Future Plasma Facing Components (PFCs) & In-vessel Components (IVCs): Strengthened Sustained and Integrated Approach for Modeling and Testing HHFCs

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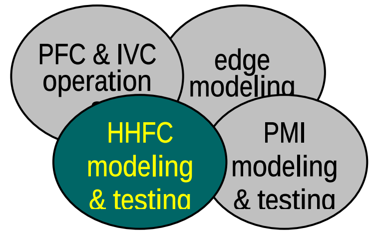
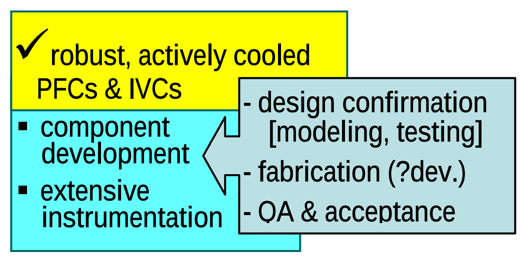


The fusion program needs a strong integrated role for fusion technology to support near term physics missions with more aggressive performance from PFC as well as ITER and other devices that lead to DEMO(s). The specific thrust here is modeling and validation through testing to develop high heat flux components for near term and future devices. The Greenwald report calls for this directly in the initiative I-6 Engineering and materials physics modeling and experimental validation. The report also makes the point (p17) about areas "traditionally designated as technology. The panel urges that these areas not be overlooked in future planning exercises. These areas are also critical as enablers of fusion plasma research as they expand options for design of new experiments."

The Report also characterized PFCs and materials as "Tier 1 *solution not in hand, major extrapolation* .." The end notes here include various references to the gaps and initiatives in the report, and other white papers in ReNew eloquently articulate various aspects of the needs related to developing appropriate, robust and reliable plasma facing components (PFCs) and in-vessel components (IVCs), such as guard limiters, RF launcher, mirrors and probes.

This white paper identifies several supporting elements (below) in modeling and benchmark testing of High Heat Flux Components (HHFCs) that are necessary complements for the development of PFCs and IVCs for upgrades of confinement devices and new devices along with enhancements of US efforts in PMI and materials (covered in other white papers).



1. Comprehensive modeling of HHFCs, including appropriate modeling in edge plasmas, PMI, thermal-hydraulics and materials behavior, plus related high heat flux testing and other experiments that provide the confirmation of performance needed for deployment of new PFCs and IVCs in existing and future confinement devices
2. A well integrated and adequately funded base technology program in which PFC/PMI efforts support the ongoing physics missions of the confinement program as well as future devices that address combined physics and technology needs
3. The technology program includes development of instrumentation for actively-cooled PFCs and IVCs needed for safe operation and to learn about their performance. (Nygren white paper)

Fundamental Point 1: The required effort in R&D in component development (and instrumentation) is challenging, time-consuming and will require strong coordination with the confinement project staff and with industrial suppliers for QA and acceptance.

The US support for the ITER first wall and limiter modules is instructive. The process and lessons learned are as important as the specific product. The machine interfaces for ITER were not all well defined. The very well received responsiveness and efforts of the US team have helped greatly in defining the scope of tasks needed, including information on machine interfaces, and in improving the design analysis. Examples: 1) state-of-the-art 3-D modeling of EM loads from disruptions that includes detailed machine configurations from ITER CAD models and the mutual inductance of the plasma and PFCs; 2) thermal-hydraulic and stress models with a suite of codes that begins with ITER CAD models; our CFD analyses have replaced correlations (e.g., Dittus-Boelter) that assume fully developed flow; (3) neutronic analyses with a fast solver that enables modeling of detailed geometry from ITER CAD models. EU fusion labs have worked continuously and extensively with industry for at least two decades. Tore Supra pioneered water-cooled PFCs and worked extensively with KFJ, Plansee and Framatom to do so. There is also a history prior to ITER of deployment of US PFCs in TEXTOR and Tore Supra prior to the dedication of the US technology program to ITER as well as work with industry on the ITER EDA that now must be restarted.

For deployments of probes and guards cooled with helium may be an effective first step and avoid the introduction of water cooling. This may also be effective for tiles that must sustain long pulses at moderate heat loads where the helium starts at room temperature rather than at the higher temperatures (and lower densities) appropriate for utilizing fusion power. Water-cooling for heat removal even for some PFCs is a big step. LHD developed divertor tiles mechanically clamped to water cooled piping and then moved to brazed tile. Tore Supra pioneered water-cooled PFCs and worked extensively with KFJ, Plansee and Framatom to do so. ITER is now developing a second generation of water-cooled PFCs. Each of these developments took many years and the deployments were planned well in advance along with supporting programs to develop and test the technology.

Fundamental Point 2: The integrated effort noted above should start when the fusion program seriously begins to consider and plan for deployment of advanced (and probably some actively-cooled) PFCs and IVCs and do so because of the complication in going to longer shots, higher power and higher wall temperatures even if active cooling is not pursued quickly. In addressing the gaps for IVCs, deployments of probes and guards cooled with helium may be an effective first step and postpone the introduction of water cooling. There has been great progress in the last decade in this area including US testing of various helium-cooled PFC targets. When we can use helium at room temperature (rather than at the higher temperatures, lower densities and with materials appropriate for extracting useful fusion power), this less-challenging adaption of the technology may even be useful for tiles that must sustain long pulses at moderate heat loads. Water-cooling for heat removal even just for some PFCs of IVCs is a big step. LHD developed divertor tiles mechanically clamped to water cooled piping and then moved to brazed tile. Tore Supra pioneered water-cooled PFCs. ITER is now developing a second generation of water-cooled PFCs. Each of these developments took more than a decade and the deployments were planned well in advance along with supporting programs to model, develop and test the technology.

When the near term physics missions include long shots and high temperatures walls, the necessary supporting program in technology becomes a continuum from upgrades for near term confinement devices through the preparation for a DEMO (see table.) Of course the challenges progress into higher reliability and robustness against long term damage from ions and neutrons as well as variations in the needs for different projects.

Table of PFC/PMI issues for various confinement devices

<u>ITER</u> ▪ long shots, active cooling ▪ Be, C, W plasma facing armor ▪ D/T inventory, T removal ▪ material erosion & transport ▪ dust control and monitoring ▪ leak detection and localization ▪ safe, reliable operation **<u>Ugraded Tokamaks</u>** ▪ higher input power scenarios ▪ longer shots ▪ mitigate/control ELMs ▪ understand/avoid disruptions ▪ protect launchers/mirrors/probes **<u>NSTX and other devices</u>** ▪ pumping with liquid lithium ▪ heat removal with liquid surfaces ▪ super-X/other divertors/targets	**<u>D/T Fusion technology test facility</u>** ▪ long shots, active cooling ▪ tritium self sufficient, T removal ▪ D/T inventory ▪ ?cold divertor, some <u>HOT TBMs</u> *[integrated FWs, instrumentation]* ▪ <u>safe</u>, <u>reliable</u>, <u>high availability</u>, <u>RAMI</u> *[so we must monitor components]* ▪ ELMs & disruptions mitigated ▪ material erosion & transport ▪ dust control, leak localization, … **<u>H/D PFC test facility</u>** ▪ long shots, active cooling ▪ some HOT PFCs, instrumentation ▪ ELMs & disruptions mitigated ▪ flexible divertor & IVC replacement ▪ ?liq. surfaces, super-X/other divertors ▪ material transport, leak localization, ..

For GA, PPPL, MIT and others to each develop on site expertise for designing and testing of high performance (actively-cooled) PFCs and IVCs would cause inefficient and costly due to the duplications and ineffective because it would less easily incorporate existing expertise in the program, including the ongoing design and R&D supporting ITER, which we can assume in this case would be less well supported. We can best address these needs in timely manner through increased resources in the technology program and stronger integration with the confinement projects, in particular modernized and upgraded facilities, more staff, and more time spent in close coordination at and with the confinement projects.

The US has made impressive accomplishments with "workhorse" PFCs made of carbon tiles on various US confinement devices and moly tiles in C-MOD. We now need a strong integrated and well coordinated US HHFC development program in the future.

Passively cooled tiles are "Model A's" compared to actively-cooled technology needed for future PFCs.

End notes

This white paper does not provide references or many specific examples. The intention is to further develop a longer white paper with examples and references in conjunction with other input aimed at the thrust of Greenwald Initiative I-6 below.

The Greenwald Panel characterized PFCs and materials as "Tier 1 *solution not in hand, major extrapolation ..*" and specifically identifies the gaps and initiatives summarized in abbreviated form below. These include strong initiatives directly to support HHFC development as well as embedded requirements related to HHFC technology to enable other initiatives.

- **G-7** Integrated understanding of RF launching structures .. compatible with the nuclear and plasma environment. The stresses ….. new materials and new cooling strategies.
- **G-12** ..engineering science base .. removal of heat at high temperatures from FW ...

Other gaps (below) emphasize separate areas that implicitly will require advancements in technology for PFCs and IVCs and must be supported for success.

- **G-2** .. high-performance burning plasmas, .. including first wall and divertor interactions, **G-5** .. off-normal events, **G-6** .. alternative configurations; and **G-7** integrated .. RF lunching structures .. new materials and new cooling strategies -- addressing these gaps is likely to require high performance HHFCs or IVCs
- **G-11** .. complete fuel cycle, particularly … separation in vessel components, **G-9** understanding of all PWI …damage to the FW, **G-13** .. evolving properties of low activation materials … FW components, **G-14** .. knowledge base for ..safety .., **G-15** .. knowledge base for efficient maintainability of in-vessel components -- addressing these gaps is likely to impose constraints upon the requirements and designs of PFCs and IVCs.

I-6. Engineering and materials physics modeling and experimental validation initiative -- This would be a coordinated and comprehensive research program consisting of advanced computer modeling and laboratory testing aimed at establishing the single-effects science for major fusion technology issues, including materials, plasma-wall interactions, plasma-facing components, joining technologies, super-conducting magnets, tritium breeding, RF and fueling systems.

I-8. Component development and testing program -- This would entail coordinated research and development for multi-effect issues in critical technology areas. Examples are breeding/blanket modules and first wall components but this initiative could include other important components like magnet systems or RF launchers. This program would most likely be carried out as enabling research in direct preparation and support of planned nuclear fusion facilities such as ITER, CTF or Demo.

I-9. Component qualification facility -- This facility is aimed at testing and validating plasma and nuclear technologies in a high availability, high heat flux, high neutron fluence DT device. It would qualify components for Demo and establish the basis for licensing. In fusion energy development plans, this machine is called a Component Test Facility (CTF).