**ST-FNSF White Paper for FESAC Subcommittee on Facilities**

M. Peng, J. Canik, C. Neumeyer, M. Ono, A. Redd, S. Sabbagh, February 14, 2013

The Director of DOE's Office of Science has issued a charge to FESAC to identify the scientific missions of possible upcoming major U.S. fusion facilities, including a Fusion Nuclear Science Facility (FNSF). At present, a wide FNSF parameter space can be envisioned, including tokamaks of differing aspect ratios and wide-ranging R&D capabilities. This paper contributes to the development of a community consensus by both documenting the need for and the levels of readiness of FNSF generally, and describing in more detail FNSF options based on the spherical torus/tokamak (ST) concept.

**What research will be performed by the ST option for FNSF? Why does this produce world-leading science for fusion energy?**

Four topical themes for the scientific and technical issues that must be resolved to achieve practical fusion energy were identified in a 2007 FESAC report:[1] (1) controlling high-performance burning plasma, (2) taming the plasma-materials interface, (3) conquering nuclear degradation of materials and structures, and (4) harnessing fusion power (tritium science, chamber technology and power extraction). The use of a relatively small volume neutron source (VNS[2]) to fulfill this integrated nuclear science mission, defined by addressing simultaneously issues (2) – (4), motivates the consideration of the recent ST-FNSF concept[3]. These studies have shown that the ST, with a single-turn toroidal field coil center post,[4] can allow a VNS[2] of reduced size and fusion power, while delivering a given D-T fusion neutron flux (up to 1-2 $MW/m^2$) on the internal components. The ST FNSF thus presents an expeditious approach to address the FNSF mission.

This mission will include database for modeling and simulation of controlled burn, at least for low $Q_{DT}$ to be interpolated from the ITER plasma, to ensure the continuous production of high neutron flux. This mission will further require chamber components and enabling technologies that are designed and built with the intention to experimentally investigate relevant properties identified in issues (2) – (4), in the full fusion nuclear environment of VNS. In return, the FNSF, with its accompanying R&D program, promises new database that enables discovery, challenges understanding, and motivates improvements toward practical fusion energy. The capability to achieve this FNSF mission for the first time will enable world-leading research and potentially accruing world-leading fusion energy science results.

The FNSF mission complements that of ITER, which aims to resolve issue (1) by achieving $Q_{DT}$ up to 10 while delivering up to 0.7 $MW/m^2$ neutron wall flux on its chamber components and up to 10 $MW/m^2$ plasma heat flux on its divertor, for up to 400 s at a time. During its second phase, ITER aims to operate at $Q_{DT}$ up to 5 for up to 3000 s at a time. The combined

---

[1] http://science.energy.gov/~/media/fes/fesac/pdf/2007/Fesac_planning_report.pdf.

[2] M Abdou, M. Peng et al, *Controlled Nuclear Fusion Research 1994,* **2** (IAEA-CN-60/F16 1995) 733; M Abdou, *Fusion Engineering and Design*, **27** (1995) 111; M Abdou et al, *Fusion Technology,* **29** (1996) 1.

[3] YKM Peng et al, *Plasma Phys. Control. Fusion,* **47** (2005) B263; YKM Peng et al, *Fusion Energy 2008*, IAEA-CN-67/FT-P3-14; YKM Peng et al, *Fusion Science & Technology* **56** (2009) 957; YKM Peng et al, *Fusion Energy 2010*, IAEA-CN-68/FTP-2-3Ra; YKM Peng et al, *Fusion Science & Technology* **60** (2011) 441; YKM Peng et al, IEEE/NPSS SOFE-24 (June 26-30, 2011).

[4] M Peng and J Hicks, *Fusion Technology 1990 (SOFT-19)*, **2** (1991) 1287; F Najmabadi et al, *Fusion Engineering and Design*, **65** (2003) 143.

experimental scientific database from ITER and FNSF will inform the U.S. decisions regarding fusion DEMO and its associated R&D program. It is thus desirable to fulfill the FNSF science mission during the ITER era,[1] which at present is expected to extend to 2030 and maybe further.[5]

It is relevant to note that this FNSF mission, framed by the four scientific topical themes, is within the FES mission.[6] This mission contrasts the energy production-oriented mission of the fusion programs proposed in China,[7] E.U.,[8] Japan,[9] and Korea.[10] There is thus interest to extend the FNSF science mission toward the DEMO mission by including net electricity ($Q_{Eng} \geq 1$) production, which in turn requires high $Q_{DT}$ (~ 10) in a "FNSF-Pilot".[11] The capability to achieve this extended mission for the first time will confirm high-$Q_{DT}$ burning plasma science for continuous operation far beyond ITER plasma durations, enable world-leading fusion power demonstration capabilities, accrue world-leading science in continuous control of strongly burning plasmas, and likely achieve world-leading advances in fusion power engineering and technology.

The FNSF-Pilot mission will most likely entail more efforts and tasks than the present ITER project, while enticed by a potential to deliver the above results at an earlier time than the ITER-only-before-full-DEMO strategies proposed by the other countries. The FNSF-science mission in contrast will aim to introduce critical science information needed to enable practical design and operation of a fusion DEMO. The leaders of the above world programs recently indicated their interest in collaboration in a U.S.-led FNSF and the associated R&D program.

**ST FNSF concept varieties description**

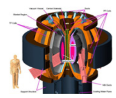
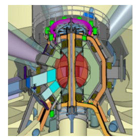
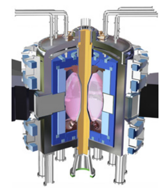
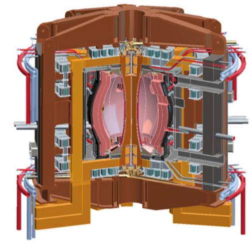
In the absence of conceptual design and cost analysis, it is premature to choose among a variety of ST FNSF concepts already available in the literature. (See Table below)

Common to these concepts is an anticipated requirement of ready replacement via remote handling of the toroidal field coil center post and the experiment modules of the chamber components (blankets, divertors, first wall, RF launchers, diagnostic front ends, etc.). The third variety further anticipates the need to modularize all activated components to make possible extensive replacement via remote handling. These will enhance flexibility for possible upgrades of the fusion nuclear science research capabilities from initial operation to full realization, in case such staging becomes appropriate to optimize the FNSF experimental program.

Regarding the fourth variety "FNSF-Pilot," an ST pilot plant is envisioned to also perform the CTF/FDF[12] missions while incorporating design features projected to enable production of net electricity. The design would be scalable directly to a power plant and be as small as possible to avoid the device cost and risk of a power plant. The overall goal is to integrate key science and technology capabilities of a fusion power plant in a next-step R&D facility while targeting electricity break-even $Q_{eng} \geq 1$ demonstration using $P_{fusion}$ = 0.3-0.85 GW (ITER level), far below the power-plant level of $P_{fusion}$ = 2-5 GW.

---

[5] Sauthoff, private communications.
[6] http://science.energy.gov/fes/.
[7] Y Wan, "Mission and readiness of a facility to bridge from ITER to DEMO," presented at First IAEA DEMO Program Workshop (UCLA, October 15-18, 2012).
[8] F Romanelli, "A roadmap to the realization of fusion energy," presented at FESAC meeting (January 31, 2013).
[9] T Tobita et al, "Reconsideration of tokamak DEMO concept based on the latest design study," *ibid, reference 7.*
[10] GS Lee, "Korean roadmap and international collaboration for DEMO R&D," *ibid*.
[11] Menard et al, *Nuclear Fusion*, **51** (2011) 103014.
[12] CTF = Component Test Facility, FDF = Fusion Development Facility. See white paper to subcommittee.

| | I. Minimalist[13] | II. Modest Tritium[14] | III. Science mission[4] | IV. + $Q_{Eng} \geq 1$[11] |
|---|---|---|---|---|
| ST FNSF Varieties |  |  |  |  |
| R (m) | 0.5 | 0.84 | 1.3 | 1.6 – 2.2 |
| $B_T$ (T) | 1.5 | 1.8 | 2.7, 2.9, 3.6 | 2.4 – 3.0 |
| $I_p$ (MA) | 1.5 | 6.5 | 4.2, 6.4, 8.4 | 11 – 18 |
| $P_{in}$ (MW) | 15 | 40 | 22, 44, 61 | 50 – 85 |
| $P_{DT}$ (MW) | 2.6 | 35 | 19, 76, 152 | 100 – 850 |
| $W_L$ ($MW/m^2$) | 0.2 (avg) | 1.0 (avg) | 0.25, 1.0, 2.0 (outboard) | ~ 0.9 – 2.0 (outboard) |

**Research gaps, needs, and opportunities to be addressed by ST FNSF**

These ST FNSF concepts encompass a wide range in size, performance, and research capabilities that in turn are subject to accessibility via remote handling, which impacts reparability, accessibility, maintainability, and inspectability (RAMI). This range likely will lead to varying ability to address the identified research gaps, needs, and opportunities articulated in the FESAC reports.[1,15,16] At a conceptual level, it can be reckoned that advancing from variety I through IV would increase progressively the scope of mission and the associated scientific opportunities and research gaps, which are described as research thrusts in the ReNeW report[15].

The table below summarizes the potential scientific contributions of these varieties, for up to Thrust 16 from ReNeW, plus the $Q_{Eng} \geq 1$ demonstration. ITER entries are added to show complementarity or overlap. Here, major contribution is indicated by 3, significant contribution by 2, minor contribution by 1, and no important contribution is left blank.

**Scientific and engineering challenges (requisite R&D) before initiating construction**

This table also provides a framework for identifying requisite R&D to resolve remaining scientific and engineering uncertainties before initiating construction. In compiling the requisite R&D levels, relevant information in a report produced recently by the ST Coordinating Committee (STCC)[17] regarding the ST physics research priorities is applied. Here, critical need is indicated by 3, significant need by 2, minor need by 1, and no important need is left blank.

---

[13] BV Kuteev et al, *Plasma Phys. Reports,* **36** (2010) 281; A Sykes et al, *IEEE Transactions Plasma Science,* **40** (2012) 715; V Yu Sergeev et al, *Plasma Phys. Reports*, **38** (2012) 521.
[14] GM Voss et al, *Fusion Engineering Design,* **83** (2008) 1648.
[15] Research Needs for Magnetic Fusion Energy Sciences, June 8-12, 2009 (Office of Fusion Energy Sciences).
[16] http://science.energy.gov/~/media/fes/pdf/workshop-reports/20120309/FESAC-Materials-Science-final-report.pdf.
[17] U.S. ST Coordinating Committee (STCC), "Five-year spherical torus research priorities in support of high-gain burning plasma, fusion nuclear science, and plasma materials interface missions," submitted to FES (Dec. 12, 2009).

| Requisite R&D | | | | | Scientific Contribution | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IV | III | II | I | ITER | IV | III | II | I | ITER | Research Thrusts + $Q_{Eng} > 1$ Demonstration |
| 2 | 1 | | | 1 | 3 | 2 | 2 | 1 | 3 | T1: Develop measurement techniques to understand and control burning plasma |
| 2 | 1 | 1 | 1 | 1 | 3 | 1 | 1 | | 3 | T2: Control transient events in burning plasmas |
| 2 | 1 | 1 | | 1 | 3 | 1 | 1 | | 3 | T3: Understand the role of alpha particles in burning plasmas |
| | | | | 1 | | | | | 3 | T4: Qualify operational scenarios and the supporting physics basis for ITER |
| 3 | 2 | 2 | 1 | 1 | 3 | 1 | 1 | | 3 | T5: Expand the limits for controlling and sustaining fusion plasmas |
| 2 | 1 | 1 | | 1 | 3 | 1 | 1 | 1 | 3 | T6: Develop predictive modeling for fusion plasmas, supported by theory and challenged with experimental measurement |
| 2 | 1 | 1 | 1 | | 1 | | | | 3 | T7: Exploit high-temperature superconductors and other magnet innovations to advance fusion research |
| 3 | 1 | 1 | | 1 | 3 | 1 | 1 | | 3 | T8: Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas |
| 3 | 1 | 1 | | 2 | 3 | 2 | 2 | 2 | 2 | T9: Unfold the physics of boundary layer plasmas |
| 3 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | T10: Decode and advance the science and technology of plasma-surface interactions |
| 3 | 1 | 1 | | 1 | 3 | 3 | 3 | 2 | 2 | T11: Improve power handling through engineering innovation |
| 3 | 3 | 3 | 3 | 2 | 3 | 3 | 2 | 2 | 1 | T12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 | 1 | 1 | 1 | T13: Establish the science and technology for fusion power extraction and tritium sustainability |
| 3 | 1 | 1 | | 1 | 3 | 3 | 2 | 1 | | T14: Develop the material science and technology needed to harness fusion power |
| 3 | 3 | 3 | 3 | | 3 | 3 | 2 | 1 | 1 | T15: Create integrated designs and models for attractive fusion power systems |
| 3 | 2 | 2 | 1 | | 3 | 3 | 2 | 1 | | T16: Develop the spherical torus to advance fusion nuclear science (including solenoid free startup to full plasma current) |
| 3 | | | | | 3 | | | | | Demonstrating $Q_{Eng} > 1$ |

As an experimental facility with a fusion nuclear science mission, capable of ready replacement of chamber components via remote handling, the test modules are to be provided by the accompanying R&D program to fit the constraints of the FNSF design and operation (thus a minor need of FNSF *per se*). ITER design, R&D and construction will contain burning plasma database and inform component design needed by the first three varieties of ST FNSF with comparatively modest parameters. The remaining critical and significant needs (challenges) in T5, T10, T12, and T16 are identified in the STCC report[17] due to the 2-week plasma durations at heat fluxes comparable to those anticipated in ITER for plasma durations up to 3000 s.

Success of magnetic fusion science applications such as the larger ST-FNSF varieties[3,11] will represent the culmination of applied physics research spanning many years. The predictive physics understanding needed to confidently extrapolate plasma transport (T3, T8), stability (T2), power handling (T9, T10), fully non-inductive sustainment (T5), and advanced control techniques enabling near-zero disruptivity (T2) will be tested and must work in a fully integrated fashion in an ST-FNSF. This integration step, and any further development that remains in these areas, will produce world-leading scientific research opportunities for the U.S. program in the low collisionality, high performance, and long-pulse plasmas (weeks of continuous operation).

The US presently holds world-leadership in ST physics research and device capability, which gives high confidence that this world-leadership would be maintained by the US taking the next logical step in the development of this research line. Continued leverage of our international collaborations with researchers on both ST, and long pulse tokamak devices will continue to significantly bolster our scientific understanding of the long pulse aspects of plasma sustainment.

An ST-FSNF device will require expertise from the majority of the existing US magnetic fusion research groups. Multi-institutional participation of groups of all scales spanning from small university programs to national labs will need to evolve into a new national research partnership, beyond today's magnetic fusion research paradigms.

Considering FNSF-Pilot, T5 values reflect the impact of differing bootstrap current fractions closer to unity (critical need) vs. ~0.5 (significant need), the former being driven by the mission of $Q_{Eng} \geq 1$ demonstration. The critical needs of FNSF-Pilot, in contrast to the minor needs for ITER or the smaller FNSF's in other research thrusts reflect the logical difference between required performance vs. proposed testing mission, respectively. The designs optimize to deliver performance to achieve mission. To deliver more will introduce more R&D needs / challenges.

T15 remains a critical need as part of a DOE Critical Decisions process for all varieties, from which the R&D needs / challenges, only conceptualize here, may be corrected.

**Construction, schedule and operation costs**

A crude sense of device cost can be indicated by comparing the ITER device volume (width, depth, height ~30m, 30m, 30m) with that of an anticipated FNSF (~ 10m, 10m, 15m, variety III), indicating a wide ratio of 3x3x2 = 18. Assuming a similar hardware fill-fraction and device construction cost per volume, the construction cost for this variety would crudely be ~5% of that of ITER. We hasten to add that the cost scaling of facility components and infrastructure from ITER to FNSF depends on a large number of systems performances and physical dimensions, and is expected to compare much closer to a small multiple of one. Estimates of the construction cost, annual operation cost, and schedule of an ST-FNSF can be obtained by carrying out a DOE Critical Decision process on FNSF or its scientific and technical equivalent.

**Ability of facility to contribute to world-leading science in next decade (2014-2024)**

*Grade: (a) – Absolutely central*

**Readiness of the facility for construction**

*Grade: (b) – Significant scientific/engineering challenges to resolve for the smaller varieties of ST-FNSF (T5, T10, T12, T16, see Table), taking advantage of ITER efforts; the scope and magnitude of the challenges increases substantially for FNSF-Pilot, acquiring it Grade (c).*