A Note on the Logic of PMI Development for FNSF or Demo

Abstract

- There is only indirect interaction between Plasma-Material-Interface (PMI) issues and Neutron-Material Interaction (NMI) issues.
- There is only indirect interaction between NMI issues and plasma performance.
- There is strong direct interaction between PMI issues and plasma performance.

As a result while tests of advanced PMI concepts applicable to a Fusion Nuclear Science Facility (FNSF) or a Demo (Demonstration Power Plant) require a toroidal confinement device with relevant power density, pulse length / duty cycle, PFC + wall temperature, and flexible configuration, this device need not be capable of producing a copious flux or fluence of neutrons.

There is only indirect interaction between PMI issues and NMI issues.
Neutron interactions affect the thermal conductivity, mechanical ductility and bulk tritium retention of plasma facing materials. They do not affect significantly the surface behavior, for the simple reason that the burn-up fraction of a DT plasma is ~ 1% and the recycling coefficient is ~ 0.9. Thus there are of ~ 1000x more DT ions striking plasma facing surfaces than neutrons. Furthermore while the D, T and He ions affect at most the first ~ 10^{-6} m of the surface, neutrons affect ~ 0.1m. Thus every nucleus in the first micron of the surface sees 10^8 more impacts from the recycling plasma particles than from neutrons.

There are of course important neutron-induced changes in the bulk properties of plasma-facing materials, but these interact with the plasma-material interface only *indirectly*, due to changes in thermal conductivity, mechanical ductility, and tritium retention. Surface temperatures can be adjusted in PMI experiments to compensate for changes in thermal conductivity, for example by changing coolant flow rates. Changes in ductility can be addressed by measuring and extrapolating stresses to reactor parameters, and then testing irradiated materials under relevant stress conditions. Tritium surface retention sets one of the boundary condition for bulk retention, but the dominant issue is the number and energetic depth of traps for tritium. The relevant boundary conditions can be measured in experiments and then replicated in the lab with irradiated samples. Hydrogenics retained in the bulk of the plasma-facing material have essentially no interaction with PMI issues, since they are not accessible to the plasma.

The February 2012 FESAC Report, “Opportunities for Fusion Materials Science and Technology Research Now and During the ITER Era”, addresses this issue specifically. The only interaction between PMI and NMI the Report finds is through thermal loads, as discussed above, stating (on p. 7) “Fusion neutrons produce volumetric defects and transmutation products, particularly helium and hydrogen. The plasma presents strongly perturbing physical processes at material surfaces, through erosion and re-deposition, and hydrogen and helium implantation. While these effects are largely separable due to the different scales, the intense heat flux and high material operating temperatures, and associated thermal gradients couple these multi-scale effects. Thermal loading can have steady, transient, and off–normal features that aggravate degradation mechanisms and can lead to failure.” Tests of failure modes of materials degrading by radiation, aggravated by features of steady, transient or off-normal thermal loading, do not require exposure to a tokamak plasma.

There is only indirect interaction between NMI issues and plasma performance.
As noted above, since the plasma does not interact with the bulk material properties of the plasma-facing components directly, it is affected by these issues only indirectly, for example through the allowed choice of materials, the expected surface operating temperature, and allowable disruption forces. In particular, desorption of hydrogenic species from neutron-induced traps requires very high temperatures and very long periods of time. Bulk neutron damage is expected to have no significant effect on plasma recycling.

There is strong direct interaction between PMI issues and plasma performance.
It is very clear that plasma-material interactions have strong, direct impacts on plasma operation. It is well known that recycling behavior can impact energy confinement strongly, and all of the techniques that are used to mitigate PMI issues, such as impurity or gas injection, changes in divertor mechanical or magnetic geometry, changes in surface conditions or plasma-facing materials have complex impacts on performance. Recent results from JET, ASDEX-Upgrade, C-Mod, DIII-D and NSTX indicate that the power scrape-off layer width in tokamaks narrows at higher field and does not change to larger size. Heat flux in the SOL emerging from the plasma scales roughly as PB_p/R. This represents an extreme challenge for the high power and high-current FNSF and Demo designs on the table, and will very likely require the development of radical new techniques for power handling.

These simple considerations have direct implications for the fusion development strategy.

- The lack of direct PMI-NMI interaction implies that there is no immediate need to address the most pressing problems of PMI and NMI on a single integrated facility.
- The lack of direct NMI interaction with plasma performance implies that solutions to the most pressing NMI problems do not require a high-power plasma.
- The strong direct interaction between PMI and plasma performance implies that solutions to the most pressing PMI problems, by contrast, do require a high-power plasma.
- As discussed in the ReNeW Report (Thrust 12, p. 325) current and planned fusion experimental devices do not begin to approach the PMI parameter regime that needs to be investigated to support FNSF and Demo. Key issues are power density (now understood to scale roughly as PB_p/R), pulse length / duty factor with high performance deuterium plasmas, ability to operate with a very hot complete vacuum chamber and PFCs, flexibility in plasma and divertor shaping, flexibility in plasma-facing component geometry and materials, and flexibility in means for on-line removal of substantial quantities of either solid or liquid eroded material.

The U.S. fusion program may choose to move towards partnering in an international Demo, particularly if financial and/or scientific reasons indicate that moving forward with a U.S. FNSF is not practicable. Under these circumstances the U.S. should take leadership in at least one area of crucial importance to Demo. This White Paper, coupled with the discussions in the ReNeW Report and in the FESAC Materials Science and Technology R&D Report, provides the underlying logic for taking the lead in the area of the plasma-material interface using a flexible, high-power-density toroidal confinement device that does not produce copious neutrons.