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Designing for Tokamak Emergent Behaviour using a Hierarchical Systems Engineering Architecture Design Process

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Fusion reactors are complex machines in which many systems operate in concert to achieve the required behaviour. Controlled fusion is dependent on a fine balance between these systems, whose functions often overlap or conflict. A tokamak's functions can be described by simple terms like fuelling, heating, current generation or plasma stabilisation, but their technological realisation can be very complex, with different systems sharing responsibilities, interacting positively or adversely in a tightly controlled balance. Heating systems can be used to affect plasma current, divertors can contribute to plasma stability and fuelling systems can be used to help or hinder both. Tokamaks are designed on this basis because the performance required is at the very edge of known technological capabilities.

A tokamak can be viewed as a system dominated by "Weak Emergence", the definition of which is a system whose desired functions exist at a holistic abstract level, although its behaviour can in principle be reduced to its constituent parts. These systems are difficult to design because their properties cannot be easily understood in terms of the properties of their constituent parts alone, instead being dominated by dynamic interrelationships between parts during operation.

Faced with such complex interrelationships, designers can adopt a conservative approach and base their designs on minimal changes to an existing known design. This is not a viable option for the DEMO fusion power plant, which has to incorporate functions not present in research reactors, such as large-scale tritium breeding, whose enabling technologies will require periodic maintenance and renewal over their lifetime.

The Systems Engineering design process, as defined by ISO15288:2015, provides a systematic approach to the design of complex systems and their emergent behaviour. It divides the system design process into the development of a two stage, top-down hierarchy; an abstract, technologically agnostic "System Architecture"high level and a more practically oriented "System Design"lower level, with formal relationships between the two. The abstract representation allows the designer to develop and represent incremental insights obtained about the system's requirements and emergent behaviours, before progressing towards its technological realisation in the System Design. This process encourages a more pragmatic and less conservative approach to solution development and optioneering.

This paper presents examples of how the interactions of complex interrelated technological systems in the tokamak can be reinterpreted as an abstract System Architecture more closely related to the desired emergent functions. Relationships between systems at a high level are represented by services and qualitative dependencies, rather than solely the flow of materials and energy. SysML is used as the representation language, encoding each system in terms of its statement of purpose, functions and performance parameters, operating within a formally defined context.

The paper shows how the complexities of the DEMO design can be managed without resorting to design conservatism. The System Architecture will be used to manage and structure the creative processes involved in the technological choices at the System Design level, providing a framework in which novel solutions and optioneering can take place, supporting the design innovations needed to_bring_DEMO_to_fruition.

Eligible for student paper award?

No

Authors: COLEMAN, Matti (UKAEA / EUROfusion); Mr BROWN, Richard (Eurofusion); Mr ELLIS, Rob (UKAEA)

Presenter: Mr ELLIS, Rob (UKAEA)

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