Report of the FESAC Subcommittee on the Priorities of the Magnetic Fusion Energy Science Program

Written in Response to Dr. William Brinkman's charge letter to FESAC of April 13, 2012

Presented to FESAC on January 31, 2013

Riccardo Betti, Michael Brown, Vincent Chan, Bruce I. Cohen, Steve Cowley, Ronald C. Davidson, James F. Drake, Nathaniel Fisch, Charles M. Greenfield, Sibylle Guenter, Ian Hutchinson, Mitsuru Kikuchi, Mark Koepke, Li Jiangang, William J. Madia, Rajesh Maingi, Michael Mauel, Ronald Parker, Donald Rej, Robert Rosner (chair), Carl Sovinec, Peter Stangeby, and Steven Zinkle

When did we meet, and who was consulted …

- Meeting calendar
  - Our subcommittee was fully constituted by early July 2012
  - Meeting #1: 18 July 2012, in Bethesda, MD (full committee, open session)
  - Meeting #2: 31 July - 1 August 2012, in Bethesda, MD (full committee)
  - Meeting #3: 31 August 2012, at O'Hare Airport in Chicago, IL (planning meeting only, with participation from the leads of three breakout groups)
  - Meeting #4: 10-11 September 2012, in Gaithersburg, MD (full committee)
  - Meeting #5: 28 October 2012, in Providence, RI (only committee members attending the regular APS Division of Plasma Physics meeting
  - Meeting #6: on 10-11 January 2013, in Gaithersburg, MD (full committee)

- Advice to the subcommittee
  - The subcommittee was given its charge at Meeting #1, in Bethesda, MD
  - At the beginning of Meeting #5, the subcommittee was given guidance by the Associate Director for Fusion Energy Science (FES) regarding conflicts of interest within our subcommittee
  - 62 white papers were submitted to the subcommittee's public web site
  - Two virtual workshops were organized and hosted by the U.S. Burning Plasma Organization (USBPO) during the deliberation period of our panel.

How we self-organized …

- Step 1: Organizing our task(s)
  - We initially set up four breakout groups, covering basic fusion science, fusion science directed principally at the ITER, fusion science in the post-ITER era, and fourth group designated to provide feedback to the subcommittee on the policy implications of our recommendations. Our aim: to organize our study.
- Step 2: Organizing our prioritization of the science, based on ReNeW
  - Subgroup 1 (*Subgroup on foundational science and technology*) focused on the transcendent science and technology issues, that is, those issues that lie at the foundational level of plasma physics relevant to fusion energy science and technology.
  - Subgroup 2 (*Subgroup on ITER-critical science*) focused on the science and technology issues that will need to be addressed in order to ensure that the ITER succeeds as a science project.
  - Subgroup 3 (*Subgroup on post-ITER fusion science*) focused on those science and technology issues that will come to the fore after the ITER era, e.g., preceding the presumable transition era from MFE as a primarily basic science-oriented discipline to MFE as a primarily engineering-oriented energy discipline

Conflicts of interest …

The subcommittee was given guidance by the Associate Director for Fusion Energy Science (FES) regarding conflicts of interest within our subcommittee; in short, the subcommittee was instructed to adhere to the FACA rules because it is an entity of FESAC, which is a FACA committee.

- In response, we
  - Identified all subcommittee member conflicts of interest, and 'published' these to all subcommittee members on our 'private' web site
  - Decided that the subcommittee as a whole would no longer discuss any issues regarding FES facilities
  - Decided that the subcommittee *would* discuss facility issues in response to Charge #2; however, only 'non-conflicted' (in fact and/or in perception) subcommittee members would participate
  - Identified the 'non-conflicted' subcommittee members who participated in the discussions leading to our Charge #2 response: Michael Brown, James F. Drake, Sibylle Guenter, Mitsuru Kikuchi, Mark Koepke, William J. Madia, Michael Mauel, Robert Rosner, Carl Sovinec, and Steve Zinkle.

Our perspective on the U.S. fusion program's key goals

1. Maintaining a strong fundamental plasma science program, which forms the base for all other efforts in the area of plasma and fusion science and technology
2. Insuring that ITER succeeds in meeting its science goals, which is a primary objective for demonstrating the *technical* feasibility of nuclear fusion as an energy source.
3. Establishing that fusion energy is a safe, environmentally sustainable, and *economically* feasible energy source, laying the basis for a transition of the present fusion science program to a fusion energy development program.

The key source material for our study …

- The *ReNeW Report*, with detailed technical descriptions for each research thrust

  http://science.energy.gov/fes/about/~/media/fes/pdf/about/Magnetic_fusion_report_june_2009.pdf

In addition to the *ReNeW Report,* the Subcommittee made use of

- *Opportunities for and Modes of International Collaboration in Fusion Energy Sciences Research during the ITER Era*, Report of the Fusion Energy Sciences Advisory Committee (FESAC), DOE/SC-0150, February 2012.
- *Materials Science and Technology Research Opportunities Now and in the ITER Era: A Focused Vision on Compelling Fusion Nuclear Science Challenges*, Report of the Fusion Energy Sciences Advisory Committee (FESAC), DOE/SC-0149, February 2012.
- *Plasma Science: Advancing Knowledge in the National Interest*, Report of the Plasma 2010 Committee, Plasma Science Committee, National Research Council (2007),
- *Fusion Simulation Project,* a research needs workshop sponsored by DOE/FES in May 16-18, 2007.
- *Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan for Magnetic Fusion Energy,* Report of the Fusion Energy Sciences Advisory Committee (FESAC), October 2007.
- *A Plan for the Development of Fusion Energy,* Report of the Fusion Energy Sciences Advisory Committee (FESAC), March 2003.

Our criteria for prioritizing the science described in the FES ReNeW

Does a given thrust:

1. Provide the technical opportunities for breakthrough discoveries and excellent science?
2. Maintain or rebuild (especially at universities) critical skills, technologies, and competencies for plasma science and fusion research and development?
3. Enable U.S. leadership contributions to ongoing international fusion research?
4. Address, mitigate, and/or solve high risks to ITER performance goals?
5. Contribute to informing decisions about the future path of fusion development?

This led to identification of three groupings of ReNeW thrusts: a. highest priority; b. middle priority; and c. third priority

A note of caution regarding our rankings …

- It is evident that the three subgroups of our panel would rank the relative importance of the five prioritization criteria differently; thus, for example, Group 1 (Fundamental Science and Technology) focused primarily on the first 3 of these criteria. However, ***our selection of the five fusion science thrusts that we have identified as the most important has been a consensus view developed by all three of the panel subgroups.***
- In making the selection of the five 'most important' thrusts, we were quite aware of the conundrum that the remaining thirteen *ReNeW* thrusts contained program elements that could be viewed as comparable in importance to what we discuss in this section, albeit that these program elements do not suffice to make the thrusts in which they find themselves embedded rise to the top. **Indeed, the key distinguishing element in these cases was not scientific importance, but rather *timeliness*, in the particular context of getting ready for ITER.**

The highest priority thrusts

- Thrust 2: Control Transient Events in Burning Plasmas
- Thrust 6: Develop Predictive Models for Fusion Plasmas, Supported by Theory and Challenged with Experimental Measurement
- Thrust 9: Unfold the Physics of Boundary Layer Plasmas
- Thrust 10: Decode and Advance the Science and Technology of Plasma-Surface Interactions
- Thrust 17: Optimize Steady-State, Disruption-Free Toroidal Confinement using 3-D Magnetic Shaping, and Emphasizing Quasi-Symmetry Principles

N.b.:

1. Although not explicitly called out as a high priority thrust, we note that research supporting steady-state scenarios is cross-cutting and has connections to each of the high priority thrusts.
2. In this case, as in the following two cases, we did not prioritize among thrusts within a given priority grouping!

… what about the rest?

- The five *ReNeW* thrust areas just discussed do not encompass the full set of science programs we view as important to the U.S. contribution to the international fusion science effort: recall that our criteria for ranking thrusts included the joint criteria of scientific importance *and* timeliness for ITER impact.
- For this reason, the remaining components of the U.S. effort should be viewed as only nominally 'secondary' research program elements. In many cases, the scientific merit of these thrusts is equal to that of the highest-priority thrusts just discussed, but share the attribute that they are not critical for the construction and/or initial operation of ITER.
- To re-iterate: The order of thrusts *within* the following middle and third priority lists reflects the ordering presented by the 2009 *ReNeW* Report, and *not* a scientific ranking.

The middle priority thrusts

- Thrust 3: Understand the role of alpha particles in burning plasma.
- Thrust 4: Qualify operational scenarios and the supporting physics basis for ITER.
- Thrust 5: Expand the limits for controlling and sustaining fusion plasmas.
- Thrust 14: Develop the material science and technology needed to harness fusion power.
- Thrust 16: Develop the spherical torus to advance fusion nuclear science.
- Thrust 18: Achieve high-performance toroidal confinement using minimal externally applied magnetic field.

The third priority thrusts

- Thrust 1: Develop measurement techniques to understand and control burning plasmas.
- Thrust 7: Exploit High Temperature Superconductors (HTS) and other magnet innovations to advance fusion research.
- Thrust 8: Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas.
- Thrust 11: Improve power handling through engineering innovation.
- Thrust 12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma.
- Thrust 13: Establish the science and technology for fusion power extraction and tritium sustainability.
- Thrust 15: Create integrated designs and models for attractive fusion power systems.

Charge 1 Response – part 1

Prioritize among and within the FY2013 elements of the non-ITER magnetic fusion portion of the Fusion Energy Sciences program, assuming the FY2013 Presidential budget request level of effort.

- Under the FY2013 budget, the highest priority research topics are the five *ReNeW* thrusts discussed previously. However, we have concluded that the FY2013 FES Budget level is inadequate to address even the highest priorities in a timely way. Specific shortcomings include:
  - 1. *It is out of balance in its budget allocation to facilities operations (10%) and research (45%)*. It therefore fails to take advantage of major past capital investments. The typical SC budget for each of its offices allocates at least 30% to facilities operations. [FY2013 Congressional request overview, page 14 – I'll return to this later.]
  - 2. *It jeopardizes ITER success because U.S. facilities are some of the best in the world to address urgent research needs*. For example, capabilities in disruption mitigation, ELM control using non-axisymmetric fields or pellets, ELM-free operation, divertor and boundary issues at high heat flux, and world leading diagnostics, make U.S. confinement facilities ideal vehicles for resolving design and operational decisions.
  - 3. *It jeopardizes the U.S. ability to take advantage of ITER in the future, because it undermines our ability to attract top minds to the field***.** U.S. leadership is based predominantly upon the quality of our scientists and engineers. High quality students, who will become our future ITER researchers, seek a vibrant graduate research field in which there are dynamic opportunities at home as well as abroad. Moreover, at the FY13 domestic funding level even experienced scientists will leave the field.

Charge 1 Response – part 2

Prioritize among and within the FY2013 elements of the non-ITER magnetic fusion portion of the Fusion Energy Sciences program, assuming the FY2013 Presidential budget request level of effort.

Finally, …

- 4. *It significantly weakens the preeminent capability of the U.S. program in innovative research and critical discovery science*. Areas range from advanced diagnostic development (*e.g*. plasma boundary, alpha particle, and Alfvén wave eigenmode diagnostics), to first-principles simulations of nonlinear processes that govern core and edge transport.

If this budget level persists, we recommend that a thorough remapping between the high priority thrusts and the elements of the whole U.S. FES program must be undertaken by DOE/FES.

Charge 2 Response – part 1

Considering the same focus as in [Charge] (1), again prioritize the elements of the non-ITER magnetic fusion portion of the FES program, but assume a restoration of the budget to the 2012 level for that part of the program. New elements may be inserted in the prioritization after FY2012

- We recommend that roughly one-third of the restored funds, $12M, should be deployed for a three to five year period of operation of C-Mod to resolve high-priority topics on ITER-relevant boundary and divertor physics, and might include upgrades as required to accomplish these goals. This restoration is consistent with our highest priority thrusts 9 and 10, focuses on completing specific urgent research tasks relevant to ITER for which C-Mod is uniquely suited, and treats C-Mod as an critical experimental device in the preparations for ITER, but not as a long-term facility. Once C-Mod has completed its critical ITER-relevant tasks, it should be closed down so that funding can be re-directed toward other high priority science goals, as discussed under Charge 3.
- We recommend that $10M be allocated to increased utilization of DIII-D, covering operations and research focused on achieving faster progress on the urgent, high-priority research that DIII-D is carrying out for ITER preparations; this work (on disruption prediction, avoidance and mitigation, and ELMs) has been identified by us as part of the highest priority thrust work (e.g., Thrust 2).

Charge 2 Response – part 2

Considering the same focus as in [Charge] (1), again prioritize the elements of the non-ITER magnetic fusion portion of the FES program, but assume a restoration of the budget to the 2012 level for that part of the program. New elements may be inserted in the prioritization after FY2012

- We recommend that $10M be allocated to a highly targeted support of theory and simulation. This support needs to be focused on the high-priority research thrusts discussed earlier, advancing specific new physics topics, and where appropriate building tools that are ultimately aimed at allowing broad use by the community. This allocation should not be viewed as a "general increase" of theory and simulation. One possibility might be to build teams that focus on issues falling within our highest-priority physics topics, and that might involve an experimental/observational component. Scientific progress should be closely monitored.
- We expect that on a time scale of order half a decade, there will be a considerable evolution of the domestic major facilities, including closure of C-Mod and the completion of the NSTX upgrade. Consistent with this evolution, the program will need to consider next steps in the fusion major facilities portfolio; possible alternatives might include upgrades to DIII-D and a stellarator. We expect C-Mod scientists to play an active role in the formulation of these plans. Given likely timelines, it will be important to start planning for a major new facility as soon as possible.

Charge 3 Response – part 1

Prioritize the elements of the non-ITER magnetic fusion portion of the Fusion Energy Sciences program for the five-year period following the roll-off in ITER project construction funding, assuming a 50% increase over that provided in the FY2013 budget in non-ITER-project magnetic fusion level of effort following the peak in ITER funding. Assume that research on fusion materials science and harnessing fusion power will capture much of this increase.

- For the period following the roll-off in ITER project construction funding, with a 50% increase in non-ITER MFE effort, we recommend highest emphasis be given to science-rich feasibility issues that will directly impact the path to be followed to a DEMO fusion device. In particular, additional resources at this level would permit moving forward with a Fusion Nuclear Science Program (FNSP) and preparing the way for a Fusion Nuclear Science Facility (FNSF).
  - A FNSF is a research facility that incorporates most of the technical components within the core of a future DEMO power plant, but built at minimum overall fusion power in order to enable fusion component testing and optimization at minimum tritium consumption and overall cost [Goldston, FESAC, 2003]. The FNSF allows research of high neutron-fluence plasmas that run reliably, without damaging transient events, and the evaluation of numerous fusion engineering issues including first-wall components that withstand fast neutron flux and the demonstration of tritium self-sufficiency.

Charge 3 Response – part 2

- At the present time, it is uncertain what materials would ultimately be selected for an FNSF, what would comprise the engineered components that make up the first wall, and what would be the magnetic configuration confining the burning plasma. The leading candidates for the magnetic confinement configuration are the advanced tokamak (AT), the spherical tokamak (ST), and the optimized stellarator. The research efforts that will inform the design of an FNSF facility were detailed in *ReNeW*. In addition to steady-state (Thrust 5), the Subcommittee recognizes especially that an expanded research effort in Thrusts 13, 14, and 15 (entitled "Theme 3: Harnessing Fusion Power") is needed when the additional funds of this charge become available.
- An expanded effort on materials research would enhance two broad categories of research: (i) fusion nuclear materials effects, and (ii) plasma surface interactions. While a full 14 MeV D-T neutron spectrum test facility (e.g. IFMIF) lies beyond the financial capacity of the U.S. program alone, the recent FESAC [Zinkle] report on fusion nuclear materials identifies several medium-scale research initiatives that would directly address some challenges, albeit with less spectral accuracy. One or more of these initiatives would form a natural part of an expanded FNSP.

Charge 3 Response – part 3

Specific examples of program elements for an expanded FNSP might include:

- Develop materials with micro-structures to mitigate transmutation produced helium and permeation of hydrogenic species
- Conduct neutron irradiation tests by leveraging domestic neutron sources, including neutron damage and tritium sequestration effects and evaluating designer materials above
- Participate in ITER Test Blanket Module program, should the opportunity arise
- Extend linear plasma devices, including appropriate upgrades from existing capabilities (e.g. tritium, liquid metals, rad. damage), to long time-scales, to help fulfill some of the critical FNS and PSI missions
- Initiate a comprehensive structural materials modeling program to address neutron damage, as part of a DOE-wide research program in this area

Charge 3 Response – part 4

- The plasma surface interactions category goes beyond present-day experiments both in the high operating temperature of the plasma facing components (at least 500 C) because of the need to minimize tritium retention and improve thermal efficiency, and in the week-long steady-state nature of the plasma exposure. It may be the best plan to establish the feasibility of such operation, which requires also reliable plasma sustainment, in a situation that is not complicated by the requirement for tritium handling and breeding. Such a facility, which does not yet exist, might be generically called a "pre-FNSF"; it is a high wall-temperature, high power-density, steady state, toroidal confinement facility.
  - A pre-FNSF would be non-DT and would be a primary test-bed for developing a DT FNSF. [It might in fact be the first stage of an FNSF.]
  - Much of the research work on a pre-FNSF would therefore necessarily be on confined plasma physics, including achievement and optimization of sustained current drive and identification and characterization of altered and new operating scenarios.
- Axisymmetric (tokamak and ST) configurations are the best understood option for a pre-FNSF. The properties of the non-axisymmetric optimized stellarator are less well developed, but stellarators are inherently steady-state, operate at relatively high plasma density, provide greater design flexibility in their magnetic configuration, and may have less damaging off-normal events than found in tokamaks.

Some final thoughts: 1-Our perspective on the U.S. fusion program's priorities and direction

- We strongly support international programs and new efforts in materials research
- However, we believe that decisions affecting the future of the U.S. fusion science program must place first priority on
  - Maintaining scientific strength in areas that U.S. has been world-leading
  - Ensuring continued excellence of the fusion science workforce
  - Delivering the key science and technology needed for ITER that has been assigned to the U.S. fusion science program
- We believe that the program priorities suggested by the FY2013 FES budget request – namely that "… overall reduction in domestic research …" needs to be accompanied by "… a modest increase in funding for scientific collaborations on major international facilities" are not consistent with our views

Some final thoughts: 2-The FES budget problems …

- Given the U.S. commitment to ITER, and the considerable cost overruns at ITER (over which the U.S. has only very limited control), FES funding has evolved into a clearly unique profile among DOE Office of Science's natural science research program offices …

	Research	Facility Operations	Future Facilities	Workforce
Advanced Scientific Computing Research	49%	50%	0%	1%
Basic Energy Sciences	46%	44%	10%	0%
Biological and Environmental Research	65%	35%	0%	0%
Fusion Energy Sciences	45%	10%	45%	0%
High Energy Physics	55%	30%	15%	0%
Nuclear Physics	32%	56%	12%	0%
Workforce Development for Teachers and Scientists	0%	0%	0%	100%
Science Laboratories Infrastructure	0%	0%	100%	0%
Total, Office of Science	47%	38%	14%	1%

- It seems that FES's funding profile is largely the result of ITER's cost overruns – which would have played out quite differently had the U.S. retained some measure of control over its ITER budget contributions …
- This issue – the impact on fusion science funding by ITER participation – was precisely why the U.S. fusion science community sought DOE's agreement that ITER participation would not occur at the expense of the FES research program …

… which brings us to questions and discussion …