the best use of the SPP to deliver both its primary performance objectives and to allow it to be used for further development towards the commercial fusion goal. Finally the schedule

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and cost is obviously key to delivery of a successful programme but most important is to use the SPP to enable an understanding to be developed of the requirements for commercially viable fusion.

This paper outlines the approach taken by the STEP programme to develop a concept for the SPP. The STEP design space is an intimidating and hostile arena to operate with extensive uncertainties in the pathway heightened by many moving parts, causality breakdown, and multiple significant decisions to be made. Many strongly interacting elements (tensions) of the requirements/constraints and the design within the physics, technology, and engineering spheres and between them makes the pathway opaque. The enabling actions that have been used as a means of navigating this design space and are listed below and detailed further within the following sections of the paper:

- Pacing development
- Providing constraints
- Broadening understanding
- Design point consolidation

2. Pacing development

It is possible and often attractive to race towards a baseline design as quickly as possible based on a range of assumptions to develop an early understanding of the integration issues that emerge as the design point matures. Within established engineering products (e.g. automotive, aerospace, fossil fuel powerplants) experiences gathered through previous products enable a fast approach to this development. While many tokamaks exist, none of these have been designed with the objective of delivering a net power output. To identify a potential design point that can deliver against the STEP objectives it was important to pace the development of the SPP concept – ensuring that the design space was explored, allowing an understanding of the design trades that could be made to be developed. To achieve this, STEP looked to the Concept Maturity Level approach that had been developed by NASA [10]

2.1. Concept Maturity Levels

NASA developed the concept maturity level approach to specifically enable monitoring of progress at the early phases of development of a design, where the progress is often harder to measure. Ultimately this leads to a design moving forwards before enough understanding of the trade space has been developed that compromises the overall performance of the final design. For the first tranche of work, scoped for 2018-2023, the STEP programme's focus for the SPP has been the progression from CML1-5. Figure 1 shows the overall process, highlighting the key outcomes at each of the maturity levels. The high level descriptions are as follows:

CML 1: Cocktail Napkin – A rudimentary sketch of the idea exists and high level objectives have created.

CML2: Initial feasibility – exploration of the basic idea using initial basic calculations to determine the viability of a concept

CML3: Trade space – exploration of the trades that can be made around the system design and the objectives.

CML4: Point design – a specific design defined at major system level developed with an understanding of the margins and reserves for the design

CML5: Baseline concept – Definition of a design is sufficient to enable a wider programme to be developed around an expected implementation approach.

The key outcome of this approach is the expansion in understanding of the design trade space that is visualized

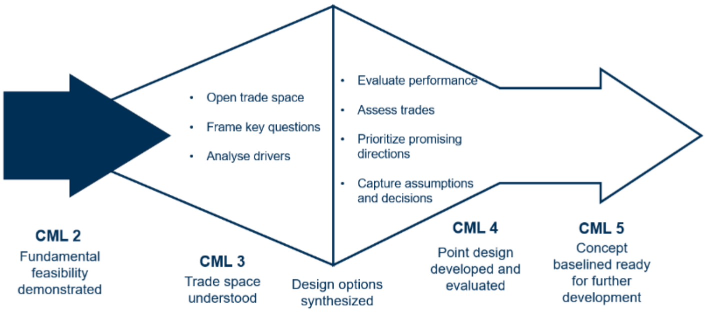

Figure 1 - Visualization of CML design process

within Figure 1 and then using this understanding to focus towards development of a singular point design and subsequent concept baseline.

2.2. Concept development

To enable the expansion of the trade space, as many concepts for the SPP as practicable must be explored within the work up to CML3, with the effort then focusing converging on a concept baseline at CML5. To ensure we keep to time and resource constraints, the methodology for generating, evaluating, and progressing alternative concepts must be agile, iterative, and follow a principle of "fail fast"; that is, generating and evaluating concepts rapidly so that (the inevitably many) unfeasible ideas are not pursued further than necessary and that promising design solutions are instead prioritised.

The strategy to achieve this is a two stage concept generation process. An initial decision set defining the basic outline of the design is made (ref section 3) then the stage 1 develops the concept using analytical tools to iteratively identify a feasible design point that answers the initial specification. Stage 2 takes the form of a design sprint, where the parameters generated are used to generate a spatial model and key aspects of the integrated design can be developed.

The stage 1 workflow is shown in Figure 2. While the diagram is shown as fairly linear for simplicity, the process is iterative. The principle is based on generation of an initial plasma and powerplant concept, using JETTO and PROCESS tools before more detail is

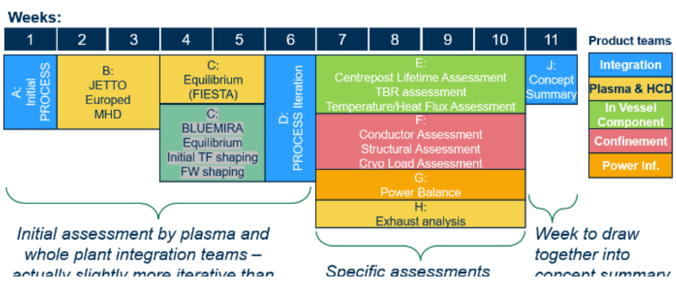

Figure 2 – Concept generation stage 1 workflow

gradually added within subsequent steps. The focus is on generating a concept parameter set, against a set of feasibility assessments from the key product areas using parametric analysis tools to optimize the assessment time.

Stage 2 is focused on moving beyond parametric assessment and performing an initial integrated design feasibility study developing a more detailed concept amending the parameter set from stage 1 and developing a spatial model. This operates as a 12 week agile design sprint. An initial concept, and a key set of focus areas and design issues or questions are added to the sprint backlog and prioritized, with outputs clearly defined. A cross functional technical team is assembled to ensure relevant expertise is available within the team. The team are empowered to drive the design forwards, taking key design decisions against. Progress and key issues are regularly reviewed. There is a clear 'stop point' either within the tasks specified within the backlog, or by reaching the time limit for the sprint period.

The concepts generated are evaluated against the objectives at the end of each stage, using these as Measures of Effectiveness (MoE). Key performance indicators have been developed against each MoE. These Measures of Performance (MoP) are then used as a means of generating an evaluation of a concept. The evaluation comprises of both a simple binary feasibility check, looking to ensure the concept meets the basic objectives, before a more detailed performance evaluation that provides a comparative capability between equivalent concepts at the same stage of maturity.

3. Providing constraints

The primary focus of the initial phase of work is on making major design decisions. These enable major system architectures to be defined and identified as physical systems, with a clear set of requirements and interfaces. The number of options and decisions that could be considered within the SPP design trade space are potentially vast and it is a complex interconnected landscape, where it is non-trivial to identify a specific set of core decisions that could be used to drive and direct the design.

3.1. Design family decisions

An approach has been developed where a core set of decisions has been identified that are device defining in so much as they would lead to an easily distinguishable different solution. This means that many decisions such as many continuous plasma parameters or material selections are not included at this stage but will be explored and determined within the concept development process. The focus of this stage is to provide a consistent and traceable framework that can be used to easily identify individual design families rather than attempting to consider and solve every aspect of a highly complex design problem at the outset.

The SPP trade space can be defined by three non-independent axes of Plasma Scenario, Architecture, and Major Performance Parameters, each of which is further decomposed into the attributes shown in Figure 3. Against each of these attributes a number of options

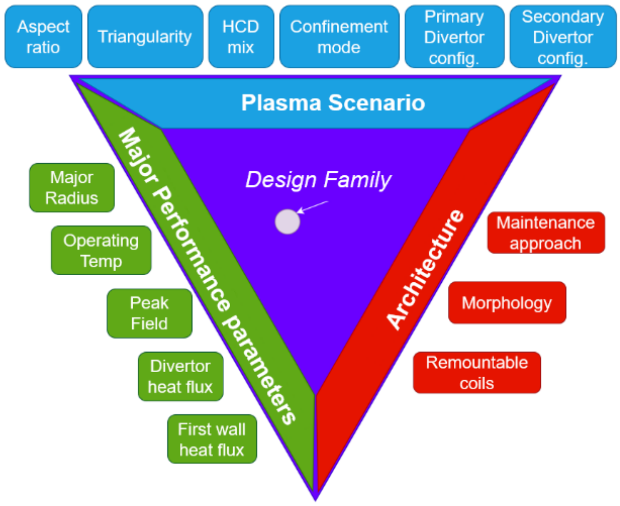

Figure 3 - SPP trade space decisions

have been identified, as part of the initial studies for CML2. While even with this much reduced decision set there are still an unrealistic set of permutations to complete, it is possible to use this as a framework to enable selection of a viable design family point for development within the concept generation process. With expert support it is possible to eliminate unfeasible combinations quickly and direct efforts towards more interesting combinations. Furthermore potential gaps in understanding can be highlighted and considered for development.

4. Consolidation of design

Over the period between CML2 and CML4 over 50 different concepts were developed with a clearly defined design family to different levels of concept generation. The outcomes of these studies can then be used as evidence for formally making the design family decisions for the SPP concept – enabling convergence towards a point design.

4.1. Decision calendar

Having focused on making decisions construct a design family, this decision making process could be extended as a means of progressively developing the design. While these decisions are likely to be made against a backdrop of high uncertainty, a lack of detail and many assumptions a decision still can be made. The key is to document the context that these decisions have been made against, so it is possible to return to the decision in the future. Making these decisions provides focus and progress of the design work, however iteration and change must be expected. By identifying and capturing these decisions this change can be more efficient and effective. A decision calendar has been developed to identify further decisions that should be made progressively as the design is developed. These decisions gradually cascade through the plant to major systems and subsystems. This enables prioritization of work around major decisions points. The early decisions tend to be highly integrated crossing multiple system boundaries. As the design progresses and further detail is developed the decisions become contained within a single system. At each stage the decision-making process is focused on ensuring the key supporting information is captured for any decision.

4.2. Construction of a preferred concept

The preferred concept is a defined set of decisions and ranges for the basic machine parameters, chosen to achieve the objectives looking at the aggregated performance and technical risk.

Studying the trade space through the range of concepts developed it became clear that the decisions broadly fall into four distinct pillars that define the boundaries of the SPP trade space:

- Plasma Confidence
- Radial Build
- Exhaust Performance
- Power Generation & Tritium Breeding

Individually each of the decisions were considered in depth and detailed proposals have been produced which identify the preferred design decision with supporting rationale and the impacts of the decision.

In parallel, further parameter sweeps were completed to identify the ranges for major machine parameters. Against the initial decision set, these ranges provide a suitable window that will enable optimisation of the design.

It is then possible to work around the trade space pillars to define a coherent set of decisions that make up the preferred concept. Starting with the plasma confidence, and acknowledging the objective to achieve net power, we look at the heating and current drive mix. The most beneficial combination was found to be a microwave heating system using a combination of Electron Cyclotron and Electron Bernstein Wave heating systems. This provides significant development opportunities, given the impact that the heating and current drive efficiency has on net power. Further details are discussed in [11]. This decision leads to a requirement for the toroidal field to be 3.2T providing allowance for greater fusion power within the expected volume.

Acknowledging the strong link between the machine's size and cost, the next pillar to focus on is that of the radial build aiming to achieve a design that is as small as reasonable with respect to risk and development flexibility. The minimum inboard radius has the biggest influence on the design, and this in turn is influenced by the toroidal field (TF) coil conductor choice. High temperature superconductors (HTS) are chosen to minimize the parasitic load for the field required – again helping deliver on the net power objective. Based on these decisions, the inboard build minimum radius has been set to 1.6m, accepting that the uncertainty of the HTS technology will lead this size to be an ongoing challenge through the design. With this size, it is possible to have a larger central solenoid to reduce risks during the first operational phase and provide scope for possible upgrades to the TF conductor configuration. This sizing leads to a tokamak design with a major radius of 3.6m.

A major challenge for the long-term operation of a fusion powerplant is the maintenance of the complex machine, which will be primarily conducted remotely. The drive to minimize the inboard build radius leads to a limit to the life of the inner limbs of the TF coils. These must be replaced periodically over the life of the plant. While there is a considerable development risk from choosing remountable TF coils, this decision enables significant benefits. Firstly, it allows for a vertical maintenance solution to be utilised. Secondly, it eliminates some of the constraints on the poloidal field (PF) coil positions, permitting an extended leg divertor design to be used, which reduces divertor heat load.

This leads focus onto the exhaust performance. The divertor heat load is expected to be a major challenge for any spherical tokamak design, especially for the inner target, and has the potential to be the driving constraint for the minimum size of the machine. A double null (DN) design imparts a significant challenge for maintenance and design integration, as well as adds significant constraints to vertical stability control. However, with a view to the pathway for a commercial powerplant being a smaller machine with increased power output, a DN design is required. This means these challenges need to be addressed to enable the SPP to demonstrate commercial relevance. The secondary divertor configuration is focused on minimizing the heat loads at the divertor target, maximizing the benefit that can be taken from detachment of the divertor. An extended outer leg, with an x-type inner leg is being developed and is further detailed in [12]

The final pillar focuses on the power generation and tritium breeding. A key challenge for any fusion powerplant is providing fuel self-sufficiency. Tritium is a scarce and expensive resource. There are a number of configurations and options available for tritium breeding, however, to achieve the greatest possible confidence in achieving fuel self-sufficiency, a liquid lithium breeder has been chosen. Use of a slow flowing breeder with a helium gas blanket coolant reduces the challenges associated with magneto-hydrodynamic load on the liquid lithium, however this represents an area of significant challenge for development of the design, specifically associated with tritium extraction, materials compatibility and safety. To maximise the efficiency of the thermal cycle a blanket outlet temperature of 600°C is chosen. Further detail of the of the power balance can be found within [13].

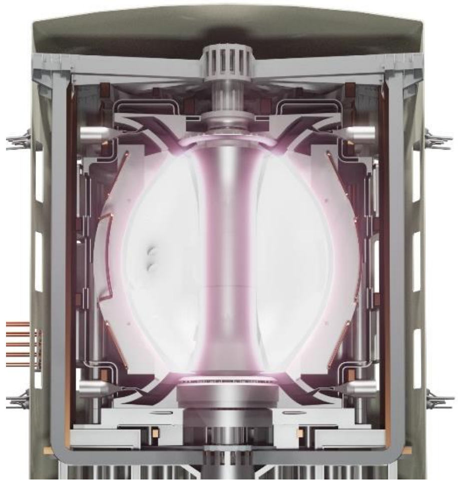

Figure 4 - SPP concept design spatial layout (CML4)

4.3. CML4 design point

Resulting from the concept exploration activities within CML3 and the decision making outlined we are able to describe a design point for the SPP. An image of the spatial design developed within CAD is shown in Figure 4 Table 1 and 2 below show the key concept parameters and design family decisions respectively.

Fusion Power	1.6 – 1.8 GW
Net electric power	100 – 200 MWe
Inboard Build	<1.6m
Major Radius	3.6m
Magnetic Field	3.2 T
Elongation	2.93
Triangularity	0.5

Table 1 - Concept parameters

Triangularity	Positive
Plasma Edge	Edge Pedestal
HCD Mix	EC + EB
Primary Divertor Configuration	Dynamic DN
Secondary Divertor Config (Inboard)	Flat Top: X Type Ramp Up: Perpendicular
Secondary Divertor Config (Outboard)	Extended Leg
TF Conductor Type	REBCO
Tokamak Morphology (Radial Build)	Plasma/Wall/Blanket/Vessel
Primary Maintenance Access Route	Vertical
Remountable Toroidal Field Coils	16 TF coils; 3 joints per TF
Maximum Inboard Radius	<1.6 m
Peak Steady State Divertor Heat Flux	<20 MW/m^2
Tritium Breeder Material	Lithium
Centre Column Coolant	H_2O
Divertor Coolant	H_2O
OB First Wall, Blanket, OB Limiter Coolant	He
Blanket Coolant Outlet Temperature	600°C
Direct or Indirect Cycle	Indirect

Table 2 - design family decisions

5. Conclusions and further work

The STEP programme has made use of the CML approach developed by NASA to enable a broad study of the trade space for the SPP. This has provided a significant amount of knowledge and understanding to enable design decisions to be made.

This in turn has led to a point design being developed and iterated, driven by the decision calendar and addressing major technical challenges.

Within this design significant technical challenges remain, especially associated with plasma uncertainty, plasma controllability and diagnostics, engineering integration, fuel self sufficiency, materials and delivering a maintainable design. The future work for STEP involves development of three key parallel workstreams. Firstly the major technical risks must be driven down, through a combination of analysis and testing, in order to verify the design assumptions, and ultimately validate the final design. Secondly the overall concept must be matured. Early sight of other issues will only come from further development of the integrated design. As the fidelity increases these issues will need to be addressed, while ensuring the integration can be maintained. Finally, as the STEP programme has chosen a site in West Burton, Nottinghamshire, some effort needs to be made to ensure the design developed can be integrated with the site.

Acknowledgments

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