Interfacing Fusion Materials Development and Component Design

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The unprecedented demands faced by fusion structures derive from severe time- and spatially varying thermo-mechanical loading of complex, large scale, and highly interconnected heat transfer-energy conversion structures. In addition to the enormous challenge of developing material systems and multifunctional structures, the fusion system designer is faced with the untenable situation that neither the fully functional materials, nor the requisite computational tools, nor experimental simulation facilities currently exist for reliable integrity and lifetime assessments of fusion reactor structures. Absence of both, material information and necessary design tools for fusion components impedes the use of standard design processes. Hence, the engineering design process has to become actively materials-related, while materials development must closely follow engineering design process needs. This results in the indispensible interaction between materials- and component design processes or a "concurrent materials-structure design" path as depicted schematically in Fig.1.

The Engineering Design Process

Under idealized conditions product-driven design is performed using materials property databases, which contain material information on functional-, structural-, and systems performance levels. Fig. 1 shows such an idealized design process flow along with corresponding material-related design activities. The product-driven design starts with a conceptual design, followed by the preliminary design, then a detailed product/engineering design, which includes fabrication criteria. The design process ends when the product is shown to satisfy integrated system performance, as well as regulatory and safety rules.

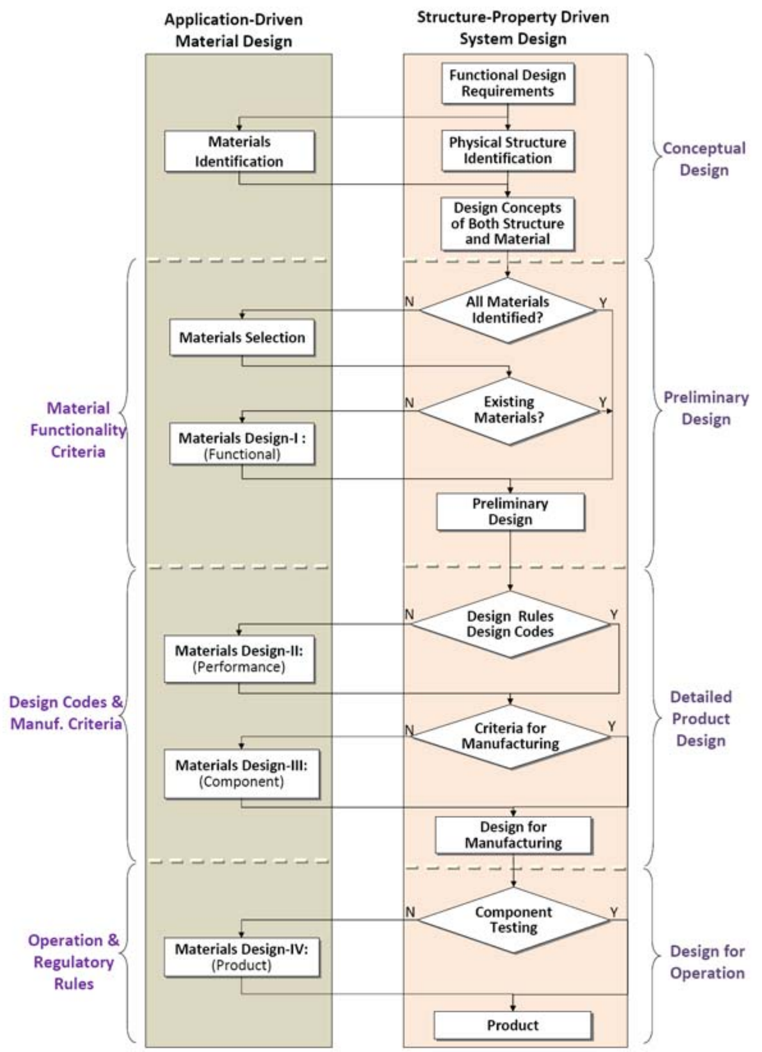

Fig. 1: Idealized process flow showing the integration of material development and design [S. Sharafat, ICFRM-13].

In the early stages of a system design process, candidate materials are identified based on their specific functionality, after which the designer will consider other requirements such as geometry and strength criteria to develop an initial design concept, which consists of both materials and structure. During the next design stage, detailed engineering, material development activities shift to developing and designing new material systems based on design requirements. When confronted with insufficient information, which is overwhelmingly the case for fusion, system design focuses on proposing new experiments that upon measurement will generate necessary information.

Material development have to be closely integrated into these design stages. The Materials Design Stage-I addresses the needs of the Preliminary Design stage, Materials Design Stage-II and III are in support of the Detailed Engineering Product Design, and Materials Design Stage-IV advances integrated System Design Requirements. Based on a specific product design stage and material needs, material development can/must involve design or development of new materials as well as testing of materials/structures.

Design Metrics for Fusion Structures

Dimensional instabilities and damage accumulation due to fatigue, creep, irradiation creep, their interactions, perhaps swelling, and fracture issues at both low and high temperatures coupled with the complexity of fusion structures that will likely never saturate, while experiencing the continuous effects of high and time/spatially varying stresses are big materials development challenges. Additionally, there are all the issues of fabrication, qualification, corrosion and mass transfer. Realistic modeling of such a structure through a life cycle including start up/shut down and abnormal transients can only be achieved following the development of extensive materials property databases, which are driven by product design needs. Loading conditions impact the material properties in fusion reactor structures, hence design and development of fusion structural materials requires knowledge of operational, both spatial and temporal loads at all stages of the design process. For example, the stress state of a component influences the response of materials to neutron damage, which affects the thermo-mechanical properties of the material. However, the stress state in the most critical fusion components cannot be established, because constitutive property equations have not been developed for corresponding fusion materials. The current state of knowledge regarding the response of materials in a fusion environment the design metrics or requirements for fusion component design cannot be adequately defined.

Material-related System Design Process for Fusion

The Conceptual Design “identifies” materials based on established functional properties, which for fusion include tritium breeding, radiation damage tolerance, thermal and mechanical properties, etc. Following the Conceptual Design, the Preliminary Design first examines whether the pool of potential materials has been adequately researched and whether the requirements on material properties can be satisfied. If a material that fulfills the functional requirements does not exists, it must be developed (Fig. 1: Material Design Stage-I). Often new materials, such as composites are developed to satisfy material property requirements at this stage. As an example for fusion, at the end of the Conceptual Design of the ARIES-I reactor study it was found that existing SiC/SiC materials do not fulfill fusion environment property requirements and consequently new systems of SiC/SiC composites (Gen. III) were developed. Other fusion Material Design Stage-I success stories include the development of Reduced Activation Ferritic Steels (RAFS), ceramic breeding materials, and refractory divertor plate materials.

During the Detailed Product/Engineering Design process phase, materials are chosen to ensure that system-level design requirements are complied with (Material Design Stage II). These design requirements, called “design metrics” are often expressed in terms of performance criteria, such as reliability, cost, efficiency, etc. The designer "matches" materials to meet design metrics/requirements first on a structural "Performance" level and then on a "Component" level. The latter is based on fabrication criteria and rules (Material Design Stage-III). At the Material Design Stage-II (structural performance-level design) the designer relies on the use of established "Design Codes" and rules to assure reliable performance of the structure, while the component level design is based on fabrication criteria and rules (Material Design Stage-III).

It is at the Materials Design Stage-II where fusion power reactor designers face a daunting predicament in that neither material property databases exist nor the requirements on material properties are well established. In other words, the designer does not have a working material pool to choose from nor does he have well defined "design metrics." Thus, at best the fusion system designer is limited to selecting materials based on a few established functional properties, without any reliable information on structural- or system-level performance. Based on this predicament the fusion power system design process is "stuck" somewhere between the end of the Preliminary Design and the start of the Detailed Product Design stage.

Concurrent Materials-Structure Design

There is an ongoing effort within the fusion community to develop a set of design rules suitable for the design of fusion reactor components with significant additions addressing some features which are expected to be more prominent in fusion reactors, relative to fission reactors. These new rules will address the following damage modes: immediate plastic collapse, immediate plastic instability, non-ductile modes, and immediate plastic flow localization, immediate local fracture due to exhaustion of ductility, fast fracture, thermal creep, ratcheting, fatigue, buckling, and irradiation effects (including irradiation-induced creep, swelling, and property changes).

The material models, structural models, and design codes must, in turn be combined with models of damage and history-dependent synergistic failure paths that are controlled by complex interactions of numerous variables, processes and properties in a fusion environment. Guided by engineering design informations, the integrated models must be informed by well-designed experiments, supported by high quality material property databases that can underpin models of the effects of long-term service, and benchmarks provided by pertinent integrated scaled component-structure level testing. Radiation induced degradation of mechanical properties is, of course a key issue, but others include corrosion-compatibility, chemical-thermal embrittlement, tritium permeation and extraction and many more.

Considering this demanding combination of requirements needed for success, fusion energy clearly presents an enormous materials-structural engineering challenge. New design and in-service performance computational tools must be developed to replace simplistic high temperature design and operational rules. These tools must ultimately be incorporated in design codes and regulatory requirements. Neither the designer nor the material developer can proceed without input from the other and the development of materials requires and becomes an integral part of system design. Thus, a "Concurrent Material-structure Design" has to replace the more common "function oriented" material design process.

Summary

Ideally, engineering design starts with first identifying and then selecting materials and if needed develop and test materials that satisfy the design metrics. Fusion design has a particular challenge in that neither the materials, nor the requisite computational tools, nor the underlying knowledge base currently exist for reliable integrity and lifetime assessments of fusion reactor structures. In addition, the fusion system designer is faced with the untenable situation of absence of fusion simulation facilities, as well as lack of fusion-relevant design rules and codes. Thus, neither the materials, nor requisite experimental setups, nor the design metrics exists to develop a comprehensive detailed fusion power reactor engineering design.

Fusion systems will have to deal with time dependent materials properties (creep, creep-fatigue, ratcheting, and high-temperature corrosion) in components with complex stress states, and long intended service lives. Routine thermo-mechanical property data and current high temperature design methodology do not provide adequate information to complete typical system design processes. Development of fusion relevant design rules necessitates close integration between materials development activities and system design processes. Thus, fusion materials development necessitates design of *material systems* *and* development of *multifunctional structures* concurrently. Thus, the commonly “function-oriented” material design process has to advance to the “Concurrent Material-structure Design” process.