

Multidisciplinary multi-physics (MDMP) system simulation and an evolutionary experimental FNSF in support of Fusion Materials Science research

YK Martin Peng, ORNL, UT-Battelle

Purpose: To respond to Charge 3 within the constraints of “five year period following the roll-off in the ITER project construction funding”, and “the roll-off allows a 50 percent increase in the non-ITER magnetic fusion level of effort ... over that in the FY2013 budget, and that research on fusion materials science and harnessing fusion power will capture much of this increase.” Assuming these constraints, research priorities are recommended to pierce the inevitable fog of uncertainty from multiple design options with varying levels of research progress. Such an emphasis also frames a mission for FNSF to develop “data base for fusion reactor internals and, in parallel with ITER, provide basis for DEMO.” These priorities, if refined and executed efficiently, will maximize progress in fusion materials science research during the ITER era, within this funding constraint.

Content: 1) Assumptions, metric, goals for the suggested priorities, 2) Requisite research elements of “Fusion Materials Science” depend on design options of the internals, 3) Tool needed to pierce the fog of benefit-cost-risk uncertainty among design options, 4) Mission of an evolutionary experimental FNSF, and 5) Supporting research priorities.

1) Assumptions, metric, goals for the suggested priorities

A) The U.S. ITER project funding would be capped so that a roll-off funding of about \$100M/yr (“50 percent increase in the non-ITER magnetic fusion level”) would appear in 2020, to enable the start of a funding-constrained experimental FNSF project and the continuation of associated research program in materials science. **B)** A funding wedge over the preceding 5-years starting in 2015 to start prerequisite research, and prepare for DOE Science critical decisions on the experimental FNSF project. **C)** The recommendations of the “Greenwald Panel,” ReNeW, and the more recent “Fusion Materials Science and Technology Research ...” reports remain correct. **D)** A metric for the recommended priorities (answering Charge 3) is the clarity of the mission and identified research to bridge the remaining science gaps toward net-electricity demonstration. Electricity demonstration, however, is assumed to be beyond the scope of DOE Science. **E)** Goals for the chosen priorities include determining whether the identified requisite research and an FNSF are adequate for the FES strategic goal of fusion materials research, and can be executed within this funding profile and schedule. **F)** Another goal is to identify research that also engages core competencies of research communities beyond Fusion Energy Science; these include DOE Science, NE, and NNSA.

These priorities aim to support the success of the FES strategic thrust on materials science, and do not assume *a priori* any engineering design cost required by any prospective FNSF project, including those assumed in the FESAC Fusion Development Path Panel report [1].

2) Requisite research depends on design options of the internals

A) Several major, mutually exclusive design options for the fusion internals are under consideration. Well known examples include flowing liquid Li (LL) surface PFC (with temperature $T \leq 450\text{C}$ to avoid excessive Li evaporation) in contrast with the more studied option of high temperature W PFC's with $T \geq 800\text{C}$ (DBTT). These two options are expected to lead to drastically divergent integrated designs for a net-electricity demonstrator. **B)** In Figure 1 are shown key topical areas of research for fusion materials science, in a manner consistent with

recent FESAC reports. Though this example addresses the tokamak options, the principles should apply equally to other magnetic configurations such as the stellarator. **C)** We see that fusion materials science research underpins the outcome of research on harnessing fusion power and fuel cycle; the research in turn aims to develop database for the design of the internals to be subjected to the extreme fusion conditions. To determine the outcome of this research will therefore require at least two divergent sets of integrated design options, each with likely divergent uncertainties in benefit-cost-risk. **D)** The WPFC research strategy is pursued worldwide, and was covered in the recent FESAC report on fusion materials science. The LLPFC oriented research covering the entire range of research components shown in Figure 1, and the determination of its compatible fusion internals, have started very recently or should start soon. This LLPFC research at present has high relative impact and uncertainty.

3) Tool needed to pierce the fog of benefit-cost-risk uncertainty among design options

A) To execute an effective research program in the frame of Charge 3, a tool is required to pierce the fog of uncertainty in benefit-cost-risk inherent in the pursuit of the present set of scientific research options with varying degrees of maturity. Without developing and applying such a tool, effective research progress at any cost and schedule, based on experience, will not be realistic. **B)** Note that D-T fusion experiments, electricity demonstrator, and DEMO are multidisciplinary multi-physics (MDMP) systems, involving internal and external components and the widest possible scales in time, space and energy found on earth. **C)** Such MDMP simulation and analysis tools are well developed and well deployed in such mature industries as aerospace [2], and are being developed for the relatively mature fission power systems [3]. In examples of developing breakthrough aerospace vehicles achieving multiple figures of merit, computational methodologies are well developed and deployed to address widely varying levels of interactions among major components, between the subcomponents, and interface to state-of-the-art simulation codes and their reduced models. **D)** Fusion systems are expected to exceed these in scope and complexity, while handicapped by the present low TRL's for all major fusion internals and an entry level TRL for the integrated fusion system. **E)** However, strong modeling and simulation tools of the fusion plasma and actuators, and more crudely for internal and external systems for fusion concepts, various designs and reactor projections have been active for the past 20-30 years within the FES research community (numerous references can be provided upon request). **F)** DOE SC, NE and NNSA have wide range of experience that can inform the development of such a simulation and analysis tool for fusion systems. This tool further has the ITER project with comprehensive and rapidly advancing scientific and systems information for use in development and benchmark. **G)** For development for and application to options of FNSF and its various options of fusion internals, the same methodology can start from the simple (including point models) toward the sophisticated as the relevant tools for Plasma Dynamics and Control and Materials can be updated under the guidance of the associated research. The tool even at the beginning levels can provide helpful information for varying FNSF mission and design options on the benefit-cost-risk stemming from uncertainties in outcome of present, planned, and prospective research. **H)** Within the funding profile and a notional schedule of Charge 3, this tool through 2019 should aim to assist in comparing various requisite research options for key FNSF options in mission and configurations including the stellarator, in developing and understanding the metrics to be met by the requisite research and the FNSF, and supporting the critical project decisions by DOE Science.

4) Mission of an evolutionary experimental FNSF [4]

A) The high level of uncertainty (and inevitably also opportunity) facing the FES fusion materials research encourages the consideration of an evolutionary experimental FNSF that has built-in flexibility to accommodate a range of likely divergent options for the fusion internals. **B)** The mission of an evolutionary experimental FNSF should be to develop the data base unique to these fusion internals, which together with ITER, to provide the basis for fusion electricity demonstration. **C)** The capabilities of such a FNSF, be it ST, AT, or Stellarator in configuration, should include **a)** reliable creation of the extreme fusion environment in a cost-effective manner, e.g., $Q=0.5-2$, moderate bootstrap current fraction ~ 0.5 , $\beta_N/\beta_{N-no-wall} \leq 0.7$, fusion neutron $W_L=0.3-1$ MW/m², minimized disruptions, hours to couple weeks plasma pulses, no net electricity demonstration goal, etc.; **b)** ready access, using remote handling techniques, for fusion internals in modular configurations including services to the internals and using chosen materials being researched; and **c)** enabling research cycles to measure, discover, understand, improve, and re-measure to avail the programmatic benefits of encountering show-stoppers and breakthroughs. **D)** These experiments on FNSF should be organized by sets of compatible options of the internals that could be replaced by another set of internals. This would lead to a higher level of facility requirements of well shielded conventional support structures and support systems, which in turn permit remote-handled internal modules and hot-cell laboratories for them. **E)** The total plasma facing surface areas where modules of the internals are readily placed and removed would be another metric for the FNSF experimental capabilities. At present, the tokamak options conceived have shown range of 10m² to 50m², allowing 10 or more separable modules.

5) Supporting research priorities

A) This MDMP simulation tool development and application should start immediately to derive most needed benefits to the fusion materials science research. **B)** This effort will require a small dedicated group of researchers to build a fusion MDMP simulation and analysis tool (\$1M-\$2M/yr), starting from small to large, simple to complex, acquiring input and guidance from an increasing number of practitioners of plasma dynamics and control and materials sciences research. **C)** The effort should also solicit feedback and in-kind contributions from practitioners of relevant research of the broader SC, NE, and NNSA (\$1M/yr equivalent). While the fusion materials science research must benefit from these, the research capabilities in an experimental FNSF should be of high interest to their research missions. **D)** This effort should aim to enable more effective materials science research through the ITER era, to be a critically needed tool to support DOE SC critical decisions on a FNSF project through 2019, and to be the basis for building a systems design integration tool beyond 2020 (\$5M/yr) in the event of project start. **E)** In the absence of any quantitative assessment, it is notionally appropriate to envision that: **a)** The additional funding of \$100M/yr beginning in 2020 be applied evenly to the requisite research in materials science (including harnessing fusion power and fuel cycle), and to a FNSF project. This partition of effort may well persist through the life of FNSF if the development and experimental measurements of modular internals are also assigned to the associated internals research programs as users of FNSF. **b)** The limited resources for FNSF construction and operations should be supplemented by in-kind leadership participations from plasma dynamics and control science (from \$5M/yr to \$10M/yr, equivalent), the broader DOE research communities based on mutual benefits (\sim \$5M/yr, equivalent), and international in-kind contributions (\sim 45% of the total materials science research program and FNSF project cost) in exchange for collaborative in-kind contributions and research access to the FNSF experimental testing environment (\sim 45% of total FNSF experimental research and operation cost).

The suggested notional level funding profile (in \$M/yr, averaged over the coming decades through 2039) would be as follows, subject to improvement via comprehensive assessment.

Components of fusion materials science research	2015-2019 (preparation)	2020-2029 (program & project)	2030-2039 (integrated research)
I. MDMP tool	1-2 (part of III)	5 (part of IV)	3 (part of IV)
II. Other DOE in-kind, equivalent	1	~10% of FES FNSF + materials science project total	~10% of FES FNSF + materials science operations total
III. Fusion materials research	10 (requisite)	50 (internals)	50 (integrated testing)
IV. FNSF	1-2 (metrics, mission and options)	50 (facilities)	50 (operations)
V. Fusion plasma dynamics and control in-kind	Guidance to MDMP tool development	5 (plasma dynamics and control design)	10 (plasma dynamics and control operation)
VI. International in-kind, equivalent	Possibly, 1	80 (45% of VIII)	83 (45% of VIII)
VII. Total DOE (II + III + IV + V)	12-13	115	120
VIII. Total level of effort equivalent (VI + VII)	13-14	195	203

With effective down-selection of sets of options in missions, internals designs, and collaborative arrangements, etc., informed by clarified performance-cost-risk tradeoffs among the options during preparation, effective design integration and impact assessments during construction, and experimental scenarios development, using a MDMP tool with advancing and up-to-date capabilities, a “fighting chance” will likely be presented by these equivalent funding levels to realize the present FES strategy goal in fusion materials science research.

In order for this effort on MDMP simulation and analysis tool to bear fruit, it is necessary for **a)** the practitioners of requisite research on fusion plasma dynamics and control, and materials science, to collaborate in shaping and formulating the models for the fusion internals; **b)** the MDMP group be allowed to outreach to and benefit from the practitioners of research on topics of interest from ITER, SC, NNSA, and NE; and **c)** consultations with international experts to take advantage of likely areas of collaboration. This new effort should accept research expert inputs without bias, and aim to produce in return in timely manner benefit-cost-risk tradeoffs of interest to improving research effectiveness. These will be necessary to improve the “fighting chance” in an effort to help realize the strategic goals of the FES for the ITER era.

Due to the strongly constrained funding profiles assumed, it should be noted that these priorities will likely favor the “adjacent possible,” smaller and lower performance options of the FNSF and the associated research program. The start of FNSF project and research operation can hopefully be realized during the 2020’s and 2030’s, respectively.

References

- [1] DOE-SC-0074, “A plan for the development of fusion energy” (March 2003); <http://science.energy.gov/fes/fesac/reports/reports-archive/>.
- [2] N.M. Alexandrov, M.Y. Hussaini, “Multidisciplinary Design Optimization, the state of art,” Proceedings of the ICASE/NASA Langley Workshop on MDO, Hampton, VA, March 13-16, 1995 (SIAM, 1997); MIT lecture notes on MSDO: <http://ocw.mit.edu/courses/engineering-systems-division/esd-77-multidisciplinary-system-design-optimization-spring-2010/lecture-notes/>.
- [3] <http://www.casl.gov/>.
- [4] YKM Peng et al., “Fusion nuclear science facility (FNSF) before upgrade to component test facility (CTF)”, Fusion Science and Technology **60** (2011) 441; and references therein.

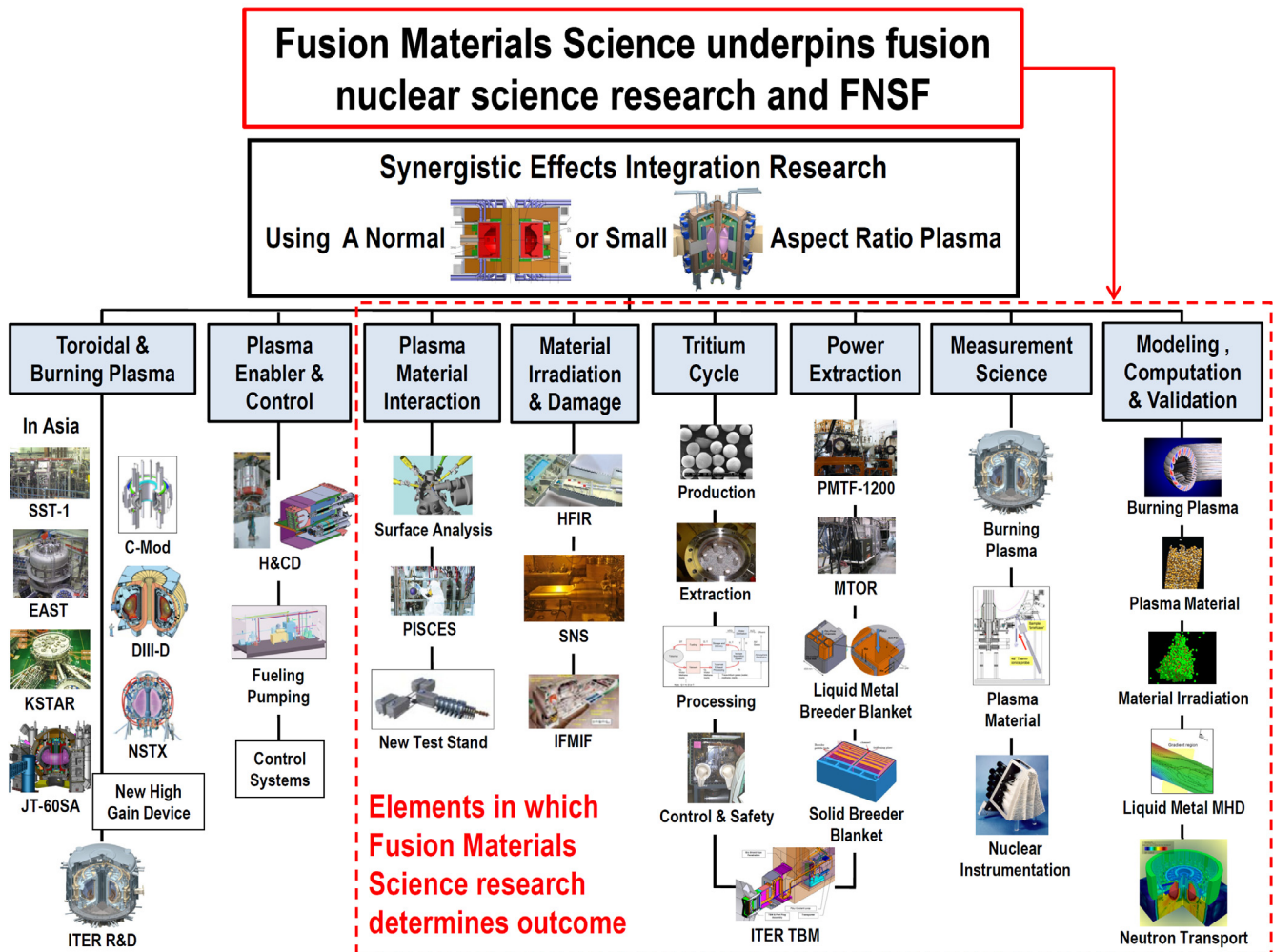


Figure 1. Topical elements in which the extreme fusion conditions benefit from and challenge materials science research.