Requirements for a Confinement Device with a Goal to Develop Tritium Breeding Blanket Modules, Based on FESAC Fusion Development Path Plan

Rob Goldston, Princeton Plasma Physics Laboratory

Introduction

The investment in a powerful high-duty-factor DT device with a goal to test blanket modules for Demo will be very considerable. Dale Meade has developed[1] a scaling for the estimated cost of copper-coil DT devices, in \$2002, of \$0.7M per metric tonne. (See Figure 1.) Escalated to \$2012 at 3.5% p.a., this comes to an easy-to-remember \$1M/t. For an estimate of the costs involved, at least at conventional aspect ratio, note that the toroidal and poloidal magnet systems alone for the FDF device weigh 4467t[2]. For a U.S.-only investment in the range of \$5B, it will be very important that the community be able to express high confidence that such a device will successfully achieve its mission. This will remain true even for the lower mass and cost of a low-aspect-ratio machine.

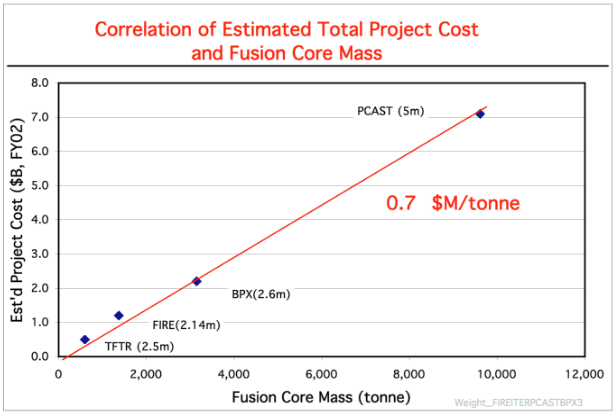

Figure 1: Meade's Scaling for cost of DT devices.

In this paper we present critieria for the R&D knowledge base required to begin construction of a device with a Component Test Facility (CTF) mission. This knowledge base will allow a CTF to proceed with confidence and quickly deliver the needed science and technology.

R&D Needs

Working from the plasma outwards one can develop a list of R&D requirements to have confidence in the design and construction of a device to test fusion blankets. For simplicity here we consider mainly the requirements for a conventional aspect ratio device. The 2003 FESAC Fusion Development Plan report[3] (the so-called "35-Year Plan") constructed by a wide community group called for key results from existing MFE experiments, from ITER, and from a first new MFE Performance Extension experiment, in order to support the decision to construct a CTF (See Figure 2.) The CTF design, however, was assumed to commence in advance of the data required for the construction decision, consistent with the "Fast Track" philosophy adopted by that group. During the construction phase, the results from a first run of the International Fusion Materials Irradiation Facility (IFMIF) were also assumed to provide necessary information for final choices of materials to be used in CTF.

Confidence that the required confinement and beta can be achieved and sustained for very long pulses. Achievement of high fusion power output for a given auxiliary power complement requires specified levels of confinement and β, at dimensionless parameters beyond those investigated to date. The presently available knowledge base, as evidenced by the results of the recent ITER Design Review assessment of the options to reduce the operating parameters of ITER[4], does not provide high confidence that ITER (or other future tokamaks) can reliably be assumed to achieve HH > 1. Initial operation of ITER at reasonably high power, however, will provide key information on the scaling of confinement, particularly with ρ^*. Indeed since there are very little data available for self-consistent, locally fully non-inductive operation of any tokamak, high confidence of high values of HH and β_n for extremely long pulses, particularly outside of the currently explored range of dimensionless parameters was viewed by FESAC as needing support by a) successful results from existing MFE Performance Extension devices, as well as the Asian superconducting tokamaks then under construction, b) successful operation of ITER at high power, and c) results from a new U.S. MFE

Performance Extension device with a mission to support CTF. The Development Path Panel, however, did not conclude that high-gain DT operation in ITER was a requirement to begin CTF construction.

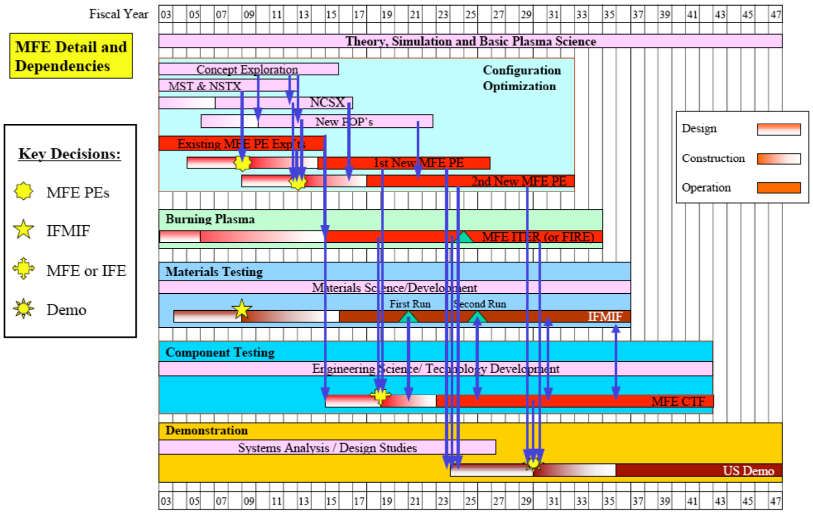

Figure 2: FESAC Fusion Development Path Report linkages.

Confidence that internal components can support the high duty factor required for high neutron fluence. While the Fusion Development Path document emphasized the importance of the development of techniques to handle normal and off-normal heat fluxes, studies on ITER have brought this issue into closer focus. For a CTF device whose plasma facing components must operate with 16x higher duty factor than ITER's planned[5] value of 1.9% (FESAC specified 30% duty factor for CTF and > $6 \mathrm{MWyr/m^2}$ neutron fluence) and 3000x longer pulses[6] than ITER's standard 400 seconds, one must advance well beyond ITER's requirements for component lifetime and dust production in order to have high confidence in the success of a CTF. Given, again, the results of the recent ITER Design Review[4], we are clearly not yet near that point. The importance of these issues, due to the time-consuming nature of component replacement, is well illustrated in Peng et al.[7]

The intensity of the steady challenge to the first wall components of CTF can be characterized by the ratio of power to major radius, P/R, for continuous heat flux with an ill-determined but not strong scaling of the scrape-off layer width with machine size. For the case of high radiated-power fraction, or the assumption of a positive scaling of scrape-off width with size, one could consider P/S, power per unit surface area. The off-normal challenge can be characterized by stored energy divided by surface area, W/S, for example if the energy is to be dissipated by volumetric radiation or localized blanket contact. In a CTF operating at $2 \mathrm{MW/m^2}$ of peak neutron wall load, these challenges range from equal to, to much greater than, the challenges in ITER.

	$P_\alpha + P_{aux}$ (MW)	W_{th} (MJ)	P/R (MW/m)	P/S ($\mathrm{MW/m^2}$)	W/S ($\mathrm{MJ/m^2}$)
ITER (Q=10)	150	320	24	0.23	0.50
FDF[5]	108	70	43	1.03	0.67
ST-CTF[6]	73	32.5	61	1.10	0.49

Clearly results from moderate-pulse, low-duty factor operation of ITER will be critical for developing realistic understanding of the steady and off-normal heat loads to be expected in the much more demanding steady-state environment of CTF. In general it should be noted that the specific solutions adopted in ITER such as 1) water-cooled PFCs, 2) periodic dust clean-up, and 3) the use of a 1cm Be – 2cm Cu – 5cm steel first wall for disruption survival, will not be acceptable in a CTF. The high first-wall temperature, high duty factor operation and high tritium breeding ratio requirements, respectively, take these three options off the table, so alternative solutions must be developed and qualified for the anticipated high-heat-flux, high-first-wall-temperature, long-pulse CTF environment. Likely CTF will require completely new technologies such as He-jet-cooled tungsten divertor targets, or liquid metals. These technologies need to be qualified in a long-pulse, high-heat-flux, hot-walls experiment before implementation on CTF, in order to assure rapid progress in CTF to its mission-critical high-neutron-fluence operation.

Confidence that tritium can be managed adequately to support high-duty-factor operation. The problem of tritium management can be broken into three categories. Tritium retention in the near surface of plasma-facing components and in dust, tritium permeation through and trapping in these components, and tritium production in breeding blankets (including permeation and trapping).

Near-surface tritium retention rates acceptable for the operation of ITER will not necessarily be acceptable for CTF. Present experimental data are controversial. Furthermore, experimental tests and innovations in a confinement device with long pulses, CTF-relevant hot walls and wall materials, as well as CTF-relevant heat and particle fluxes will be required to have confidence that near-surface tritium accumulation in CTF will permit mission-critical high-duty-factor operation. The ability to predict dust production and to clean up dust in real time in a high-power, long-pulse, hot-walls environment also needs to be demonstrated, in order to have confidence that the required high duty factor blanket testing can be achieved.

Tritium permeation through and trapping in bulk materials is a topic that can and should be studied in appropriate test stands, using neutron-irradiated materials, prior to the design of CTF.

The FESAC Fusion Development Plan focused particularly on the importance of the initial Tritium Blanket Module tests in ITER, to provide data for the selection of the technically most attractive approaches to develop further in CTF. The ability to increase the isotopic concentration of ^{6}Li *vs.* ^{7}Li greatly mitigates previous concerns about details of neutron transport and tritium production in the blanket[8]. However a very pressing question, as noted above, is the degree of neutron absorption by the first wall in front of the blanket modules, which must withstand normal and off-normal heat fluxes. High-power results from ITER will be critical for assessing the requirements on the CTF first wall. It was also recognized by FESAC that a first run of sample tests in IFMIF was required to finalize the materials choices, assuring adequate initial lifetime of blanket modules in the much more costly CTF.

Conclusions

There are very serious design requirements for a high-power, high-duty-factor DT device with a mission of blanket testing, including adequate neutron shielding of the inner wall[9], divertor regions, and around neutral beam ducts. These will drive the size and mass of such systems. The device cost will be large, and its accessibility for diagnostics and flexibility to adapt to surprises will be limited. Thus a strong R&D program is required to support the decision to begin construction of such a device. The FESAC Fusion Development Path report indicated critical support for a CTF from existing and future Performance Extension confinement experiments, from high-power operation of ITER, and from IFMIF. The analysis presented here supports and strengthens those conclusions, particularly in the areas of normal and off-normal plasma-wall interactions.

---

[1] Meade, D. M., http://fire.pppl.gov/snow_ITERFIRE_cost.pdf

[2] Smith et al., APS 2008, http://fusion.gat.com/fdf/files/SmithAPS08.pdf

[3] FESAC, "A Plan for the Development of Fusion Energy",
http://www.ofes.fusion.doe.gov/More_HTML/FESAC/DevReport.pdf

[4] Hawryluk, R.J., et al., http://www-pub.iaea.org/MTCD/Meetings/FEC2008/it_1-2.pdf

[5] Ciattaglia, S., et al., submitted to 25th SOFT Conference, 2008

[6] Stambaugh et al., APS 2008, http://fusion.gat.com/fdf/files/StambaughAPS08.pdf, VG#5

[7] Peng et al., IAEA 2008, http://www-pub.iaea.org/MTCD/Meetings/FEC2008/ft_p3-14.pdf

[8] El-Guebaly L., Malang, S., White Paper at "Harnessing Fusion Power" workshop

[9] Wong et al., APS 2008, VG http://fusion.gat.com/fdf/files/WongAPS08.pdf, VG#22