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Materials and design interface

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ABSTRACT

The unprecedented demands faced by fusion structures primarily derive from severe time varying thermal-mechanical loading of complex, large scale, and highly interconnected heat transfer-energy conversion structures. This grand challenge is often much too narrowly couched in terms of the development of radiation damage resistant materials, while the enormously larger challenge is the creation of material systems and multifunctional structures. In addition, 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. Considering the absence of material information and design tools, neither the materials nor the fusion designer can follow standard design processes. The design process has to become actively materials-related while materials development must closely follow design process needs. This indispensible interaction between materials and design processes leads to a 'concurrent materials-structure design' path, which is necessary to meet the enormous materials-structural engineering challenges of fusion.

1. Introduction

An overriding issue in the development of fusion energy as a large scale energy source for the millennia, is the feasibility of designing, constructing and predictably operating reliable, safe, and long-lived first wall, blanket and divertor structures. The unprecedented demands faced by fusion structures primarily derive from severe time varying thermal-mechanical loading of complex, large scale and highly interconnected heat transfer-energy conversion structures. High stresses can result from thermal expansions and temperature gradients, as well as primary loads [1–4]. The stresses will continuously redistribute during stages of startup-shutdown, quasi steady-state operation and unplanned transients. Electromagnetic loading may also be significant, especially under fast transient conditions [5,6]. This grand challenge is often much too narrowly couched in terms of the development of radiation damage resistant materials. In reality, the enormously larger challenge is the creation of material systems and multifunctional structures that can survive and safely perform in the incredibly hostile fusion environment [7–12].

Neither the functional materials, nor the requisite computational tools, nor the underlying knowledge base currently exist for reliable integrity and lifetime assessments of fusion reactor structures. Predicting the interplay between high performance demands and eroding in-service property limits will require revolutionary advances in computational and experimental methods. 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. Absence of both, material information and necessary design tools impedes the use of standard design processes.

In this paper we outline the interrelationship between material development and the engineering design process. This document is organized as follow. A brief description of a system design process flow and fusion design metrics are presented. This is followed by characterization of the requisite materials-related engineering design process, which leads to the inevitable conclusion that fusion material development needs to go beyond strictly functional material development and advance into a 'concurrent materials-structure design' effort. We conclude with a short discussion on fusion specific design rules and codes and how they can only be addressed by following a 'concurrent materials-structural design' process.

2. The design process flow

Under idealized conditions product-driven design is performed using materials property databases, which contain material information on functional-, structural-, and systems performance levels.

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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.

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 is closely integrated into to these design stages. The Materials Design Stage-I addresses the needs of the Preliminary Design stage, Materials Design Stages-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.

3. 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 does not exist that fulfills the functional requirements 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. Similarly for fusion, at the end of the Conceptual Design of

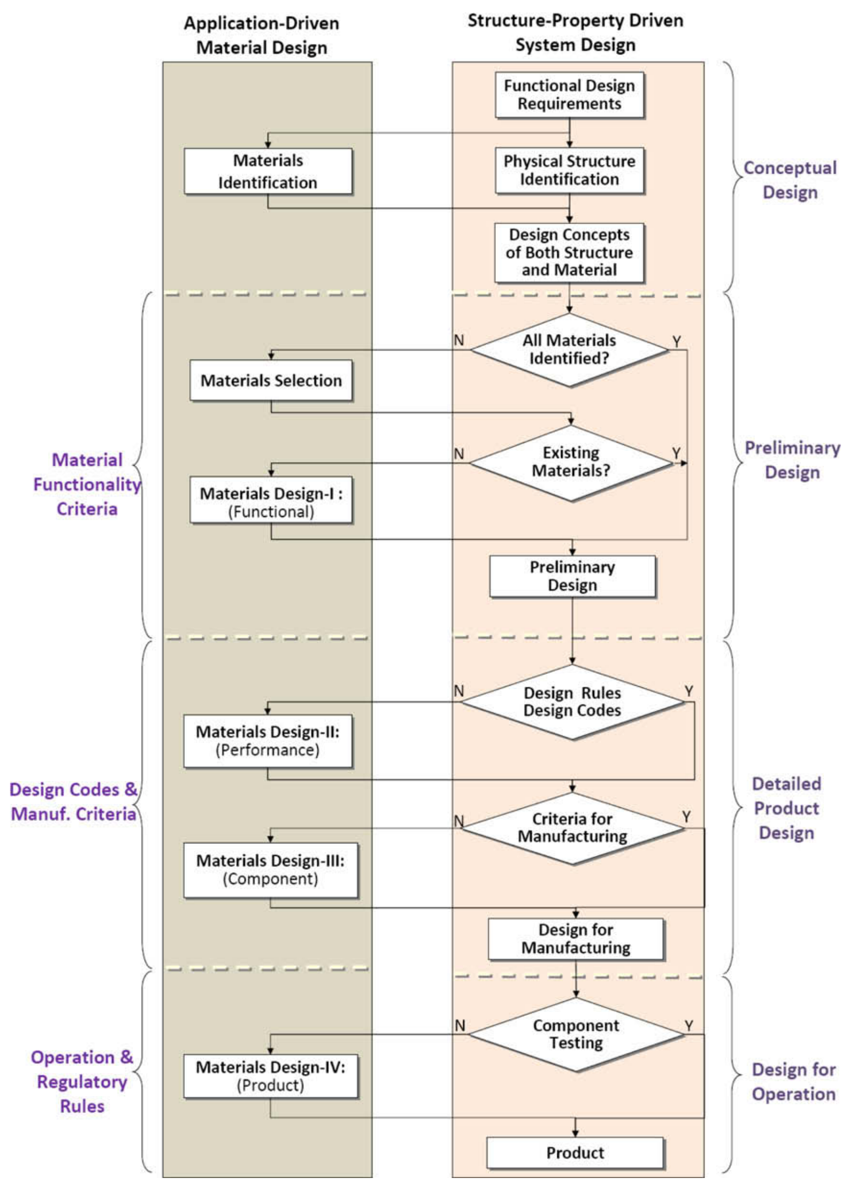

Fig. 1. Idealized process flow showing the integration between material- and design.

the ARIES-I reactor study [13] it was established that existing SiC/SiC materials do not fulfill fusion environment property requirements and consequently new systems of SiC/SiC composites (Gen. III) were developed [14]. Other fusion Material Design Stage-I success stories include the development of Reduced Activation Ferritic Steels (RAFS) [12], ceramic breeding materials [15], and refractory divertor plate materials [16,11].

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.

4. Design metrics for fusion structures

Dimensional instabilities and damage accumulation due to fatigue [4,17], creep, irradiation creep, their interactions [18], perhaps swelling, and fracture issues at both low and high temperatures [19] coupled with the complexity of fusion structures [20,21] that will likely never saturate, while experiencing the continuous effects of high and time/spatially varying stresses are really big materials development challenges. Additionally, there are all the issues of fabrication, qualification, corrosion and mass transfer, in service. 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. In summary, with 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.

5. Concurrent materials-structure design

Over the past decade the ITER project has focused materials design activities beyond simple functional requirements (Stage-I; Fig. 1) and advanced towards Materials Design Stage-II activities (structural performance level). No longer is material functionality the sole criteria of development, but satisfying newly updated design rules for fusion has become a primary goal for the ITER material development community [22]. The design codes comprise a set of rules that permit the designer to choose materials and geometric parameters to ensure that a structure will survive the prescribed loads for the desired life of the component. In the absence of adequate testing facilities, such as is the case for fusion reactors, design rules are the critical meter by which component failure or success can be estimated.

Use of Design Codes, such as the US ASME PV (Pressure Vessel) Boiler Codes or the French (EU) design and construction rules for nuclear components (RCC-MR) begins with an identification of the service limits relevant to a particular component, classifying the stresses in the component according to whether or not they are self-limiting, and compares these stresses to allowable stresses, depending on the material, temperature, etc. If the rules are satisfied, then the designer is assured that the operation of the component will be safe. In the absence of material property data, the designer may start with an existing design rule set – even if it has minimal information support – and extend these to new rules suggestive of improved performance. Unfortunately, in simplifying this process, the Codes introduce conservatism and lead to excessive design margins. It also does not explicitly treat high temperature materials or address microstructure in any way, both of which are critical in fusion environments.

There is an ongoing effort within the fusion community to create a set of design rules [23,24] suitable for the design of ITER. The ITER Structural Design Criteria (ISDC) are based on the ASME and RCC-MR (French) rules, with significant additions addressing some features which are expected to be more prominent in fusion reactors, relative to fission reactors. These new rules 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).

In summary, 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. 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 [25,26]. Considering this demanding combination of requirements needed for success, fusion energy clearly presents an enormous materials-structural engineering challenge. 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.

6. Summary and conclusions

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 conduct a comprehensive fusion power reactor design process.

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, long intended service lives and severe operating environments. Routine thermo-mechanical properties 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 with system design processes. Thus, fusion materials development has to be redirected towards designing *material systems and* developing *multifunctional structures* concurrently.

Development and design of fusion materials requires becoming an integral part of the system design process, and the commonly 'function-oriented' material design process has to advance to the 'concurrent material-structure design' process.

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