Extreme Thermo-mechanical Challenges In Developing Fusion Power Reactor Materials and Structures

G. R. Odette (UCSB) and S. Sharafat (UCLA)

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Co-equal with achieving a burning plasma, *an overriding* issue in the development of fusion energy as a large scale energy source, is the feasibility of designing, constructing and predictably operating reliable, safe, and long-lived first wall, blanket and divertor structures. This *grand challenge* is often much too narrowly couched in terms of the development of *radiation damage resistant materials*. In reality, the enormously larger challenge is the creation of *material systems <u>and</u> multifunctional structures* that can survive and safely perform in the incredibly hostile fusion environment for extended periods of time. A corollary challenge is to combine physically based predictive models of the long term evolutions of performance sustaining material properties, with a new class of large-scale three dimensional life cycle structural analysis supercomputer codes, capable of dealing with 10^8 or more degrees of freedom. These codes should aim to incorporate all relevant sources of short and long term, time-dependent loading to predict the evolving distributions of stresses, strains and dimensional changes in large fusion structures that may require sub-mm tolerances. Most fusion reactor stress analysis studies that have been carried out to date are elastic static evaluations for simplified components or subcomponent geometries.

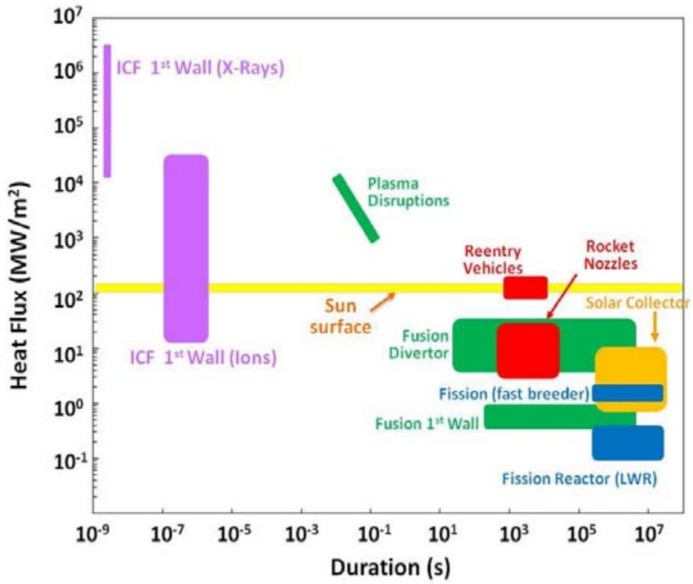

Figure 1: Comparison of heat fluxes in a variety of technologies and nature (after S. Zinkle)

The material- and structural models and codes must, in turn, be combined with models of damage and history-dependent synergistic failure paths that are controlled by complex interactions of numerous variables, processes and properties. The failure paths are not just limited to major events, but may include much more frequent and seemingly benign occurrences, like the local debonding of layered structures. The integrated models must be informed by well-designed experiments, supported by high quality material property databases that can underpin models of the effects of long-term service, and benchmarks provided by pertinent integrated scaled component-structure level testing. Radiation induced degradation of mechanical properties is, of course, a key issue, but others include corrosion-compatibility, chemical-thermal embrittlement, tritium permeation and extraction, to name a few. Considering this demanding combination of requirements needed for success, fusion energy clearly presents the greatest materials-structural engineering challenge of all time.

The unprecedented demands faced by fusion structures primarily derive from severe time varying thermal-mechanical loading of complex, large scale and highly interconnected heat transfer-energy conversion structures. High stresses can result from thermal expansions and temperature gradients, as well as primary loads. The stresses will continuously redistribute during stages of startup-shutdown, quasi steady-state operation and unplanned transients.

The mechanical loads act in combination with high temperatures, intense neutron and particle radiation fields and chemically reactive environments, often leading to severe degradation of a host of performance sustaining properties, internal damage, macroscopic cracking, corrosion-erosion and inherent dimensional instabilities due to irradiation creep and possibly swelling. Radiation induced microstructural evolutions, that are controlled by the combination of many variables and synergistic interactions between displacement-induced defects and transmutation products, including very large quantities of helium and hydrogen, are likely to be a major source of property degradation, internal damage and failure events.

Neither the materials, nor the requisite computational tools, nor the underlying knowledge base currently exist for reliable integrity and lifetime assessments of fusion reactor structures, and they will take an enormous *scientific* effort to develop. Predicting the interplay between high performance demands and eroding in-service property limits will require revolutionary advances in computational and experimental methods. New design and in-service performance computational tools must be developed to replace simplistic high temperature design and operational rules. These tools must ultimately be incorporated in code and regulatory (or safety case) requirements.

Key Thermo-mechanical challenges to functional fusion power reactor components:

- Structure target lifetimes of 5 to 10 FPY.
- Large surface areas (FW ~ 680 m^2 for ITER) to remove heat non-uniformly.
- Wall thickness of plasma facing structures are of the order of a few mm (reliability of very large, thermally loaded, pressurized thin wall structures, erosion due to sputtering and an ability to survive disruption induced large and rapid thermal and structural load transients are the major mechanical challenges).
- Plasma facing heat transfer structures are geometrically much more complex than fast reactor fuel cladding (although heat fluxes on the FW are comparable to those experienced by thin section fast reactor fuel cladding they experience larger thermal stresses, furthermore debonding of protective armor layer (Be or W on FW) is a key issue).
- The high heat fluxes and pressurized coolants (helium, liquid metals or molten salts) result in a combination of thermal and primary stresses (local thermal stresses increase and primary stresses decrease with the effective thickness of the coolant channel walls).
- Stresses will also arise from thermal expansions and heating plus other gradients that occur over much larger distances of meters and in three dimensions, depending on how the components (FW/Divertor/Blanket) are supported or connected to other components and dimensionally constrained.
- Loads and stresses in the plasma facing structures will be time dependent due to both start-up and shut down transients (perhaps more than 100) and irradiation and thermal creep during quasi steady state operation.
- Thermodynamically efficient power reactor structures will operate at high temperatures near their thermal creep regime (stress redistributions and some dimensional instabilities due to

irradiation creep probably cannot be avoided even in advanced NFAs, which have low thermal creep rates even at higher temperatures).

- The FW/Divertor/Blanket structural and armor materials must also withstand a wide range of neutron radiation damage phenomena (swelling at high helium levels may also be an issue: effects of high levels of helium and hydrogen are not known, but there is evidence that they may significantly shrink the temperature window in both the high and low temperature regimes due to the degradation of fracture toughness)
- Stresses and dimensional instabilities may also arise from density decreases due to helium bubble and void swelling, or slight density increases due to precipitation (materials that swell to any degree may not be usable in fusion structures).
- Neutron fluxes vary spatially, thus the corresponding irradiation creep strains and stress relaxations will also vary with position in the fusion structures (modeling time-dependent stresses and strains will require three dimensional multiphysics neutronic-thermal hydraulic-stress analysis codes, that incorporate accurate constitutive laws, treat inelastic strains and reflect sufficient details of complex, multimaterial structural geometries over the entire loading history of the component operation, including start-up, shut-down and unplanned transients).
- In the simplest case, irradiation creep is insensitive to temperature and is linearly dependent on stress and damage (dpa) (with creep compliances of up to 10^{-6}/dpa-MPa, stresses of 200 MPa and lifetime irradiation doses of 100 displacements per atom result in inelastic irradiation creep strains of about 2%; the corresponding unconstrained displacements over meter length scales are centimeters).
- Divertor structures suffer most of the same issues facing FW structures, but operate at a factor of ≈ 20 higher particle and heat loads and require higher performance as plasma facing engineered structures over a wide range of length scales that are made of embrittlement prone refractory W-alloys.
- With the exception of irradiation creep the accumulation of radiation damage due to atomic displacements is minimal at sufficiently high temperatures. However, there are portions of the blanket that operate at lower temperatures, such as support structures (bolts and joints), coolant supply pipes, back plates and coolant manifolds, etc., that will experience radiation damage.

Even *without radiation damage*, the challenges of developing fusion FW structures that can withstand such severe thermo-mechanical loading are unprecedented. Other phenomena that could synergistically interact leading to a variety of failure paths, include:

- High-cycle fatigue and fatigue crack growth such as those associated with flow induced vibrations
- Low-cycle thermal mechanical fatigue, cyclic softening and possible ratcheting for less frequent but larger thermal transients
- Irradiation creep and possible swelling induced dimensional strains and stress redistributions
- Thermal creep, creep rupture, creep-fatigue interactions and creep crack growth
- Microstructural instabilities and softening due to thermal aging and cyclic strains
- Fast fracture

Transient events related issues:

- Power reactors must operate in a quasi steady state mode and be able to survive off normal transient events (the EM forces and bending moments, that are generated in conducting materials, depend also on structure dimensions and design features, such as electrically insulating breaks; disruption forces may cause bending stresses with maximum values well above the yield limit).

Common Issues:

Due to the intricate, multifunctional, large scale but dimensionally precise nature of all the major components of fusion power reactor structures, they all share a number of common challenges

- Fabrication and joining, including dissimilar materials, in very complex and high tolerance geometries.
- Coatings on fusion components will be required for a variety of functions, especially as particle- and T-barriers.
- In-service inspection, surveillance data, distributed in-chamber sensors and NDE will be required to assure that fusion structures will be operated with sufficient safety margins over long periods of time.
- Updatable physically based reliability and performance models will also be needed to continuously analyze NDE, surveillance and sensor data and extrapolate fusion reactor component performance and safety margins.