Where are we going?
The need for an integrated view of in-vessel technology and the path forward

Comment to FESAC Priorities Panel by RE Nygren, Sandia National Laboratories, 16august2012

<u>Problem statement</u>: Critical skill sets and the knowledge base needed to build in-vessel components for fusion are vanishing from the program due to retirements and redirected scope. Also vanishing in the physics-dominated program is a critical perspective from engineers and technologists about what is real and achievable in the future. The continuing wait for a significant expansion of R&D in materials (i.e., all of fusion nuclear technology) brings a very real threat of losing the experience base in the program needed for an informed well-led transition to a future stronger program in materials and technology.

***Recommendation**: FES should develop and fund a limited set of R&D activities that engage a cadre of "experienced elders" to work with young researchers (future leaders) in two ways.*

1. ***design and build in-vessel components -** One idea is a US-supplied plasma facing component with refractory armor for an Asian tokamak. A less ambitious activity would be He-cooled refractory mockups for testing in a foreign facility. (US recently terminated this test capability.) Many countries have stated their interest in this type of activity. China, Japan, Korea, India have done so in discussions on bilateral exchanges. The EU and Russia already have an active program.*
2. ***design studies on next device -** Establish one or more design studies for the next machine(s) after ITER. Initially develop a self-consistent set of requirement for exhausting heat (may require an innovative divertor and new approach for protecting the first wall), heating and fueling the plasma, self-sufficient breeding of tritium, and systems for starting up, maintaining and shutting down the plasma. Then iterate to define subsystems in more detail and refine requirements. Use this to push important decision points. Can the advanced tokamak line succeed and what are the decision criteria? As we look at power handling and the poor conductivity of ferritic first walls and the difficulty of moving to solutions with refractory materials, what are the criteria and the pathways (program elements with progress and branch points) needed to make the decisions?*

A key point here is a transfer of knowledge from those with the perspective of an integrated view of fusion nuclear technology (see discussion) to young researchers – a hand off of the baton. So the selection of the team is important, and it seems unlikely that FES would achieve the objectives stated above through an RFP since the members of the most effective team for this would likely end up competing in various proposals.

Discussion

What is an "integrated view" of in-vessel technology?

An integrated view must has two general features: (1) a reasonable basis in the physics of confining the plasma in terms of the scenario for operation, control, heating and fueling and robustly maintaining the plasma in a state that prevents significant damage to the device; and (2) credible in-vessel systems. The integrated view of in-vessel technology combines understanding of the functions and requirements of the in-vessel subsystems and how a successful design can satisfy many overlapping and competing requirements. ITER is our first really detailed design of a nuclear core for a magnetic fusion device and has provided a wealth of information about the integration of systems.

But the integrated view of in-vessel technology for post-ITER fusion devices also includes an understanding of how the needed engineering is supported by the underlying science and what is needed to progress, and what types of solutions are accessible through existing technology and what development is possible within a specified time frame. This integrated view is also needed to address how progress in plasma science depends on technology and engineering.

US program should be ready in future to capitalize on the knowledge base from designing and building ITER. But "being ready" means the program has access to people with an integrated view of post-ITER in-vessel technology that is <u>fundamentally different than the ITER knowledge base</u>. (Additional comments later include examples of these differences.)

Will we know what we want? What underlies a credible view for in-vessel components?

The central issue is whether the program will try to maintain some minimal capability to look forward with this integrated view or will have to recreate this in the future. The latter seems to be our present path simply by default. It saves money but has two big drawbacks.

First, and perhaps more important, is the likely additional damage to the program's capability to develop a plan that leads to a credible path toward fusion energy. Fusion is under scrutiny for relevance and has been asked repeatedly for such a plan and has failed to deliver. Major objectives on this path are confinement with a stable plasma and reliable scheme to exhaust power and subsystems to safely breed and harvest tritium. The issues in materials and technology are well documented (Greenwald Panel, ReNeW, FNSPA and FESAC Materials Panel). Credibility comes when good science can underpin our projections for future and more detailed engineering, i.e., design and modeling of subsystems have a well-supported basis in R&D.

Second is the cost and delay in program to recreate an integrated view after we lose the small cadre of people now in the program who have such experience and could mentor the future specialists who must come to understand the complex interdisciplinary problems in the engineering of fusion components. This is important not only because the increased cost, but the likely delay (years) to develop effective experimental programs would come at a time when quick results would be expected because of a strong new initiative in materials (including fusion nuclear science and technology).

The point here is one of urgency to continue to develop and maintain an integrated view about the science and technology of plasma facing components (and other in-vessel components). A core capability in the near term means retaining experience, continuing some experimental programs, recruiting new talent and building appreciation for an integrated view in some young leaders.

A vanishing perspective - where have all the builders gone?

An assumption that the US can develop PFCs to address the gaps and needs identified in ReNeW+ and will set reasonable objectives based on the distilled wisdom from past experience may be wrong because our access to this past experience is disappearing. Let's look briefly at the evolution of the US program. The fusion program in the late 1970s and early 80s included the elements below.

- At its high plateau in 1977-83, our budgets of $850-900M in inflation-adjusted 2010 dollars were ~3 times that in flat period from 1997-2008 and the mix of people in the program differed from today.
- Teams with industrial partners built TFTR, DIII-D and Alcator C-MOD and designed other devices that were not built, including the Elmo Bumpy Torus and the ITER-like US Fusion Engineering Device.
- industry brought expertise about materials, fabrication, quality assurance, etc. and large integrated systems to various design studies of power plants. Interest by industry continued in part because the US had a near term plan to build a large fusion device (that eventually morphed into ITER) and seemed to be moving forward toward the goal of fusion power.
- The US built several limiters for TEXTOR (German tokamak) and three limiters for Tore Supra (French tokamak) including a water-cooled limiter that removed ~1 MW of heat from the plasma under essentially steady state thermal-hydraulic conditions. The FES redirection of US scope toward the first ITER eliminated such collaborations.
- For the first iteration of ITER, the US and Japanese successfully built a divertor cassette body using a US precision casting process that other countries did not believe could deliver adequate quality. In other work in design with intent to manufacture, we identified realistic processes (available or near-term) and performed high heat flux testing to gage methods of fabrication and how the parts failed.

In the initial US scope for the current ITER project, our commitment for 20% of the first wall included design and manufacturing and would again have brought US industry into the program. Two years ago, this scope changed. The responsiveness and the high quality of the US work led to much more design work, but now the US will not build any plasma facing components.

Few involved with the activities noted above are still in fusion. And, FES is terminating funding for the Plasma Materials Test Facility, which has a long history of high heat flux testing and development of refractory plasma facing components, and for ALCATOR C-MOD, the only US plasma confinement with metal walls. (We anticipate that post-ITER devices and ITER will have metal walls.) And, at this point we lack direction in how the US program will develop advanced plasma facing components.

Additional comments on an integrated view and post-ITER devices

Among many issues raised in the development of ITER itself are the items below. What we can project about in-vessel components based on our current knowledge plus their resolutions for ITER is limited.

a. Due to uncertainties in how heat flows from the plasma, ITER's design changed from its initial design with a smooth first wall and heat load of 0.5 MW/m^2 to a non-conforming first wall (explained further in item **i**) and maximum heat load of 5 MW/m^2.
b. The ability to manage the heat load on the divertor depends on a knowledge of the plasma edge (and especially the power-scrape-off length that determines the peak heat load and width of the toroidal stripe where most of the power is deposited), which at this point is highly uncertain.
c. Management of the heat load in the divertor also includes the measurement and control systems used to maintain the position of the plasma. Important attributes of these systems are, when instabilities occur, the time to sense the problem and issue proper commands to restore stability, the reliability of these systems, and the power and current-carrying capability in the magnets needed to restore stability within a time that does not damage in-vessel components while the plasma is away from the desired location.
d. Reliable systems are needed to control and mitigate plasma instabilities (disruptions and large ELMS) that otherwise would present unacceptable heat loads and electromagnetic loads.

The operation of ITER wilt eel us a lot about the issues above. In looking forward toward a DEMO or its precursors after ITER, several aspects of the needed nuclear technology are not addressed in ITER, including the items below.

e. The water-cooled plasma facing components (PFCs) is a dead-end technology. DEMO-relevant PFCs need high temperature coolants that couple to efficient power cycles. The likely candidates are solid wall cooled with helium or salts, or liquid walls that continually replenish the surfaces bombarded by ions from the plasma.
f. DEMO-relevant operation means operation with a plasma edge different than that in ITER and in proximity to a hot wall where the physical chemistry of the plasma interacting with the surface will differ, for example, deuterium and tritium not embedded will quickly recirculate back into the plasma and implanted helium may cause gross rearrangement of the surface microstructure.
g. The wall-mounted modules in ITER do not have tritium-breeding blankets. Breeding blankets have an integrated first wall and the nature of this system is fundamentally different from ITER because of the integrated solution of the first wall cooling, and the production and harvesting of both heat and tritium from the blanket. In regard to the ITER Test Blanket Module program, the R&D and preparation of these modules will provide the most information and experience about fusion blankets rather than the actual testing in ITER. Also, the US has minimal engagement in the program at this time.
h. Most of the design studies of power plants in the past have relied on what we call "conforming walls" (as in item **a**) where the surface of the plasma facing components follows a surface parallel to the edge of the plasma and the heat is spread out fairly evenly over the first wall. (This came from an assumption that only radiated power went to the first walls.) We do not have design solutions for power plants based on this current understanding of power distribution and with appropriate structures (e.g., poloidal limiters or other protection) that will withstand heat loads significantly higher than the average power loading were it spread evenly over the first wall.

While discussions in various forums (ReNeW, the Fusion Nuclear Science Pathways Assessment and the FESAC Materials Subcommittee) have raised these points, the answering arguments tend to be presented in a piecemeal fashion. Below are two examples.

i. *Proposed: Move the wall back.* Comment: we still may need structures closer to the plasma to launch power and these now protrude and require cooling and protection.
j. *Proposed: Rely on non-inductive current drive.* Comment (quoting others): Achieving quiescent heat exhaust, dealing with erosion and accessing non-inductive scenarios are tightly coupled. With the constraint of fixed global power density, P/S, (where P is power and S is surface are wetted by the plasma) raising the operating density increases collisionality and radiation efficiency. This eases heat exhaust requirements but simultaneously impacts core scenarios through the Greenwald limit and current drive. The divertor temperature must be lowered to control erosion. The use of impurities in the plasma edge for radiative dissipation of energy can impact the pedestal. The limits for plasma surface interactions (e.g., coming from erosion and

surface modifications) and the limits for plasma facing structures on temperature of materials and control of erosion must be an integral part of the development of advanced non-inductive core/pedestal scenarios, rather than an issue examined "after the fact."

Conclusion

The nature of the discussion here does not fit neatly into a discussion of giving priority to one type of research over another. However, the aspect of building on past experience and attracting and training new talent for the program is a general theme.

Fusion technologists who have worked with physicists for a long time acquire the perspective of how nuclear in-vessel systems perform (engineering with underlying science base) and how these systems are inter-related and constrained (overlap with systems engineering and physics basis for design). This is a highly specialized knowledge base and those who have it are an endangered species in the program. This valuable knowledge will be lost if the program does not take positive action.