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The materials-design interface for fusion power core components

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Executive Summary

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What is the "materials design interface" and why is it important?

Research on individual material properties, informed by conceptual design studies, is not sufficient to resolve the fundamental issues of survivability and performance of in-vessel components, which is absolutely required in order for fusion to be useful as an energy source. The mechanical behavior of components in the fusion environment is highly complex and design-dependent, requiring research into the critical design-dependent phenomena that might lead to failure. The research area that we describe as "the materials-design interface" requires strongly coupled investigations of the mechanical behavior of materials within a design context.

This topic is critical for the success of fusion as an energy source.

In-vessel components must survive a challenging, unique and unexplored environment involving extreme conditions of heat flux, plasma particle flux, radiation fields (high-energy neutrons and gamma rays), strong magnetic fields and the ubiquitous presence of hydrogen. They must satisfy a set of requirements to fulfill their own functions as well as overall plant requirements. Because failures can have catastrophic consequences on plant operations, and overall plant availability must be high, high confidence in the reliability of components is needed. Given our current understanding of how to produce and sustain burning plasmas, the primary remaining challenge is how to extract the energy in a way that is commercially and environmentally acceptable. Without structural materials that can function reliably in real components, and not only as small test specimens, fusion energy will not be realized as a viable power source.

This area has been neglected in the past, leading to a very low level of maturity.

The amount of past research in this area has been small within the US, and much of the work is not relevant to next-step nuclear devices or Demo. Large gaps in knowledge remain. Related efforts on the mechanical behavior of components have been performed within the ITER project, which has advanced the state-of-the-art in methods for fusion component "design by analysis", design rules and component validation. However, the requirements, designs and materials for ITER are all very different from those of a fusion power plant. ITER has no breeding requirement (which impacts design choices and design details), operates at low temperature, and will experience very low neutron dose. The materials chosen for ITER could not be used in a power plant. Furthermore, our involvement in ITER has declined: for example, the US has chosen not to participate in the fabrication of first wall modules or the divertor, and our connection with the first wall design ended in 2013.

Research must expand immediately for FNSF and Demo to succeed in this century.

The time required to build and operate experiments, generate data, develop design rules, and prepare for qualification of nuclear components can be measured in decades rather than years. Starting from the current state of neglect, a rapid increase in funding in this area of R&D will be needed to meet the timelines under discussion for FNSF and Demo, as noted in the recently completed "FESAC Report on Strategic Planning: Priorities Assessment And Budget Scenarios".

In addition, being such a crucial aspect of in-vessel component behavior, results from this program should be used in overall fusion program planning and design selection. Without strong input from the materials-design interface, the basis for decision-making will be incomplete.

Needed research includes modeling, design rules, fabrication techniques and experiments.

At present, neither functional materials, nor the requisite computational tools, nor the underlying knowledge base currently exist for reliable integrity and lifetime assessments of fusion in-vessel structures. 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.

The greatest challenge is a lack of understanding with respect to material behavior. A few examples of this limited understanding include failure mechanisms in tungsten alloys, radiation damage effects on mechanical properties in the presence of fusion-relevant helium concentrations, surface morphology of plasma-facing structures and their effects, effects of synergistic radiation and thermomechanical damage on first wall and blanket components, and models of ferromagnetic materials, especially in the presence of transient magnetic fields.

In addition to these deficiencies, there is only limited understanding of macroscopic failure mechanisms, especially in the harsh environment experienced by a fusion component. For example, the damage due to the interaction of creep and fatigue is difficult to model under normal conditions, but adding radiation damage, helium, *etc*. increases the uncertainty dramatically. Similarly, the dual nature of brittleness and ductility in tungsten is not well understood, especially in plasma and neutron environments, because it has not typically been used as a structural material. It is possible to make some progress on enhanced understanding of these phenomena using coupon tests, but it is impossible to properly address failure mechanisms without comprehensive structural models, which include coolant pressure, coolant chemistry, static thermal gradients, thermal transients, and radiation damage. Hence, a multi-disciplinary, multi-scale effort is needed to comprehensively address the materials-design interface and permit substantial progress towards the design of high performance, optimized components.

This program can begin to make progress at a modest funding level.

The resources needed to fully develop, test and qualify fusion in-vessel components will be large. However, significant progress can be made to establish the scientific foundations for this field and provide a credible path forward, to FNSF and beyond, with levels of funding that could be obtained within the current OFES budget. A coordinated program involving participation from universities, laboratories and industry, as well as international collaborations, provides the most effective path forward. We estimate that funding of the order of $2M per year for several years would be sufficient to lay the groundwork.

In order to develop expertise required to advance this area, active outreach (beyond the current set of contributors to OFES-sponsored programs), planning workshops and programs to support student training should be an integral part of the near-term program. All of these efforts will require financial resources. At the end of the first phase of this activity, we would be in a better position to evaluate the required tools and experiments to establish the feasibility and lifetime of in-vessel components and to determine the funding and research requirements for the next phase of research toward qualification of FNSF components.

The Materials-Design Interface for Fusion Power Core Components

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1. Introduction

1.1 Problem statement

The anticipated operating environment of components in a fusion power plant involves extreme conditions of heat flux, plasma particle flux, magnetic fields and radiation fields (*e.g.* high-energy neutrons). Hydrogen, including radioactive tritium, will permeate all structures. Loading conditions may include strong transients under both normal and off-normal conditions, as well as warm and cold shutdown for maintenance. Survival within this environment will be challenging.

But survival of in-vessel components alone is not sufficient. They must satisfy a set of requirements to fulfill their own functions as well as overall plant requirements. For example, they must operate at elevated temperatures in order to generate electricity. They must not contain isotopes that would lead to unacceptable safety risks or waste disposal burdens. Because failures can have catastrophic consequences on plant operations, and overall plant availability must be high, extremely high confidence in the reliability of components is needed.

Requirements for a practical and attractive energy source are well known, following many years of integrated conceptual design studies. What is **not known** is whether any of our existing design concepts can meet these requirements. If we cannot establish acceptable solutions, then fusion will never fulfill its promise as a source of energy for mankind.

Since the early days of fusion research, it was clear that new materials would be needed to survive the fusion environment and meet the operating and safety requirements. Large materials research programs have been carried out worldwide, leading to the identification and characterization of a small number of candidate structural materials. Most notable among these are ferritic/martensitic steels, tungsten alloys and SiC/SiC composites. Even after many years of research and development, there are still gaps in our knowledge of basic materials behavior, especially under neutron irradiation, and uncertainties still remain in the choice of materials for certain components (such as divertors). Advanced materials still under development, such as nano-structured alloys, offer potential advantages; *materials research remains an important activity that should continue*.

However, research on individual material properties, informed by conceptual design studies, is not sufficient to answer the fundamental questions of survivability and performance of in-vessel components, which is absolutely required in order for fusion to be useful as an energy source. The mechanical behavior of components in the fusion environment is highly complex and highly design-dependent, requiring research into the critical design-dependent phenomena that might lead to failure. This we call the "materials-design interface".

Properties are almost always strongly dependent on the time-dependent history of temperature and stress in the component. These are adjustable parameters. Solutions often can be found if basic materials properties are used to determine mechanical behavior, which then can be used to modify designs in order to alleviate problems. Success depends upon tight coupling of materials properties, mechanical behavior and component design.

One good example of this interface relates to failure resulting from fracture, both brittle and ductile. Some of the materials under consideration for fusion exhibit relatively low unirradiated ductility, which can become even worse under the influence of neutron irradiation. Both ferritic steels and tungsten alloys suffer from this problem. Measurements of the Ductile-to-Brittle Transition Temperature (DBTT), fracture toughness, uniform elongation, and reduction in area alone will not establish the feasibility of component survival. The phenomena of crack nucleation and growth depend strongly on design details and operating conditions, which are not fixed *a priori*. Since components will operate at high-temperatures, creep and creep-fatigue interactions during operational cycles will result in stress re-distributions from cycle-to-cycle, rendering it difficult to predict fracture behavior from simple small sample tests.

Such efforts on the mechanical behavior of components have been performed within the ITER project. ITER has advanced the state-of-the-art in methods for fusion component "design by analysis", design rules and component validation. However, the requirements, designs and materials for ITER are all very different from those of a fusion power plant. ITER has no breeding requirement (which impacts design choices and design details), operates at low temperature and will experience very low neutron dose. The materials chosen for ITER could not be used in a power plant. We urgently need to initiate a similar activity specific to the designs and materials we expect will be used in technology development facilities as well as future power plants.

With ITER now entering the construction phase, and expected to demonstrate successful control of a burning plasma, increasing attention is being given to the next steps on the road to a practical fusion energy source. Throughout the world, the next step is universally believed to involve a higher fluence device with features and materials that are more relevant to a commercial power plant. In the United States, the next-step machine under consideration is called "FNSF" (Fusion Nuclear Science Facility). The detailed mission of FNSF is yet to be established, but all of the options under consideration require reactor-relevant materials operating under reactor-relevant conditions, with device requirements on reliability, performance, safety and environment. Our current guidance on the timing of FNSF is very ambitious, perhaps to be built and operated during a period of time overlapping ITER.

Expanded effort on the materials-design interface is urgently needed. The time required to build and operate experiments, generate data, develop design rules, and prepare for qualification of nuclear components can be measured in decades rather than years. Starting from the current state of neglect, a rapid increase in funding will be needed to meet the timelines under discussion for FNSF and Demo. In addition, being such a crucial aspect of in-vessel component behavior, results from this program should be used in overall program planning and design selection. Without a strong input from the materials-design interface, the basis for decision-making will be incomplete.

1.2 Scope and assumptions

The core of a fusion power plant is highly complex, using many materials for a variety of functions. For the purpose of this white paper, we chose to focus our attention on the structural elements of the blanket (which includes the plasma-facing first wall) and divertor systems that contain coolant under high pressure. These are the most stressed components that are exposed to the highest heat and particle fluxes, and are the most likely to fail inside the vessel with catastrophic consequences to the plant. We do not specifically consider inertial fusion chambers, although many of issues, materials and operating conditions are shared in common. The main candidate structural materials include conventional low-activation ferritic martensitic steels, advanced steels (such as oxide dispersion strengthened and nano-structured variants), SiC/SiC composites and tungsten alloys. Each class of materials contains variations in composition, and may additionally depend on the precise fabrication steps. Results of work on the materials-design interface may lead to recommendations on changes to materials as well as recommendations on new measurements that are required for further component development.

Environmental conditions within fusion blanket and divertor structures include high temperature, high stresses, radiation fields (including transmutation of elements), and chemical interactions (*e.g.* with the coolant and ever-present hydrogen isotopes). These must all be considered in component design and research. Plasma interactions are usually confined to armor attached in some way to the surface. For our purposes, we consider the influence of armor on component behavior, but do not specifically address the impact of plasma-material interactions on the mechanical behavior of the armor or substrate.

Important in any R&D effort is a clear articulation of the goals of the program. In the US, the Department of Energy funds research to establish the scientific foundations of fusion energy. The long-term goal is a power-producing facility (a commercial power plant or a "pre-commercial" demonstration power plant), but no such facility is explicitly included as part of the research portfolio. The final facility to be constructed and operated by DOE is FNSF. That facility must be qualified for operation, and to be successful it must meet its goals to demonstrate the nuclear science and technology foundations for an attractive power plant. These aspects of FNSF – qualification and construction of the facility, as well as successful testing of nuclear components – will be used to establish the quantitative goals of our program. Close cooperation between the materials, design, and materials-design interface communities together with the FNSF project team will be essential to maintain consistency.

1.3 Program needs

The materials-design interface currently has no home within the DOE management structure, and no established constituency group. Relevant work has been carried out in an *ad hoc* fashion within the design studies program and the materials program, but this topic is not a priority for either program. Efforts on the mechanical behavior of components have been performed within the ITER project, which has advanced the state-of-the-art in methods for fusion component "design by analysis", design rules and component validation. However, the requirements, designs and materials for ITER are all very different from those of a fusion power plant. The amount of reactor-relevant research in this area has been small, leading to a very low TRL level. Large gaps in knowledge exist not only for power plants, but more importantly for next-step nuclear machines like FNSF. The credibility of any FNSF design certainly depends on the credibility of its nuclear components.

The Office of Fusion Energy Sciences should support this area in order to establish its scientific underpinnings and prepare for a nuclear test facility such as FNSF. Research should be well coordinated with existing programs, especially the materials and design studies programs. Modeling is an important and high-leverage activity to pursue, but progress ultimately will depend on a full spectrum of research activities including multi-scale modeling, manufacturing research, experiments, code verification, establishment of design rules and design improvement. Because these activities span a range of studies from fundamental to applied, the most effective program would involve participation from universities, national laboratories and private industry. Opportunities for international collaboration exist, and should be effectively integrated into the program.

The resources needed to fully develop, test and qualify fusion in-vessel components will be large. However, significant progress can be made to establish the scientific foundations for this field and provide a credible path forward, to FNSF and beyond, with levels of funding that could be obtained within the current OFES budget. A phased program is advisable given the small current level of effort and the large growth that will be needed for successful development and qualification of components. We estimate that funding of the order of $2M per year for several years would be sufficient to lay the groundwork in Phase I. At the end of the first phase of this activity, we would be in a better position to evaluate the feasibility and lifetime of in-vessel components and to determine the funding and research requirements for the next phase of research toward qualification of FNSF components. Additionally, stable funding at several universities during the first phase will allow training of a new generation of fusion scientists that will be needed to carry this effort forward into the future.

1.4 Content overview

The remainder of this document consists of 3 main parts. (1) In Section 2 we review past studies in the US and abroad in the areas of conceptual design, materials research, component design and testing, and the materials-design interface. (2) Section 3 contains the main body of this white paper. There, we describe the research needs in 4 sub-areas: modeling, design rules, fabrication and experiments. (3) In Section 4 we address a set of programmatic issues related to the practical implementation of a program on the materials-design interface. We explain how this activity relates to other existing activities funded by OFES, possible international collaborations with institutions engaged in similar studies, and mechanisms to involve industry in the development of fusion components.

2. Background

In this section we provide a brief review of past efforts related to the materials-design interface and an assessment of the current status in four areas:

(1) Integrated conceptual design studies have been performed for many years, covering a wide range of plasma confinement concepts and technology options. The most urgent needs today are to focus efforts on reference and backup concepts, to expand the level of engineering detail in designs, and to use R&D results to improve and validate designs.

(2) Materials research has played a major role in fusion programs from the earliest days, and currently represents the largest funded activity on fusion power plant technology within the US. However, without a strong complementary program on component R&D, progress is

impeded by a lack of guidance on specific materials, operating conditions and properties that are required.

(3) Plasma-facing component R&D has been performed by US institutions in the past, most notably for confinement experiments such as JET, Tore Supra, Alcator and ASDEX. Unfortunately, the technology used in experiments has little relevance to actively cooled PFCs for a Demo or FNSF. The US has chosen not to participate in the fabrication of first wall modules or the divertor for ITER, which leaves us dependent upon foreign research programs.

(4) Efforts on the materials-design interface currently take place within the US at only a very low level, funded as a subelement of the OFES structural materials program mainly at UCLA [1]. *Ad hoc* efforts have been carried out over the years within the design studies program, but the ARIES program was terminated in 2013. Neither the functional materials, nor the requisite computational tools, nor the underlying knowledge base currently exist for reliable integrity and lifetime assessments of in-vessel structures. A substantial increase in effort will be required in order to prepare for FNSF and to resolve one of the most challenging and neglected problems for commercial fusion energy.

2.1 Past efforts on integrated design studies

Several alternative design concepts are being pursued worldwide for the blanket and divertor in fusion Demo and power plant applications. In this section we summarize some of the current leading concepts from the US and Europe, followed by a brief description of the ITER base blanket and divertor for contrast and comparison.

US Studies

In the US, power plant design studies have been conceptual in nature and usually short in duration (1-3 years), with limited continuity from one study to the next. Conceptual designs can provide broad guidance to R&D programs, but the level of detail in R&D specifications can be only as great as the level of detail in the designs. Issues are highly design dependent, and so changes in design details can lead to large changes in R&D needs. R&D programs can not respond to rapid changes in design and, in any case, the emphasis for the past 20 years in R&D programs has been on fundamental rather than design-dependent issues. In conjunction with increasing effort on design-dependent component R&D, it will become important as part of the proposed activity to establish reference design concepts, provide continuity in the evolution of these concepts and add details to their specific design features.

During the past 20 years, nearly all of the effort on integrated conceptual design has been carried out under the ARIES program. The ARIES team carried out studies of several different magnetic confinement configurations for electric power plants in the range of 1 GW net electric output. These include a stellarator (ARIES-CS), low aspect-ratio tokamak (ARIES-ST), and several moderate aspect ratio tokamaks (A=4) covering a wide range of design space (ARIES-AT and ARIES-ACT). In those designs, PbLi became the preferred breeder. Both self-cooled and dual cooled (PbLi and He) blanket designs were explored using either ferritic steel or SiC composite structures. Divertor designs were developed using PbLi in SiC (at lower heat flux levels) or helium-cooled tungsten alloy. Extensive documentation on blanket and divertor designs is available [2-5].

The level of detail in the design of blankets and divertors has steadily increased over the years, as computational tools for design and analysis have improved and prices for high performance workstations have declined. It is not uncommon nowadays for analysts to perform full 3-dimensional analysis, in some cases including nonlinear material properties, of full components. For example, Figure 1 shows the results of analysis in four different areas of the recent ARIES-ACT study:

(1) Inelastic response of a divertor transition joint, including braze material
(2) Crack analysis in the helium-cooled tungsten plate divertor
(3) Finger divertor thermofluid analysis
(4) Vacuum vessel thermal and stress analysis.

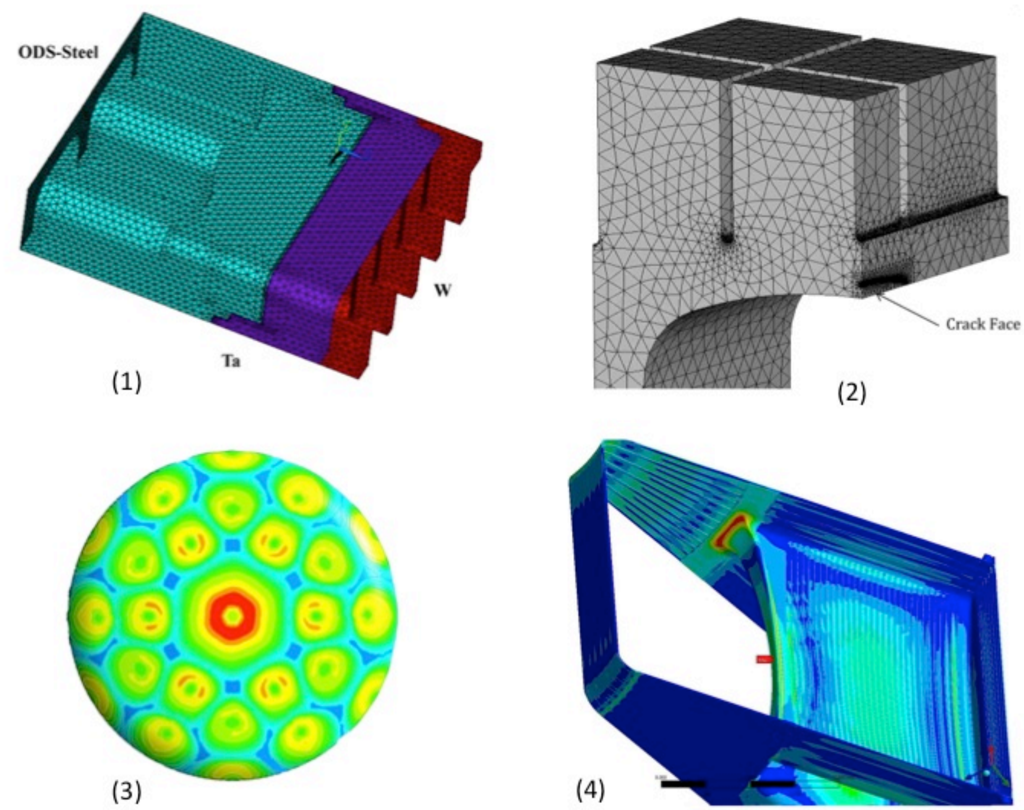

Figure 1. Examples of 3D analysis of the ARIES-ACT divertor and vacuum vessel: (1) yield, creep and ratcheting in the divertor transition joint, (2) fracture analysis in the He-W divertor, (3) heat transfer and fluid flow in the finger divertor with multiple impinging jets, and (4) elastic analysis of a full vacuum vessel sector in 3D including individual ribs between face sheets.

European designs for a fusion power plant and Demo

For many years the EU has considered several alternative concepts for a power plant blanket. The PPCS study, completed in 2005, considered four combinations of coolant and breeder (called "Models") [6]. The original blanket concepts in the PPCS were:

Model A: water-cooled PbLi
Model B: helium-cooled ceramic breeder blanket
Model C: dual coolant PbLi blanket
Model D: self-cooled PbLi blanket

Later on, a Model AB was added with a helium-cooled PbLi blanket. The EU is continuing to evaluate these blanket options within their Demo project, with the exception of Model D [7]. As a result of their long-term commitment to the evolution of these mainline designs and substantial R&D programs, the level of detail is far greater than US studies.

Although much work has been done in Europe to demonstrate helium cooling of divertor target plates with surface heat flux of 10 MW/m^2 or higher [7], only water is being considered at present in the EU divertor within the framework of their near-term DEMO study [8]. That divertor design is likely to be derived from ITER, using copper as a heat sink and Eurofer97 for the supporting structures.

ITER

ITER is a tokamak experiment under construction that is expected to demonstrate the creation and control of burning plasma in the tokamak configuration. Many of the technologies required for a tokamak power plant, such as superconducting magnet systems and tritium fueling systems will be demonstrated at power plant relevant scale. The base blanket does not breed tritium and does not operate at a temperature capable of generating electricity. Small ports allow in-vessel testing of more reactor-relevant technologies for blankets. The total accumulated neutron fluence will be much lower than required in a power plant. The lower fluence and reduced requirements on the base blanket enable the use of more established technology choices.

Water has been selected as the coolant for all in-vessel components of ITER. The blanket and divertor operate normally with inlet water temperature of 70˚C and 4 MPa pressure. The outlet temperature is typically ~50˚C higher than the inlet.

The structural material for all in-vessel components is 316L(N) austenitic steel. This steel is in direct contact with the water coolant within the blanket, whereas a copper alloy is used for the heat sink in the divertor target plates. Both 316SS and copper alloy are compatible with the use of low temperature water coolant in ITER. However, at the higher required operating temperature and higher fluence of a power plant, both of these materials are expected to suffer from severe property degradation. In order to use water in a power plant, either alternative materials must be utilized or the performance and safety requirements of the device must be reduced.

The water coolant in the ITER divertor flows in specially designed small cooling channels (the “hypervapotron” concept), allowing steady state heat fluxes up to ~ 10 MW/m^2 at the target surface. The maximum copper temperature is typically < 500˚C, and the maximum temperature of the tungsten tiles remains below 2000˚C at the location of the peak surface heat flux. There are different options for the attachment of the W-tiles to the Cu-alloy heat sink, including flat tiles brazed to the heat sink and a brush-like concept where small tungsten pins are embedded into a cast Cu plate. Such target plates have been successfully tested with pulsed heat fluxes up to ~20 MW/m^2. However, all these tests were performed without any neutron irradiation impact. The excellent performance relies heavily on the very high ductility of the Cu-alloy, which will be lost under power plant relevant neutron exposure.

The ITER blanket and divertor have undergone extensive design and analysis, R&D have been performed and prototypes have been constructed. The design has been guided by detailed structural design criteria [9]. It serves as a good example of the type of program that will be needed in order to develop and establish design concepts for power plants. Unfortunately, little of the ITER experience beyond their methodology will be applicable to power plant blankets and divertors. ITER's choice of materials and designs would not be viable for a power plant for several reasons: the requirements are different (for example the need for breeding and high temperature operation), the loading conditions are different (in some cases, such as pulsing, perhaps less severe in a power plant), and the neutron fluence is very different. The higher neutron exposure in a power plant rules out many of ITER's materials due to both radiation damage and waste disposal considerations. As a result of these differences, very little of the results obtained from ITER's extensive R&D program will be applicable to a power plant.

2.2 Past efforts funded by the materials program

One of the blanket concepts considered by the US Fusion Nuclear Science and Technology program is the Dual Coolant Lead Lithium (DCLL) concept as a potential Test Blanket Module (TBM) for ITER. The DCLL concept has the potential to be a high-performance Demo blanket with a projected thermal conversion efficiency of >40%. Reduced activation ferritic/martensitic (RAF/M) steel is the structural material, helium is used to cool the first wall and blanket structure, and the self-cooled Pb-17Li breeder is circulated for power conversion and tritium extraction. The DCLL TBM has undergone major design changes since 2005. Although TBMs are not classified as safety important ITER components, they must fulfill all required ITER codes and standards for reliable and safe operation of ITER. Therefore, as an in-vessel component the TBM must follow the ITER SDC-IC design rules (SDC-IC: Structural Design Criteria - In-vessel Components [9]). The ITER structural design criteria (SDC-IC) were developed collaboratively by the ITER home teams adopting many of the rules of national codes (*e.g.,* the ASME Code [10] and RCC-MR [11]).

A detailed thermo-structural analysis of the DCLL TBM was performed and high- and low-temperature SDC-IC design rules were applied to ascertain the DCLL anticipated performance under ITER normal operating conditions. We present here a summary of the most recent thermo-mechanical analysis of the newly revised DCLL TBM. The analysis described here is aiming to verify the thermo-mechanical response of the DCLL TBM under relevant normal operating conditions as well as during a loss of coolant accident (LOCA).

A full 3-dimensional solid model of the entire DCLL TBM structure was developed, which included FW, top and bottom lids, internal supporting ribs, manifolds, plena, and flexible frame-attachment supports. A coupled thermo-mechanical analysis was performed for both normal- and off-normal operating conditions. Thermal loads included surface heat load, volumetric heating, as well as detailed position- and location dependent heat transfer along all coolant channels. Structural loads incorporated helium coolant pressure loads, self-weight, as well as the weight of the PbLi. Maximum structure

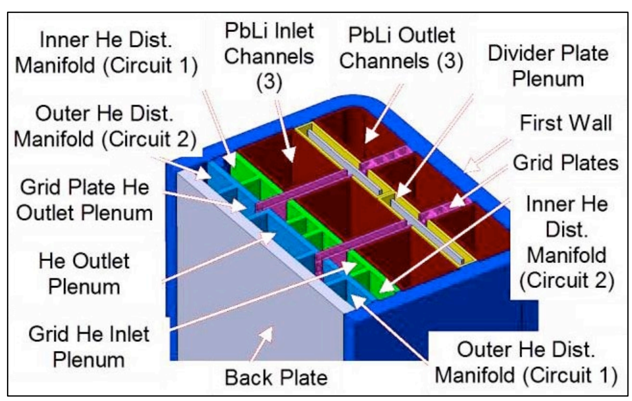

Figure 2: DCLL TBM assembly mid-plane section view

temperatures of nearly 560°C along with a maximum resultant net displacement of more than 10 mm were mapped for normal operating conditions and a number of stress concentration locations were identified. The basic structure is shown in Fig. 2.

The general approach used to perform this thermo-mechanical finite element analysis (FEA) includes several steps:

1) Pre-process the TBM solid model.
2) Generate necessary data tables and ANSYS scripts.
3) Mesh model, and apply loads and boundary conditions (BCs).
4) Perform thermal analysis.
5) Perform elastic structural analysis with and without thermal effects.
6) Apply the ITER design rules for in-vessle components (SDC-IC rules) to FEA results. Solid modeling operations were performed using the SolidWorks CAD software by Dassault Systèmes.

All analysis tasks were performed using ANSYS Mechanical APDL (ANSYS Classic) FEA software by ANSYS, Inc. Thermo-mechanical loading included spatially dependent volumetric heating, internal helium pressure (8 MPa), PbLi pressure (2 MPa + gravitational effect), structural fixtures (flexible joints), and structural gravitational loads (including PbLi). The surface of the first wall receives a heat flux of 0.5 MW/m^2 in the radial direction (normal to its main, flat surface). The flat first wall surface receives the full magnitude of the heat flux, while the curved surfaces receive lower amounts of heat proportionally to the cosine of the angle of incidence. A static thermal analysis is performed to obtain the temperature distribution within the TBM structure. The TBM model is imported into ANSYS and meshed using ~2.82 million elements. A section view of the meshed model is shown in Fig. 3.

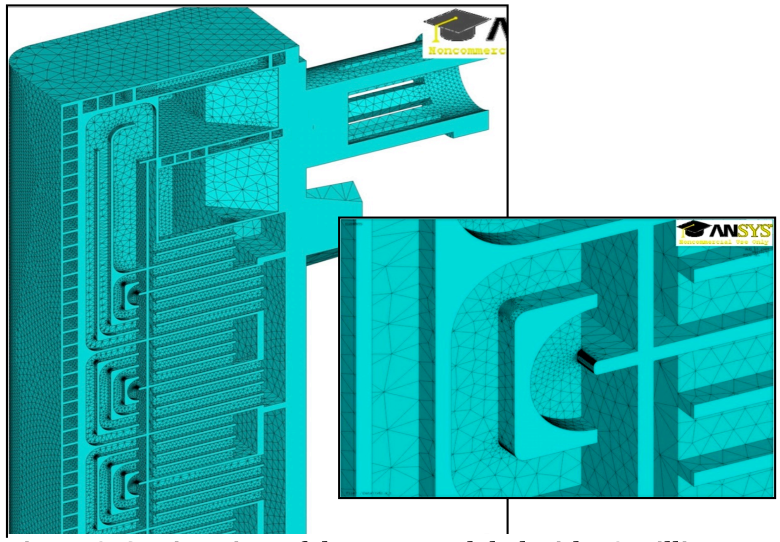

Figure 3: Section view of the TBM modeled with ~3 million elements.

Thermal loads and BCs applied on the FEA model include the first wall surface heat flux, convective BCs, and volumetric heating. The internal geometry of the TBM contains numerous channels through which He and PbLi flow, effectively cooling the structure. For the thermal analysis, this contribution is modeled as heat convection boundary conditions using prescribed heat transfer coefficients and bulk temperatures which vary spatially based on knowledge of the cooling behavior of the flow. The results of this approximate thermal analysis are shown in Figure 4.

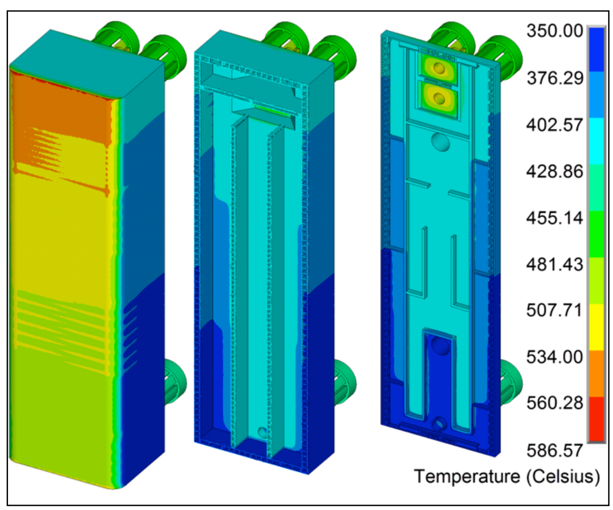

Figure 4: Temperature distributions in the TBM

Structural analysis results are shown in Figure 5. A maximum displacement of 5.224 mm was found in the top and bottom first wall lips. Although the maximum calculated Von Mises stress is in the range of 2.23 GPa, further investigation revealed that these values are a result of geometric discontinuities. It was clear that an inelastic analysis is needed, and that stresses will redistribute close to discontinuities. The Von Mises stress in the majority of the TBM was found to be around 250 MPa. Although the effort of developing a reliable data base for constitutive properties, thermal analysis, and coupled elastic structural analysis have been substantial, it revealed several deficiencies of the approach. It was clear that the following steps are needed:

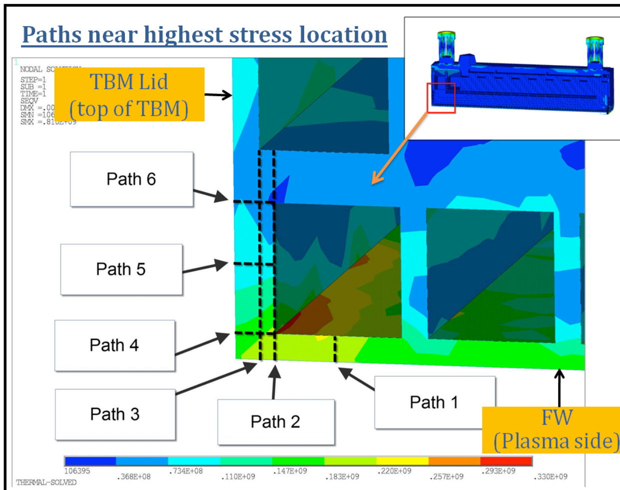

Figure 5: Von Mises stress distribution in a section of the TBM.

(a) Perform transient analysis with the inclusion of disruption loads.

(b) Redesign and optimization around discontinuities by adding fillets and rounds to redistribute high stresses.

(c) Couple fluid flow, CFD-based temperature, pressure, and heat transfer rates with thermal and structural analysis.

(d) Perform elastic-viscoplastic structural analysis (which would include creep, fatigue, and creep-fatigue) to understand how stress is re-distributed around geometric discontinuities.

(e) Perform fracture mechanics and reliability assessments on critical locations, where cracks are likely to nucleate and grow.

(f) Perform design optimization that can lead to the best geometry with the longest life.

2.3 Historical Perspective on PFC Development

In this section we summarize some specifics of what has been and is being done in regard to development of PFCs and comment on the relevance of this experience in implementing a pathway for developing Demo-relevant PFCs[1]. To begin let us clarify what we include in the scope of PFC development.

Demo relevance for the PFCs in a successful FNSF means use of a Demo relevant coolant and operating temperature for at least some of the PFCs that confirms adequate projected performance for a Demo. Helium (or perhaps CO_2) is the most likely coolant for the structure surrounding the plasma. Flowing lithium or another liquid metal or salt might also be possible alternatives, but the engineering of all concepts remains to be proven.

[1] We recognize the current dilemma in the program. The US and world fusion programs direct large resources to support ITER, the first magnetic fusion device with nuclear systems and full remote maintenance of water-cooled plasma facing components (PFCs). With current budgets, this commitment has gutted much of the US domestic program. Although significant funding is not currently directed toward the development of PFCs and blankets relevant for an FNSF or DEMO, sufficient understanding of the nature and requirements of these subsystems is needed for the program to develop a credible vision for a path forward.

In the present context, we use the term "PFC" to include not only the divertor targets and the first-wall/blanket, but also other specialized plasma-facing hardware such as guards (cooled armor) for RF launchers and engineering instrumentation that are likely needed meet demands for the higher power and longer shots to accomplish more aggressive physics missions for upgrades of existing devices or for wholly new machines, such as an H or D confinement device for testing advanced divertors. For some or all of these devices, the PFCs must be actively cooled. To obtain adequate breeding of tritium in a FNSF or a Demo, the first wall and blanket must be an integral structure.

Beyond the specific use of a PFC technology, such as water-cooled limiters in Tore Supra, is a more encompassing scope that includes the modeling and planning and testing as well as the integration of this technology into the operation of the device with respect to the direct interfaces, such as plumbing and vacuum systems and diagnostics, and also the processes necessary to mount such deployments. We make this distinction because, within the FES Enabling Technology activities, we typically see only the R&D related to materials development and PFC testing, and how this information is used in design studies where publication of self-contained design with its physics basis is an objective. Much of the understanding of the details of component integration and machine interfaces is developed at the working level of the operational staffs of confinement devices and may be presented in design reviews and distilled in other working documents. ITER is providing an example of such work in progress. However the US has chosen not to participate in the fabrication of first wall modules or the divertor, and our connection with the first wall design ended in 2013.

When the US was building confinement devices, then "builders" were a part of the integrated staff at the major labs and they provided another critical perspective in how the competing design requirements were resolved in constructing a new device. But this perspective is mostly lost in the US program.

Our most extensive experience is with inertially cooled carbon systems in many devices as well as beryllium tiles in JET and high-Z metal plasma facing surfaces in C-MOD and ASDEX. This history is important for the information we have on the distribution of heat and particle loads and plasma surface interactions as far as it is relevant for the future. But there is little relevance in its technology to actively cooled PFCs for a Demo or FNSF.

Our experience supporting deployment of actively cooled PFCs is primarily from water-cooled limiters in Tore Supra, water cooling of mechanically attached tiles in LHD and the development and testing of first wall and divertor components for ITER. While these are foreign devices, US has had significant involvement through collaborations. The development of water cooled beam dumps for the JET neutral beams, including testing of hypervaportrons, and the water cooled divertor targets for W7X and additional supplemental scrape-off targets now needed are also a part of this deployed technology. While liquid surfaces may also offer a potential solution for advanced PFCs, the limited deployment of liquid metal surfaces primarily for pumping rather than cooling in fusion experiments including T-10, the Frascati tokamak and NSTX is not covered here.

In regard to the experience with deploying water cooled PFCs, the experience from Tore Supra in the practical problems of water leaks and provisions for drying and sealing the systems has been extremely valuable for ITER. The Tore Supra Team published many articles to archive this knowledge (*e.g.,* [12]) and prepared an extensive technical report.

The knowledge base from these deployments included notable failures as well as successes. The water-cooled Phase III mid-plane pump limiter had two drastic water leaks. The causes were 1) shortcomings in the logistic of the controls system that failed to recognize a “stop shot” flag until after the shot had been executed; and 2) an unforeseen failure mode in which a filament of runaway electrons pierced the leading edge coolant tube. This happened during startup before the plasma reached its typical circular shape riding on the limiter. The filament precessed in several toroidal passes down the leg of a lateral X-point that led to the limiter. [13-15]

The resulting shutdowns and vents from the leaks took time was taken from other planned experiments. And in this regard the experiments might be considered a failure. But just the opposite is true. This experience was part of the experimental path to optimize the use of water-cooled PFCs for heat removal in Tore Supra and was important for the development of the toroidal floor limiter in the CIEL rebuild of Tore Supra. The Tore Supra team has recently proposed the WEST Project, which would be a rebuild of the successful floor limiter and added coils to form an abbreviated x-point and diverted plasma with the floor replaced by an array of ITER-like tungsten armored fingers along with other tungsten armored wall surfaces.

The main point here thus far is that the deployment of PFCs typically provides new information on the operation of the plasma because the PFCs are part of a complex integrated set of systems needed to manage the plasma. The deployments take place after a vetting process in which the design and projected performance of the component are evaluated and a judgment is reached that the potential risks to the machine itself have been mitigated sufficiently to justify introduction of the new component. For example, for Tore Supra, substantial R&D that included high heat flux testing of prototypes and QA testing for braze flaws preceded the deployment of the mid-plane water cooled limiter. Sandia initiated the type of hot water testing for braze flaws [16] that was subsequently refined by the French in their SATIR facility and also by the Japanese. Similar types of high heat flux testing have been a part of the development of the divertor and first wall panels for ITER. [17]

The remarks above are about cooling with water, but helium is the likely choice for PFCs in a FNSF or Demo. The fusion program has not yet deployed any helium-cooled PFCs, and our experience is limited to design studies, high heat flux testing and modeling of heat transfer and fluid flow.

The leading effort on helium cooling for fusion PFCs is the EU program (with Russia) with helium-cooled heat sinks (HEMJ) developed initially by the Karlsruhe Institute of Technology and tested in Russia. These thumb-sized modules have radial helium flow up a central manifold and through an array of jets that impinge on a hemispherical head to which a crown of tungsten armor is brazed. The coverage of HEMJ modules is roughly $1000/m^2$ and a divertor would have of the order of 10,000 such modules. The modules have tight tolerances and require use and joining several dissimilar materials (tungsten, a tungsten based alloy and the manifold material, e.g., EUROFER, an advanced ferritic steel). And the EU is investing in materials development and testing. [17,18] Other countries, notably Korea, China and India, are bringing high heat flux testing facilities on line to develop helium cooled PFCs. The US, in contrast, has given up capability.

US helium cooled PFC targets with various innovative concepts came primarily through DOE’s SBIR program. High heat flux testing at Sandia flourished for about a decade preceding 2011and included new ideas to enhance heat transfer from surfaces and new approaches to flow in porous media. The tests also identified an important instability in which the helium flow at high temperatures and densities in a channel with a higher heat load (hot spot) tends to decrease as the helium flows preferentially to the cooler channel(s) which then exacerbates the hot spot problem. This may have significant implications for how we design the manifolds and flow of helium cooled PFCs.

The issue related to flow instability may be more important for flow through porous media than for flow jets. Among the US contributions on helium cooling is fusion's first CFD model with full fluid physics describing flow through an irregular porous medium. With regard to flow jets, preliminary 3-D CFD analyses that suggest that the current leading design for helium cooling, e.g., HEMJ, is less efficient and likely to produce higher stresses that an approach with jet flow on a much tinier scale as is used in cooling of electronics[2]. The small scale features may only be achievable with additive manufacturing. In that case the cooling technology and manufacturing method would be linked implicitly. Clearly more R&D will be needed to understand how to exploit helium cooling. However the Sandia facility has been shut down and the primary researcher in this area is no longer funded. Georgia Tech also performs both modeling and experimental work on helium cooling but cannot access the regime of high density and high temperature where Sandia observed the instabilities.

As we look toward future deployment of helium-cooled PFCs as part of the pathway toward a FNSF, we should anticipate a commitment to long pulse hot wall experiments, i.e., deployment of helium cooled PFCs over a large area of some new or upgraded confinement experiment to confirm that the removal of heat and particles at the plasma edge and the coupling of the edge with the core plasma confirms expected behavior. The introduction of any new technology into a confinement experiment represents a threat of new modes of failure. This in turn demands an adequate development program for preparation and integration of the new PFC into the experimental program of the chosen device.

Thus we should anticipate that progress toward adequate high heat flux components for applications like FNSF must be preceded by parallel progress in development of adequate materials and technology, e.g., helium-cooled plasma facing components with tungsten armor, and the preparation and deployment of materials probes, experimental modules and component prototypes that will enable hot wall experiments on one or more long pulse high power fusion experiments. Accompanying such activities will be the parallel development of adequate engineering diagnostics with which to evaluate the performance of these probes, modules, etc. both for the protection of the experimental device and for the knowledge gained about the performance of the probes, modules, etc.

Several aspects related to system integration and deployment will be important as the effort in Enabling Technology strives to supply a credible path forward toward FNSF and Demo. We also need to understand and acknowledge the differences between the past experience and the type of knowledge we will need in the future.

1. Detailed Design Integration

The initial design requirements set the coarse integrations of systems based on the size of magnets, arrangements for power launching power and fueling the plasma, etc. Detailed design integration happens at the subsystem level. The impact from competing

[2] Both are contributions by D.L. Youchison of Sandia.

constraints may drive the design but not be apparent until significant design engineering of the subsystems occurs.
ITER provides us a view of the detailed design integration and changes at the subsystem level. One of many examples is the evolution of how the first wall and its water cooling manifolds are mounted to the vacuum vessel. *Typical design studies provide a cursory coarse integration but do not get into much detail of subsystems.*

2. Design for Scalable Manufacturing

The scale of production is among many challenges in preparing components for a CTF or DEMO. The number of units, their complexity and cost will utilize industrial processes and large (for fusion) contracts will preclude the type of hand correction and fitting of individual pieces that has typically taken place for confinement devices to date.
In our experience with relatively small projects (pre-ITER), correction of individual parts by reworking and hand fitting was an acceptable practice. That will not be true for larger projects. ITER provides examples for the scale of procurements in the relatively near future, and various issues are evident. *One concern is QA for FW sectors. The procurement specs define the QA. But in a larger sense (not apparent in ITER), QA related to fabrication should be embedded in the vetting of the design, e.g. studies of failure mechanisms of PFCs and experts from industry involved at an early stage, to incorporate an understanding of the decision points in the design and fabrication that are critical for cost control as well as to establish continuity and shared responsibility.* *Another concern for ITER is the number of variants of first-wall-shield sectors and the implications for spare parts.* *Helium cooling of fusion PFCs has yet to be developed. The EU leads the world and others are building capability. Some US researchers believe additive manufacturing may be needed for PFCs. Scalability would then be less of an issue, but there is no US plan for development at present.*

3. Evolution from Day 1

In most devices to date, the PFCs have evolved. We may have to consider this in a CTF.
For example, JET had several fully deployed divertors as the power increased and eventually had beryllium walls. *Typically our design studies for a DEMO seek to clarify a mature design for which the operation is assumed to be relatively well understood. This will not be true for a CTF. And ITER has differing PFCs for the H and D and D-T phases.* *The lead time in producing and delivering the PFCs is years in advance of the time we will actually observe their extended performance. Likely results of poor performance are (a) significant limitation of plasma power and (b) a program to develop and install modified or upgraded PFCs. But such a dilemma would severely reduce the early output from the experiment and perhaps even threaten the project*

The approach we have to take in considering a FNSF is different and has been the subject of the FNSF Pathways activity (as well as in older planning activities such as the FED, INTOR and FINESSE). In the discussion above we have tried to elucidate some of the differences. We believe that the US must strengthen its effort in design integration of PFCs and blankets and that the best step in the near term is a focused activity on helium cooling with a design-to-build mindset. This will likely require testing using foreign facilities and we believe the opportunity for other parties to engage US expertise would provide a good basis for such collaboration.

2.4 Status of our understanding of the materials-design interface

The design of fusion components has advanced dramatically in the last decade. Models are capable of high spatial resolution, long time-scales, incorporation of a wide variety of materials behaviors, and consideration of a large number of failure modes. However, there is still a long way to go before we can reliably design these components. Presently, neither the functional materials, nor the requisite computational tools, nor the underlying knowledge base currently exist for reliable integrity and lifetime assessments of these structures. Predicting the interplay between high performance demands (loads) and eroding in-service property limits will require significant 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.

The greatest challenge is a lack of understanding with respect to material behavior. A few examples include:

- There is limited understanding of the failure of tungsten. Needed fracture data, especially with respect to crack growth, but also for irradiated materials, is lacking. There is also a lack of understanding of recrystallization, especially given the complex temperature history expected in plasma-facing components (assuming the occurrence of transients due to ELMS and disruptions).
- Our understanding of radiation damage in structural materials in the presence of fusion-relevant helium quantities is severely limited.
- Surface morphology of plasma-facing structures is uncertain, particularly with respect to erosion, redeposition, and the formation of features such as “whiskers” and “nanorods.”
- Comprehensive models for ferromagnetic materials in MFE devices are also lacking, especially in the presence of transient magnetic fields.

In addition to these deficiencies, there is only limited understanding of macroscopic failure mechanisms, especially in the harsh environment experienced by a fusion component. For example, the interaction of creep and fatigue is difficult to model under normal conditions, but adding radiation damage, helium, etc. increases the uncertainty dramatically. Similarly, fatigue failure and creep rupture in tungsten is not well understood because it has not typically been used as a structural material.

It is possible to make some progress on enhanced understanding of these phenomena using coupon tests, but it is impossible to properly address failure mechanisms without comprehensive structural models that include coolant pressure, coolant chemistry, static thermal gradients, thermal transients, and radiation damage. Hence, a multi-disciplinary, multi-scale effort is needed to comprehensively address the materials-design interface and permit substantial progress towards the design of high performance, optimized components. We believe that the efforts to engineer or "design" the microstructure of the material for maximum resistance to radiation damage cannot be very fruitful if made without proper coupling with their utilization in real design environments. Thus, we believe that the coupling between "materials-by-design" and advanced hierarchical thermomechanical design is necessary for the success of materials development efforts.

3. Research Needs

3.1 Modeling

3.1.1 Overview

Modeling related to the materials-design interface is a challenge because the materials issues are inherently multi-scale, both in time and space. Irradiation effects begin with cascade events that occur on the picosecond time scale, but are largely influenced by much slower time scales governing diffusion of defects and alloying elements as well as phenomena such as corrosion and creep. Advances in fundamental research on structural material degradation in a fusion environment serve two distinct purposes: (1) enable a rational process of alloy design and optimization for service life and performance, and (2) have a connection with mechanical design of fusion components. However, it is impossible to model all relevant phenomena at all relevant size and time scales because the required temporal and spatial resolutions do not permit all phenomena to be represented macroscopically using contemporary computational platforms. Hence, tools capable of macroscopic modeling at the component level will dominate modeling in the near term, but state-of-the-art microscopic models will inform these models.

The microscopic models employed today to study materials issues relevant to structural materials for fusion can be summarized as follows:

- ***Ab initio*** models are capable of resolving very fine details in materials. They typically involve approximate solutions of Schrodinger's equation and density functional theory (DFT) is the most commonly used approach. DFT is useful for determining local structures and macroscopic properties, but it is limited to models containing approximately 1,000 atoms. Given that a typical grain contains at least 10^{12} atoms, it is clear that DFT is unable to resolve the phenomena we must consider to model component failure.
- **Molecular dynamics** avoids the solution of Schrodinger's equation by introducing a potential function that describes the interactions between atoms. This tool is excellent for simulations of the dynamics of collision cascades and for studying small defect cluster formation. Simulation times are limited to less than 1 microsecond, so coupling is still needed to continuum models in order to allow failure modeling.
- **Kinetic Monte Carlo** is a stochastic modeling approach is excellent for modeling the time evolution of physical phenomena. To employ this technique, one must specify the mechanisms responsible for the evolution of the microstructure and their associated activation energies. This, though, permits analysis on a much larger scale than the models

described above. Hence, this approach can be used, for instance, to model the interaction of defect clusters with dislocations.

- **Dislocation Dynamics** models dislocations as dynamic entities and follows their evolution by tracking and accounting for the forces they experience from interaction with other dislocations, grain boundaries, defect clusters, etc. These tools are excellent for modeling phenomena such as crystal plasticity and are capable of mesoscopic-sized models carried out to relatively large strains.
- **Phase Field** models replace interface boundary conditions with partial differential equations that represent an order parameter. These can be used to study phenomena such as radiation-induced segregation or void swelling.

None of these microscopic or mesoscopic approaches are capable of modeling component failure because they cannot model the full range of time scales, size scales, and phenomena to address all relevant failure mechanisms. In addition, component level models will include primary loads (from coolant pressure), secondary loads (from thermal gradients), spatial variation in damage levels and gas production rates, and relevant transients. Hence, a macroscopic model is required. This is generally the finite element method, which can model detailed geometric models over large size and time scales, incorporating complicated material properties. The microscopic models will be used to inform these continuum models through sophisticated constitutive laws relating macroscopic deformation (generally strains) to microstructural evolution. This hierarchical design approach is schematically illustrated in Figure 6, where successive levels of models are applied to a given fusion components, with increased levels of spatial resolution and accuracy. At the largest scale, an elastic model with roughly 5 millions degrees of freedom (~5 MDOF) is used to determine the Critical Region (CR), where failure is likely to occur. The CR is then modeled with a viscoplastic model (with ~0.5 MDOF) that has traditional constitutive time-dependent material data. This, in turn, determines a crystal plasticity Macro Representative Volume Element (Macro-RVE) with ~0.1 MDOF for further detailed modeling. A Micro-RVE is then extracted from the Macro-RVE for discrete DD modeling of plasticity and surface crack nucleation, with ~ 10-100 K DOF. Finally, elasto-plastic solutions for the J-integral and crack propagation of the critical law in this region are performed. Iterations can be made within this sequence of models.

3.1.2 Plasticity and creep

The recognition of the need to ensure safety and reliability of fusion components compels us to develop methods of non-linear mechanics that are capable of including radiation effects on the one hand, and that are amenable to practical implementation in a component setting, on the other. In particular, the FW and PFC components will operate at high temperatures, and will undergo cyclic thermal stresses of various magnitudes and durations. This will lead to an evolving spatial redistribution of stresses and distortions in the FW/ Blanket and PFC structural elements. In the hierarchical design strategy proposed here, plasticity and creep (viscoplasticity) models must be incorporated at some design level to assure proper accounting for stress evolution in the structure, and to be able to predict component lifetime and failure mode.

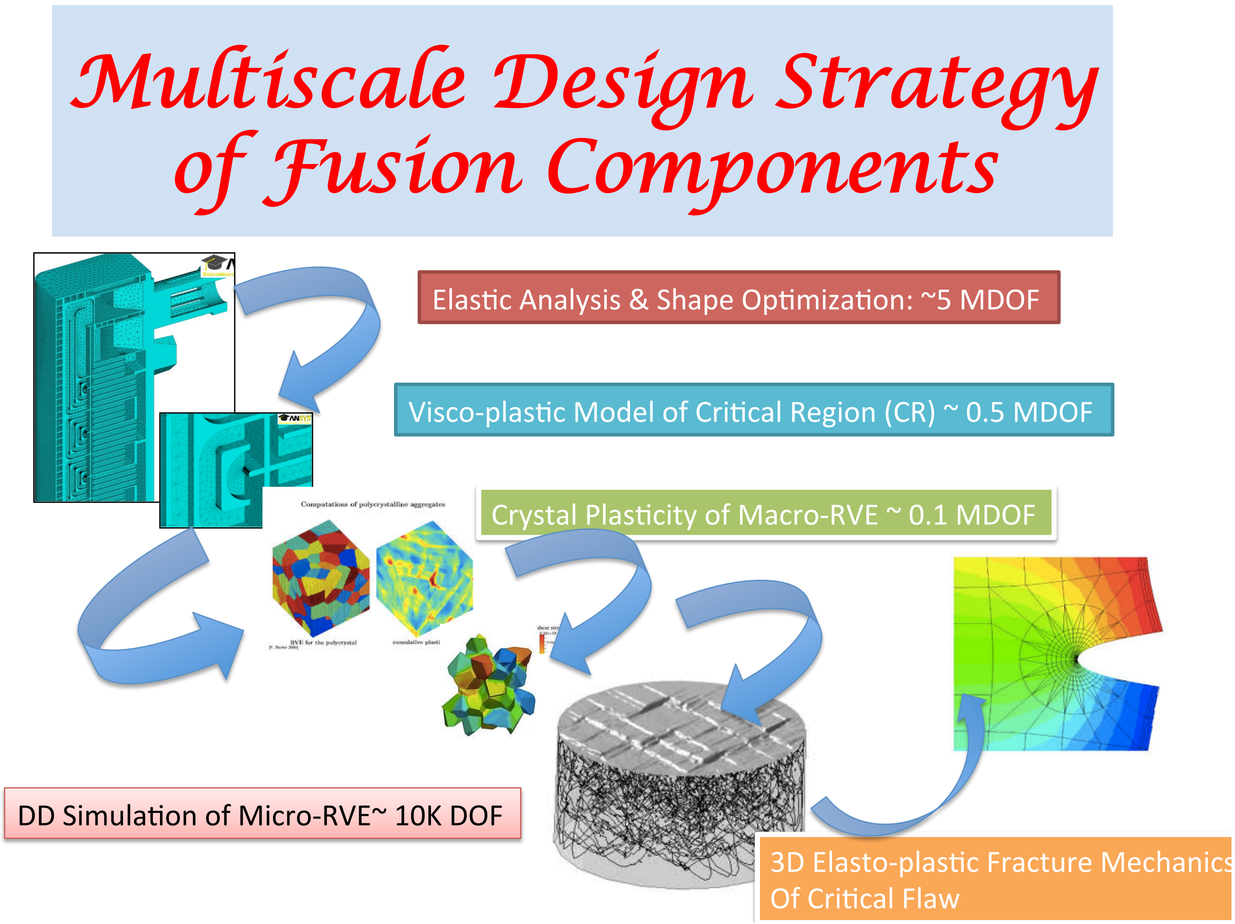

Figure 6: Hierarchical Multiscale Design (HMD) Strategy for fusion components.

The terminology of plasticity, creep, and fatigue is a traditional way to classify the post-yield deformation behavior of structural members. However, the "constitutive relations" between stress, strain, and time are more accurately classified as: (1) elasticity, (2) viscoelasticity, (3) rate-independent plasticity, (4) and viscoplasticity. While most of what has been done so far for fusion component design was based on elasticity, together with a few empirical parameters to account for all other effects, we expect the full-range of deformation behavior to take place in the FW/B/PFC type of components. The elastic behavior can be easily described by two elastic constants for isotropic materials, and irradiation does not play a role in changing these constants. The key problem here is that, beyond the elastic regime of deformation behavior, there is no clear way to describe material deformation under the tri-axial loading conditions that will exist in practice. Often, a few parameters are used to describe the rate of hardening or softening, and the overall ductility at failure. The issue with this approach is that such parameters are not unique, and are not directly accessible to measurements at all, and their values must be inferred indirectly from macroscopic mechanical deformation tests. Thus, full characterization of the post-elastic deformation regime, whether the behavior can be described by rate-independent plasticity, viscoelasticity, or viscoplasticity, is clearly challenging without an immense experimental database.

The phenomena of creep, and creep-fatigue, are more accurately described by dissipative viscous mechanisms in thermomechanically-loaded components, and they are theoretically interlinked as “time-dependent cyclic viscoplasticity” Since irradiation creep is viscoelastic, it does not lead to damage accumulation and failure, while thermal creep and creep-fatigue, being dissipative viscoplastic in nature, are the primary causes of thermomechanical damage accumulation. With long hold-times, which may be expected in a fusion machine, thermal creep of parts of the FW and PFC are expected. When followed by thermal load cycles from intermittent plasma excursions, or larger thermal cycles during startup, shutdown, and staged machine operation, cyclic plasticity hysterysis loops can either stabilize after a small number of cycles, or may “ratchet” plastic strain from cycles-to-cycle, finally rupturing the structure. Methods of non-linear mechanics with FEM modeling can track such creep and creep-fatigue ratcheting behavior. However, the data uncertainty and the complex nature of non-linear time-dependent FEM computations make it certainly impossible to characterize large components with current state-of-the-art methods, and some level of quantifiable approximation is needed [19-21]. The approach we advocate here is the “Hierarchical Multiscale Design (HMD)” approach described pictorially in Figure 6 above, where the designer “zooms in” on smaller structural RVEs with greater accuracy and more sophisticated analytical design tools.

One additional complication in considering creep, and creep-fatigue phenomena in the context of component design is the fact that as the material “ages,” it accrues “mechanical damage” by the accumulation of plastic strain that cannot be reversed. The arrival of dislocations to the grain boundaries is known to result in controlled diffusional vacancy flow to grain boundary cavities, to incompatibility strains at grain boundaries and triple point junctions, and to the initiation of internal cracks at precipitates. This form of “creep damage” is also accelerated by the arrival of helium to the grain boundary and the by the concentration of dislocation movement in “dislocation channels” that can result in larger incompatibilities and internal cracking. A branch of mechanics has been developed with some level of success to deal with these types of phenomena, dating back to the work of Katchanov [22]. Specific mechanical tests (such as creep relaxation) are required to characterize changes in the constitutive (e.g. stress-strain-time) behavior of the material as it ages. Including high-temperature thermomechanical damage mechanics in design applications brings the analysis to an entirely new level of complication, as one designs a component that is defined by an elasto-viscoelastic (irradiation creep)-viscoplastic (thermal creep, and creep fatigue)-damage (thermomechanical and radiation) description. Only a few examples exist, where such sophisticated design approach has been applied to high-temperature jet engine turbine blades [23-26].

3.1.3 Fracture mechanics

The trend towards structural materials based on ferritic steels or tungsten alloys requires development of design rules for materials with limited ductility. This requires the modeling of crack evolution within the materials and the standard approach for this is fracture mechanics, which is based on crack growth models based on local, crack-tip stress fields. For materials without ductility, the models predict catastrophic failure when a measure of the local stress field (the stress intensity factor) reaches a critical value (the fracture toughness). For materials with some ductility, plasticity is expected in the vicinity of the crack tip and models involving line integrals around the crack tip are used as the failure criterion. Failure, in this case, generally occurs incrementally, rather than in the catastrophic fashion expected in brittle materials. One difficulty of this approach is that the crack geometry must be assumed prior to development of the model, so one must make assumptions regarding the initial crack size and orientation, based, in part, on the most critical crack geometry and capabilities for non-destructive testing. It also requires high spatial resolution to properly characterize the crack-tip stress fields. This approach has been used extensively to model the failure of components in both MFE and IFE devices and will continue to be vital to attempts to address component failure.

3.1.4 Fatigue and creep-fatigue

Fatigue is deformation caused by cyclic loads, generally in the form of incremental crack growth. Creep is time-dependent, inelastic deformation caused by stress-induced dislocation motion. The failure mode is often cavitation within the solid, facilitating crack growth and, ultimately, failure. In situations where a cyclic load will also lead to significant creep strain, then both must be accounted for simultaneously and the modeling is substantially more complicated. In cases where fatigue is more prominent, models can be formulated as "fatigue accelerated by creep," whereas, if the opposite is true, models can be formulated as "creep accelerated by fatigue." In either case, the deformation is a combination of incremental crack growth, grain boundary sliding, and cavitation. Testing requires consideration of a variety of mean stresses, stress amplitudes, and hold times in order to address all relevant deformation scenarios. Modeling generally consists of some type of cumulative damage model that accounts for deformation from either mechanism. This is a situation that is ripe for advancement and is a perfect example of the advantages of a model combining both microscopic and continuum modeling. The microscopic models permit a mechanistic understanding of the interaction of creep and fatigue, coupled with continuum models that permit design calculations. In this context, there is potential for a breakthrough.

3.1.5 Radiation effects

The effects of neutron irradiation on the operational temperature window of structural materials in a fusion system have been thoroughly investigated by Zinkle and Ghoniem [27]. In their analysis, the lower temperature limit for reactor operation will be dictated by a gradual shift in the Ductile-to-Brittle-Transition-Temperature (DBTT), manifest in a drastic reduction in the fracture toughness of both ferritic martensitic steels and tungsten alloys alike, In the intermediate temperature regime, neutron-induced swelling is expects to play some role, although progress on ODS steels have led to a significant reduction in the rate of neutron-induced swelling. It appears that the volumetric swelling can be accommodated in much the same way as thermal expansion of thermomechanical components. At high temperature, it is expected that the thermal creep rupture limit will be reduced to lower temperatures and operating stresses as a result of helium diffusion and agglomeration at grain boundaries. Currently, there are no guidance or clear pathway as to how to include these radiation effects phenomena in design procedures. In past studies, ad hoc rules were used (e.g. an arbitrary 5% volumetric swelling limit), but there is nothing in the literature that comes close to what has been done for similar components operating in severe environments, such as jet engine single crystal turbine blades [23].

What compounds thermomechanical design of fusion components is the fact that neutron and plasma damage can alter the deformation characteristics as the component "ages" in service. Neutron irradiation is known to result in new phenomena, such as irradiation creep, which may be described as a viscoelastic type of deformation, where the full elastic response is recovered after a "relaxation" period. Thus, it is considered to be non-damaging by itself, although it leads to stress redistributions within the structure. On the other hand, irradiation results in the general impedance of dislocation motion, which manifests itself in the form of an increase in the yield point, changes in the hardening rate post-yield, plastic flow localization, and general loss of ductility. Other forms of ductility loss are manifest as an "acceleration" of the growth rate of grain boundary bubbles, leading to fracture at lower strains, as compared to non-irradiated materials.

Post-irradiation experiments have consistently demonstrated that drastic changes occur in irradiated metals and alloys, such as the phenomenon of yield drop in fcc metals, a complete loss of work hardening ability and concomitant drastic reduction in uniform elongation (*i.e.* ductility). It is worth emphasizing here, however, that the vast majority of our current knowledge regarding the adverse effects of neutron irradiation on mechanical properties is based almost entirely on the results of post-irradiation experiments, and that our understanding of the effects of concurrent damage and deformation is still in its infancy. It is observed that as the applied stress is increased, it raises the stored elastic energy in the material, and at some critical threshold, this energy is dissipated in either localized or homogeneous plastic flow. The nature of this massive transition critically depends on matrix hardening induced by neutron irradiation, and is controlled by nano-scale mechanisms of dislocation interaction with radiation-induced defect clusters. If the matrix is extremely hard (*i.e.* large rate of defect cluster production compared to the rate of plastic deformation), the material develops spatially heterogeneous intense micro shear bands rather than spread the deformation evenly. During in-reactor mechanical tests, the transition from the elastic to plastic regime occurs smoothly and without any sharp transient in the form of yield drop, which is common occurrence in the case of post-irradiation tests. Whereas the work hardening in the case of post-irradiation tests is almost completely absent, in-reactor tests show strong hardening in the plastic regime. Furthermore, and depending on the dose before application of stress during in-reactor tests, plastic flow occurs in a homogeneous or heterogeneous fashion in localized defect-free dislocation channels (or micro shear bands). Traditional models of plasticity and failure do not include the simultaneous effects of radiation. On the other hand, radiation damage models do not include the simultaneous effects of stress on damage accumulation. We believe that this is an area of considerable importance, and thus requires our proposed HDM strategy in order to include radiation effects on the mechanical deformation at the microscopic level of dislocation-defect interactions.

3.2 Design rules

The primary purpose of structural design rules is to assess if a structure has adequate design margins against postulated failure mechanism, which the structure could experience during lifetime operation. A number of important design rules for low and high temperature applications are reviewed here.

<u>*Failure Modes:*</u>

Failure modes of fusion reactor first wall/blanket (FW/B) components, such as the TBM can be immediate at the start of operations, or delayed by prolonged damage accumulation due to thermal stress and radiation effects on the microstructure. In qualifying FW/B components, one must therefore consider the following possible modes of failure:

1. M-type (monotonic) damage induced failure
   (a) Immediate plastic collapse.
   (b) Immediate plastic instability (due to large deformation or to plastic flow localization).
   (c) Immediate fracture (brittle or with exhaustion of ductility).
   (d) Thermal creep cavitation and rupture.

2. C-type (cyclic) damage induced failure:
   (a) Progressive deformation (ratcheting).
   (b) Progressive cracking (fatigue).
   (c) Fatigue-creep type failure.

3. Irradiation accelerated and induced failure:
   (a) Irradiation-induced immediate plastic instability due to flow localization.
   (b) Irradiation-induced immediate fracture due to hardening, loss of ductility, and embrittlement due to helium and phase instabilities.
   (c) Irradiation-accelerated thermal creep cavitation and rupture.
   (d) Dimensional instabilities due to irradiation- induced creep and swelling.

These failure mechanisms must be considered when determining the reliability of TBM structures for ITER.

The SDC-IC design rules relate deformation/failure mechanisms to design criteria. The SDC-IC design rules are divided into a low temperature-, high temperature-, and all temperature criteria, depending on whether thermal creep effects are or are not important. The low-temperature rules are further classified as: limit load collapse, under a single load application, excessive displacement and/or deformation, limiting functionality, under a single load application, below the limit load, structural instability or buckling, under a single load application, progressive collapse by ratcheting under cyclic load, fracture by the initiation and/or propagation of a crack under a single load application, fatigue failure under cyclic loading, breach of the pressure boundary, or structural collapse caused by corrosion induced loss of section. On the other hand, the high-temperature design rules encompass: excessive deformation - loss of functionality, due to creep deformation under essentially steady load, creep buckling - time dependent structural instability leading to catastrophic collapse or loss of function, cyclically enhanced creep deformation (creep ratcheting), accelerated creep deformation caused by repeated resetting of stresses by cyclic plastic strain, due to cyclic loads superimposed on a sustained load history, accelerated creep rupture, and accelerated creep damage caused by repeated resetting of stresses by cyclic plastic strain, due to cyclic loads superimposed on a sustained load history. Whether one applies the low- or high-temperature rules, some additional overarching criteria must also be satisfied. These include corrosion, oxidation, and mass transport phenomena, and irradiation induced failure mechanisms.

3.3 Fabrication and subsystem integration

We use the term fabrication in its broad sense of transferring the intent of a conceptual design into a finished product for deployment. This definition includes (a) vetting of the design itself for a given device, *e.g.,* the machine interfaces and functionality of this components (PFC) in relation to other subsystems, and confirming that the operational space and related requirements, *e.g.,* loads from unplanned events, are in fact adequate, and for a D/T device that the considerations for remote maintenance and repair are sound, and (b) that the process for R&D

includes appropriate steps to show that the fabrication is or can be developed and scaled up as needed with materials that can be produced in the quantities necessary and with the forming and joining processes, quality and delivery times needed. Rather than give space to the various types of fabrication processes (HIPping, plasma spraying, additive manufacturing (3D printing), near net shape spark-gap sintering, PVD coatings and structures, etc.), we show here the framework in which the fabrication processes will be considered in a design-to-build project that we believe should start soon.

When we expand this as a general topic in the development of fusion, then the pathway includes the activities for series of devices that confirm the design bases, implementation and performance of R&D for the science-based engineering that will produce and outcome of robust and reliable components deployed in these devices that lead to the performance needed in each stage and eventually for a fusion reactor. Various papers and studies have explained his connection. [28-31] The area of fabrication draws upon the results of modeling of materials and systems as well as an understanding of how these systems fail. (More on this latter topic in Section 3.4.)

The primary concern in this paper is how an interim program proceeds in its early stages in the next few years from the knowledge base on actively cooled PFCs we have from ITER, Tore Supra, and high heat flux testing. Several references are provided here on the important past R&D, but our knowledge base comes from the progression of these activities and the integration of new information. For example, work during the ITER EDA showed that intermetallics form with Be and that diffusion bonding as tested then would not work [32]. Hypervapotrons were investigated for the divertor [33] but dropped, and then later adopted for the enhanced heat load modules of the ITER first wall. Among the lessons learned was the need for full CFD analyses because use of correlations based on the assumption of fully developed flow were inadequate. [34-35] Early work on Tore Supra showed the importance of how joining flaws affected heat flow and set a criteria for quality assurance. [36-38] This approach was later adapted for ITER testing in the EU and Japan. The need for confirmation of performance for ITER PFCs has brought a large test program for the divertor, first wall as well as material testing and design development for the ITER-like divertor in JET. [39-43] Less but still significant high heat flux testing was aimed at Demo-relevant technology. [44-45]

A modest, targeted design activity can add value to this program in the near term. For this, we propose to set the deliverable hardware for fabrication to be several helium-cooled refractory PFC mockups that are designed for one of two possible applications (a) an FNSF or DEMO, or (b) a nearer term deployment such as a module for EAST. Or if sufficient funding were available, we would pursue these in parallel. The main difference would be in how we treated the issue of design and subsystem integration.

One outcome from the proposed activity is the series of mockups and a test program. A larger and complementary outcome is the design support and analysis that shows the modeling of materials and subsystems that confirm the robustness of the design, justify the choices of configurations and materials, establish the basis for the test program to confirm its performance as well as the rationale that the test program and its results and the coordinated modeling will show a specified advancement in TRLs.

In the case for an FNSF, the design would be instructive for the details of the integrated subsystems and the types of interactions, e.g., how EM loads are reacted, how coolant budgets interact with other systems, what is needed in the manifolds and headers to stabilize potential flow instabilities in helium PFCs, how do the helium and tritium recovery systems interface, etc.

In the case for deployment in a near term device, the point of interest will be how such a PFC can be integrated into the device to mount a meaningful experiment. This addresses an important near term issue of interest of how to use existing or upgraded devices to advance PFC technology needed for the future. It may also be the groundwork for a US collaboration to deploy such PFCs in EAST or another non-US device. Even if the FNSF application is chosen, both the design and a test program would be likely to generate interest in Asian partners.

The activity will also likely utilize fabrication processes that have been initially developed through SBIR grants, such as integral structures with graded layers and various possibilities channel coatings that enhance heat transfer and fabrication processes to produce structures with jets and porous media. And the activity would provide a useful target for future SBIR calls that would serve technology development.

3.4 Experiments

3.4.1 Code validation through testing

Experiments that are not guided by advanced theoretical and modeling approaches are not very helpful, as they accumulate data that cannot be used in a meaningful way. We advocate that the proposed HMD be the framework against which experimental research can be validated. A series of experiments would be designed to validate and measure the parameters that characterize the deformation of microscopic specimens, macro-specimens, subcomponents, and finally full-size components. The array of experimental tests would be designed so as to probe three types of behaviors: (1) fundamental macroscopic visco-elastic and viscoplastic behavior under mechanical loads; (2) fundamental macroscopic visco-elastic and viscoplastic behavior under transient thermal loads; and (3) coupled irradiation-mechanical-thermal load experiments. These tests can be designed to validate dislocation dynamics codes, using indentation and pillar compression experiments of pristine and irradiated samples. At higher length scales, crystal plasticity type codes can be calibrated against thermomechanical experiments of macro, polycrystalline specimens in tension, bending, and combined tension/ torsion experiments, The thermomechanical behavior needs to be calibrated by cyclic high heat flux exposures, with and without an applied mechanical load. Future efforts may also include such tests in an IFMIF or FNSF type facilities to provide additional calibration of design codes with neutron irradiation data.

3.4.2 Failure modes and unforeseen effects

So far in fusion we have developed PFCs and many other components primarily by a series of tests in which a few small representative PFC mockups pass a performance test of some type. For example, for the ITER first wall, mockups fabricated by the various parties were subjected to thermal tests of 10,000 cycles at a heat load of ~0.65 MW/m^2 with additional cycle tests at higher heat loads to represent transient events such as heat loads from plasma disruptions and then, as the design requirements changed, new designs for Enhanced Heat Flux panels with hypervapotron fingers were tested at 4.7 MW/m^2 [46-47], and there is a plan for testing prototypes and QA acceptance tests such as 100% of the first 10% of the panels produced and 10% thereafter. However, such proof tests are anecdotal and somewhat different than an approach in which the testing program is part of the validation of performance models with some predictive capability.

Some of this has happened. For example, Sandia developed a first-of-a-kind predictive model of the thermal performance of hypervapotrons based on CFD modeling of two phase flow with the full fluid physics in detailed boundary layers. [48-49]. This kind of science-based understanding for the engineering of PFCs and other components is what we have in mind. But the excellent and groundbreaking CFD modeling in this case represents but one portion of what is needed in assessing failure modes. We do not yet see in fusion the type of coordinated modeling and testing that explores failure modes as a path to mitigating threats and moving toward optimizing designs.

A deceivingly simple question is: how to PFCs fail? Among the various possibilities are (1) a crack grows and penetrates the vacuum boundary, (2) overheating and melting cause excessive release of impurities or (3) causes distortion or movement of melted material that provides bridging paths for electrical currents that cause further problems or would interfere with remote maintenance, (4) accumulated damage in the surface of the PFCs results in degraded properties that promote cracking, or (5) decrease the diffusion of heat and cause overheating, or (6) produce microstructures and morphology that lead to unacceptable release of material as micro-particles (dust).

Other causes of failures could be movement or distortion due to EM-induced mechanical forces that create hot spots in further service or compromise the remote maintenance and obstructions or differences in manifolding that adversely affect the distribution of coolant to PFCs. Recent evaluations of the tendency for mal-distribution of helium flow in parallel paths under conditions of hot temperature, high density (high coolant pressure) and high heat loads has been seen in experiments, but not in modeling [50]. Also, recent analyses show important difference between the instabilities observed for porous media, and for jets and in the scale of the jet flow [51]. This latter observation brings us to the coordinated role of modeling and testing.

The path of simply testing various effects singly and then collectively will work only within a well-coordinated program that uses the testing to support the development of predictive models. The cycle is then that the testing can be designed to provide needed benchmarks that confirm the predictive capability of the models. The testing is also needed to uncover behavior in materials and systems that is not predicted and then provides the basis for revising the scope of modeling and testing. Two examples are the potential for instability in helium flows noted above and the only recently discovered growth of tungsten fuzz under fusion-relevant conditions for hydrogen and helium implantation.

Sometimes experiments lead the modeling through the discovery of unexpected behavior. And sometimes the modeling leads the testing through the specifications for test conditions that will confirm and expand the range of the models. Always a high level of coordination is essential. In fusion we find this in the physics side of the program, and a similar level of coordinated and appropriately funded activities will be needed in technology for successful outcomes.

The activity that we would hope to have initiated as a result of this white paper, would include an initial attempt to optimize design through progressive evaluations of stress and crack growth and design mitigation. And a part of the process would be to assess and document the decision-making process that accompanied the design development and to identify the types of testing that are appropriate to provide missing information.

4. Programmatic Considerations

4.1 Interfaces with design, materials and component (e.g. chamber) programs

The US fusion program has a long history of design studies for commercial fusion devices, but these efforts often have been disconnected from the research efforts in materials and high heat flux component design. However, the ITER project and recent FNSF and Demo design projects have made it abundantly clear that progress requires cooperation among all of these activities. Ultimate realization of a successful commercial fusion device requires the following:

- A comprehensive materials development program that will develop and qualify the materials needed for high performance plasma-facing components.
- An experimental program to study the performance of these components under high heat flux (including transients), relevant coolant pressures, and, ideally, relevant ion and neutron fluxes.
- A verified set of design rules relevant to the fusion environment and capable of addressing design with materials that have limited ductility.
- An upgraded modeling capability that can address the synergistic issues we expect to encounter as we move towards component-level testing in future programs, while still providing understanding of local failure modes.
- Integration into a systems-level study to ensure that this work is moving in a direction that will lead to a viable commercial program.

Historically, efforts in design, testing, materials development, *etc*. have been carried out independently. Cooperation across these efforts has largely relied on luck or the initiative of individual investigators to provide the necessary synergies. Understandably, these efforts have not been sustainable. Real progress in these areas will require sustained, institutionalized avenues for cooperation and the required collaboration must be an inherent part of the programs. Otherwise, we will continue to address these issues in a vacuum, leading to wasted effort as we explore options that are not viable at the system level.

4.2 International collaborations

A similar program to what we are proposing here is already underway in Europe, and is led by researchers at the Karlsruhe Institute of Technology (KIT). We have established collaborative ties with the materials development group at KIT in the area of PFC technology. For example, high heat flux experiments are planned at UCLA on the HEFTY device. KIT researchers have developed a new technology to manufacture sintered W that has good isotropy of grain size distribution, and better ductility than currently available. Samples made of Powder Injection Molding (PIM) of W, fabricated at KIT, will be tested and used for code validation at UCLA. This collaboration will be expanded in the future to include R&D efforts in Europe on advanced design methodologies for fusion components.

4.3 Involvement of industry

We consider coordination with industry an important aspect of the path forward. There are two quite different approaches in viewing this involvement.

The first, which is the present status and the default approach, is that industry will become involved with in-vessel technology for fusion at the point where a relatively near-term path for some significant device, such as an FSNF, is sufficiently evident in the funding support for the program that the involvement of industry in the production of components draws interest. There is some precedent for this approach in the US during the pre-ITER era, when the US was building fusion experiments and also planning for a fusion nuclear test device (*e.g.,* the Fusion Engineering Device, FED and later other options). In that time TFTR was constructed, the FED Design Center was formed at ORNL and other devices had also been considered. Boeing (then McDonnell-Douglas) and various other industrial partners had sent participants to the Design Center, and there were "machine builders" on staff at PPPL and others from industry involved in fusion, and the US had a much stronger link with industry. At that time there was also more funding for foreign collaborations that involved the building of hardware, some of which also involved industry.

With the decrease in funding for fusion during the 1980s, activities that involved building of components decreased dramatically. The later step into ITER into the 1990s drastically altered the emphasis in the program in that many of the foreign collaborations involving hardware related to PFCs were terminated and subsumed into the ITER activity. Industrial participation, particularly with Boeing, continued in the first phase of US ITER activity in the design of the divertor cassette, and parts of the divertor targets and dome. Two examples of the industrial involvement in these activities were (1) development of joining processes for tungsten armor to an actively cooled CuCrZr heat sink, and (2) near net shape fully dense casting of the divertor cassette body. ITER had not accepted that such casting could deliver either the mechanical properties specified by ITER, due to the changes that might occur during the low cooling of a thick casting, or the required density, i.e., lack of porosity. But US industry delivered a prototype casting that proved that we could do so. As ITER proceeded, the US activity changed later to the design and production of a portion of the first wall, an activity that had industrial partners identified, and then to a design only activity.

The first path makes perfect sense from the point of view of business investment. However the fusion program loses the knowledge and insights it could gain from industry. We need to find a second path to stimulate some collaboration with industry to gain knowledge about what is possible now and in the future in materials and manufacturing. *This is a critical issue within the program at a time when we are trying to develop a credible path forward: one that is not only credible to us, but also to our critics.*

In theory, an individual might be able to glean a great deal of information by searching the literature and contacting people in industry. But this is not realistic nor practical because our program is sufficiently thin that no one has the resources to do this, nor could they likely obtain adequate cooperation.

We gain some foothold from the few people on the technology side of the program who are at universities or national labs and involved in programs outside of fusion that have activities relevant to fusion. And we need to promote engagement with industry by leveraging what contacts we have, creating new activities that involve industrial participation and young researchers in the fusion program, and using those still in the fusion program with appropriate experience to provide guidance.

We do not have a good mechanism to get technical expertise about industrial processes. And we need guidance about what changes are coming in materials and their preparation as well as what is realistically possible for development paths. This is particularly true for the development of PFCs based on tungsten, but is also true for the combination of materials and fabrication processes that will be needed to make integrated first-wall-blanket structures. An extreme view here would be that the solutions are or could be available but the fusion program remains unaware, or that fatal flaws in our approaches would be noted by others who criticize the program but are not recognized by those within the program.

Ideally, we would like to attract a few of the best and brightest in industry and develop them as continuing participants in fusion, but this is unlikely at present because the program is not building anything, nor is there a clear path toward the next US device. A limited step in this direction is an activity that (a) identifies one or more target subsystems, e.g., a divertor or a first wall blanket sector, (b) develops the engineering in sufficient detail to uncover and resolve issues in its design integration and component fabrication, and (c) engages some industrial participation in design development and reviews. We cannot expect significant and useful industrial participation simply as a matter of good will. We will need an organized activity with objectives that are relevant to the future of fusion and sufficient funding to pay for some involvement with industry as well as a vision that FES expects a growth in this type of activity and increased involvement with industry.

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