FESAC Planning Panel Final Report

Presented by Martin Greenwald

UFA Meeting

Orlando, 11/12/2007

From Charge by Under Secretary Orbach

"To assist planning for the ITER era, it is critical that FESAC identify the issues arising in a path to DEMO, with ITER as a central part of that effort"

1. "Identify and prioritize the broad scientific and technical questions to be answered prior to a DEMO."
2. "Assess available means (inventory), including all existing and planned facilities around the world, as well as theory and modeling, to address these questions."
3. "Identify research gaps and how they may be addressed through new facility concepts, theory and modeling."

Panel

- Martin Greenwald – Chair
- Richard Callis
- Bill Dorland
- David Gates
- Jeff Harris
- Rulon Linford
- Mike Mauel
- Kathryn McCarthy
- Dale Meade
- Farrokh Najmabadi
- Bill Nevins
- John Sarff
- Mike Ulrickson
- Mike Zarnstorff
- Steve Zinkle

My personal thanks to all for hard work and cooperation

Outline

- Brief Review of Charge and Interpretations
- Process
- Outline/structure of report
- Findings and Recommendations

Report on FESAC web site:
http://www.science.doe.gov/ofes/fesac.shtml

Scope of Charge

_ We didn't treat entire fusion sciences program, for example

- ITER baseline was to be assumed successful
- Highest priority is making ITER a success (just pencil it in above anything we come up with)
- IFE Not considered
- Alternates to tokamak considered to the extent they have "short term" potential for facilitating or influencing the development path
- All above are left out of prioritization by construction – nothing is implied about their importance relative to what we are considering

Discussion of Charge

- What do we need to learn and what do we need to do, aside from ITER and other existing elements of the international program, to develop the knowledge base, and to be prepared for DEMO?
- We've used DEMO and the development plan to set a rough scope, timeline and path
- We've used the priorities panel (and recent NRC report) to help define issues
- Our focus was on informing near-term decisions for next major steps in the program by
  - providing technical groundwork
  - placing near-term program into context of long-term needs and directions
  - identifying needed missions
  - laying out options

How Did We Define DEMO For The Purposes Of This Charge ?

- DEMO mission = prototype, electricity producing fusion reactor demonstrating high availability, reliability and all relevant technologies
  - Last step before commercialization
  - Industry will set the bar quite high
- We cannot predict DEMO instantiation
  - How advanced in operating mode (or concept)?
  - How aggressive in use of new materials?
  - How aggressive in terms of technologies employed?
  - What is the funding source – public, private, hybrid?
- Since we don't know, we take a broad view of the technical issues in order to ensure that the program is prepared

Resources – Existing Reports and Studies

- FESAC Priorities Panel (2005)
- FESAC Review of Major Facilities (2005)
- FESAC Fusion Development Plan (2003)
- NRC Plasma 2010: Assessment and Outlook for Plasma Science (2007)
- NRC Burning Plasma (2003)
- International fusion development plans including
  - Japan; National Policy of Future Nuclear Fusion Research and Development (2005)
  - EU Fast-track Fusion Development Plan (2005)

Resources – Community Input

- White papers (60 submitted)
- Workshop presentations and discussion of white papers
  - June 25 at General Atomics (13 presentations)
  - August 7 at PPPL (21 presentations)
- Website
  - http://www.psfc.mit.edu/~g/spp.html
- Online discussion board (>90 registered users)
- (In addition the panel had three 2-day meetings and over 20 conference calls)

Structure of Report

- Executive Summary
- Summary of Findings and Recommendations
- Chapter 1: Background and discussion of charge
- Chapter 2: Identification of themes and broad issues
  - Detailed discussions of issues and extrapolations to Demo
  - Prioritization
  - U.S. strengths and opportunities
- Chapter 3: Assessment of available means to address issues
  - ITER and other existing and planned experiments
  - Large scale modeling projects
  - Technology facilities
  - International fusion development plans

Structure of Report (2)

- Chapter 4: Analysis of gaps
  - Compilation of fine-scale gaps and mission elements
  - Organization of gaps into broad categories
- Chapter 5: Possible new initiatives, facilities and programs
  - Relation of initiatives to gaps

Findings

- **Finding 1:** Achieving the required state of knowledge
  - Panel recognizes the substantial scientific progress already made
  - Significant challenges remain before we have the knowledge base sufficient to take the step to Demo
  - The panel is optimistic about resolving remaining issues, given adequate resources

- **Finding 2:** Broad scientific and technical questions
  - 14 questions identified
  - Organized into 3 themes

Themes: In Preparation for DEMO

A. Predictable, high-performance steady-state burning plasmas
   - *The state of knowledge must be sufficient for the construction, with high confidence, of a device which allows the creation of sustained plasmas that simultaneously meet all the conditions required for practical production of fusion energy.*

B. The plasma material interface
   - *The state of knowledge must be sufficient to design and build, with high confidence, robust material components which interface to the hot plasma in the presence of high neutron fluences.*

C. Harnessing fusion power
   - *The state of knowledge must be sufficient to design and build, with high confidence, robust and reliable systems which can convert fusion products to useful forms of energy in a reactor environment, including a self-sufficient supply of tritium fuel.*

A. Predictable high-performance steady-state plasmas

1. Measurement
   – *Make advances in sensor hardware, procedures and algorithms for measurements of all necessary plasma quantities with sufficient coverage and accuracy needed for the scientific mission, especially plasma control.*
2. Integration of steady-state, high-performance burning plasmas
   – *Create and conduct research, on a routine basis, of high performance core, edge and SOL plasmas in steady-state with the combined performance characteristics required for Demo*
3. Development of validated predictive models of plasmas
   – *Through developments in theory and modeling and careful comparison with experiments, develop a set of computational models that are capable of predicting all important plasma behavior in the regimes and geometries relevant for practical fusion energy.*

A. Predictable high-performance steady-state plasmas(2)

4. Control
   - *Investigate and establish schemes for maintaining high-performance, burning plasmas at a desired, multivariate operating point with a specified accuracy for long periods, without disruption or other major excursions*
5. Avoiding off-normal plasma events
   - *Understand the underlying physics and control of high-performance magnetically confined plasmas sufficiently so that ‘off-normal’ plasma operation, which could cause catastrophic failure of internal components, can be avoided with high reliability and/or develop approaches that allow the devices to tolerate some number or frequency of these events.*
6. Heating, current drive, rotation drive, fueling
   - *Establish the physics and engineering science of auxiliary systems that can provide power, particles, current and rotation at the appropriate locations in the plasma at the appropriate intensity.*
7. Magnets
   - *Understand the engineering and materials science needed to provide economic, robust, reliable, maintainable magnets for plasma confinement, stability and control*.

B. The Plasma Material Interface

8. Plasma wall interactions
   – *Understand and control of all processes that couple the plasma and nearby materials.*
9. Plasma Facing Components
   – *Understand the materials and processes that can be used to design replaceable components that can survive the enormous heat, plasma and neutron fluxes without degrading the performance of the plasma or compromising the fuel cycle.*
10. Antennas, diagnostics and other internal components
    – *Establish the necessary understanding of plasma interactions, neutron loading and materials to allow design of RF antennas and launchers, control coils, final optics and any other diagnostic equipment that can survive and function within the plasma vessel.*

C. Harnessing Fusion Power

11. Fuel cycle
    - *Learn and test how to manage the flow of tritium throughout the entire plant, including breeding and recovery.*
12. Power extraction
    - *Understand how to extract fusion power at temperatures sufficiently high for efficient production of electricity or hydrogen.*
13. Materials for breeding and structural components
    - *Understand the basic materials science for fusion breeding blankets, structural components, plasma diagnostics and heating components in high neutron fluence areas.*

C. Harnessing Fusion Power (cont.)

14. Safety

    – *Demonstrate the safety and environmental potential of fusion power to preclude the technical need for a public evacuation plan, and to minimize the environmental burdens of radioactive waste, mixed waste, or chemically toxic waste for future generations.*

15. Reliability, Availability and Maintainability

    – *Demonstrate the productive capacity of fusion power and validate economic assumptions about plant operations by rivaling other electrical energy production technologies.*

Prioritization

- Challenge: All of the issues we have listed are important and must be resolved before we are ready for DEMO
  - Adding to the difficulty - Important interactions and couplings between issues
  - Context for priorities – a resource limited environment
  - Prioritization implies: we may have to accept additional risk or delays toward the ultimate goal
- Defined: a set of criteria with clear definitions
- Created: a scoring system with as precise definitions as we could manage
  - Iterated on criteria definitions and scoring
  - Allow for differentiation between issues (all of which are important)
  - Get as consistent result from panel as possible

Criteria For Prioritization

- **Importance:**
  - *Importance for the fusion energy mission and the degree of extrapolation from the current state of knowledge*
- **Urgency:**
  - *Based on level of activity required now and in the near future.*
- **Generality:**
  - *Degree to which resolution of the issue would be generic across different designs or approaches for Demo.*

- After evaluation, the issues were grouped into three tiers. The tiers defined to suggest an overall judgment on:
  - the state of knowledge
  - the relative requirement and timeliness for more intense research for each issue.

Finding 3: Results of Prioritization

- **Tier 1:** *solution not in hand, major extrapolation from current state of knowledge, need for qualitative improvements and substantial development for both short and long term*
  - *Plasma Facing Components*
  - *Materials*
- **Tier 2:** *solutions foreseen but not yet achieved, major extrapolation from current state of knowledge, need for qualitative improvements and substantial development for long term*
  - *Off-normal events*
  - *Fuel cycle*
  - *Plasma-wall interactions*
- **Tier 2:** *(Continued)*
  - *Integrated, high-performance plasmas*
  - *Power extraction*
  - *Predictive modeling*
  - *Measurement*
- **Tier 3:** *solutions foreseen but not yet achieved, moderate extrapolation from current state of knowledge, need for quantitative improvements and substantial development for long term*
  - *RF launchers/internal components*
  - *Auxiliary systems*
  - *Control*
  - *Safety and environment*
  - *Magnets*

Assess available means

- Comprehensive inventory existing and planned programs (Chapter 3)
- In addition: Assessed U.S. strengths and opportunities
- Panel polled for 3 questions
    1. Areas of current and historical U.S. strength or leadership?
    2. Areas where the U.S. in greatest danger of losing leadership or competitiveness given current trends?
    3. Areas where the U.S. has an opportunity to sustain or gain leadership by strategic investment?

Findings: U.S. Strengths and Opportunities (1)

- **Finding 4:** Scope of world program
  - Issues identified by this panel were generally recognized by international programs
  - Thus: ample opportunities to collaborate on their resolution
  - But: ability to partner effectively or compete for leadership may be threatened without adequate U.S. investment
  - We note that our ITER partners are actively talking about their own paths to Demo

Findings: U.S. Strengths and Opportunities (2)

Finding 5:

- **Areas where U.S. could claim leadership**
  - Measurement
  - Predictive modeling
  - Control
- **Areas where the U.S. is strongly competitive**
  - Plasma wall interactions
  - Integrated, sustained, high-performance plasmas
  - Safety/environment

Findings: U.S. Strengths and Opportunities (3)

Finding 5 (cont):

- **Areas where U.S. was at risk of losing leadership or competitiveness**
  - Measurement
  - Control
  - Antennas and launchers
  - Materials
  - Integrated, sustained, high-performance plasmas
  - Plasma-wall interactions and plasma facing components
  - Safety
  - Magnets

Findings: U.S. Strengths and Opportunities (4)

Finding 5 (cont):

- **Areas where investment could sustain strength**
  - Measurement
  - Predictive modeling
  - Control
  - Plasma-wall interactions
- **Areas where investment could provide new opportunities for leadership**
  - Plasma facing components
  - Materials

Findings:

Finding 5 (cont):

- **U.S. Strengths in 3D physics may provide opportunity for resolution of some off-normal event issues via exploitation of quasi-axisymmetric helical shaping**

- **There is a need to maintain core competencies in all relevant areas – even if they don't receive additional stress**
  - For effective international partnering
  - To provide/build knowledge base for eventual U.S. Demo

Approach to Gap Analysis

- Extrapolations in the knowledge required to be prepared for Demo were assessed in chapter 2
- Fine-scale gaps identified in each issue (in chapter 4)
- Gaps grouped into 15 broad categories
- These are similar, but not identical to list of issues – important distinction
  - These gaps have been filtered through an assessment of existing and planned programs (including successful ITER)
  - Gaps are defined as residual questions or issues likely to be left after completion of these programs
  - So don't be confused by labels – details are important here
  - Example: measurements (general) → gap in nuclear capable diagnostics for control of high-Q, sustained, burning plasmas

Finding 6: Assessment of Gaps (1)

- **G-1** Sufficient understanding of all areas of the underlying plasma physics to predict the performance and optimize the design and operation of future devices. Areas likely to require additional research include turbulent transport and multi-scale, multi-physics coupling.
- **G-2** Demonstration of integrated, steady-state, high-performance (advanced) burning plasmas, including first wall and divertor interactions. The main challenge is combining high fusion gain with the strategies needed for steady-state operation.
- **G-3** Diagnostic techniques suitable for control of steady-state advanced burning plasmas that are compatible with the nuclear environment of a reactor. The principle gap here is in developing measurement techniques that can be used in the hostile environment of a fusion reactor.

Finding 6: Assessment of Gaps (2)

- **G-4** Control strategies for high-performance burning plasmas, running near operating limits, with auxiliary systems providing only a small fraction of the heating power and current drive. Innovative strategies will be required to implement control in high-Q burning plasma where almost all of the power and the current drive is generated by the plasma itself.
- **G-5** Ability to predict and avoid, or detect and mitigate, off-normal plasma events in tokamaks that could challenge the integrity of fusion devices.
- **G-6** Sufficient understanding of alternative magnetic configurations that have the ability to operate in steady-state without off-normal plasma events. These must demonstrate, through theory and experiment, that they can meet the performance requirements to extrapolate to a reactor and that they are free from off-normal events or other phenomena that would lower their availability or suitability for fusion power applications.

Finding 6: Assessment of Gaps (3)

- **G-7.** Integrated understanding of RF launching structures and wave coupling for scenarios suitable for Demo and compatible with the nuclear and plasma environment. The stresses on launching structures for ICRH or LHCD in a high radiation, high heat-flux environment will require designs that are less than optimal from the point of view of wave physics and that may require development of new RF techniques, new materials and new cooling strategies
- **G-8.** The knowledge base required to model and build low and high-temperature superconducting magnet systems that provide robust, cost-effective magnets (at higher fields if required).
- **G-9.** Sufficient understanding of all plasma-wall interactions necessary to predict the environment for, and behavior of, plasma facing and other internal components for Demo conditions. The science underlying the interaction of plasma and material needs to be significantly strengthened to allow prediction of erosion and re-deposition rates, tritium retention, dust production and damage to the first wall.

Finding 6: Assessment of Gaps (4)

- **G-10.** Understanding of the use of low activation solid and liquid materials, joining technologies and cooling strategies sufficient to design robust first-wall and divertor components in a high heat flux, steady-state nuclear environment. Particularly challenging issues will include tritium permeation and retention, embrittlement and loss of heat conduction.
- **G-11** Understanding the elements of the complete fuel cycle, particularly efficient tritium breeding, retention, recovery and separation in vessel components.
- **G-12** An engineering science base for the effective removal of heat at high temperatures from first wall and breeding components in the fusion environment.

Finding 6: Assessment of Gaps (5)

- **G-13** Understanding the evolving properties of low activation materials in the fusion environment relevant for structural and first wall components. This will include the effects of materials chemistry and tritium permeation at high-temperatures. Important properties like dimensional stability, phase stability, thermal conductivity, fracture toughness, yield strength and ductility must be characterized as a function of neutron bombardment at very high levels of atomic displacement with concomitant high levels of transmutant helium and hydrogen.
- **G-14** The knowledge base for fusion systems sufficient to guarantee safety over the plant life cycle - including licensing and commissioning, normal operation, off-normal events and decommissioning/disposal.
- **G-15** The knowledge base for efficient maintainability of in-vessel components to guarantee the availability goals of Demo are achievable.

Findings 7 & 8

- **Finding 7:** Mitigation of programmatic risks through breadth of program including international collaboration
  - Alternate approaches to critical issues should be explored at each step
  - Stressing deep scientific understanding
  - Most important where uncertainties are greatest
  - Includes opportunities for international cooperation

- **Finding 8:** Importance of maintaining support for ITER
  - Nothing in report should be construed as diminishing the importance of successful execution of the ITER project
  - Includes support from within the domestic research program

Recommendations: Support for strategic planning

- **Recommendation 1.** A long-term strategic plan should be developed and implemented as soon as possible to begin addressing the gaps identified in this report.
  - Such a plan should include metrics to prioritize research areas, scientific milestones to judge the progress, and should identify means to educate and train a new generation of scientists.
- **Recommendation 2.** Such a strategic plan should recognize and address all scientific challenges of fusion energy including fusion engineering, materials sciences and plasma physics.
  - It is clear from the identification of issues, priorities and gaps that there are many important **scientific questions** that are not directly or entirely related to plasma physics.
- **Recommendation 3.** The plan needs to include bold steps
  - The panel encourages the adoption of new initiatives or the construction of new facilities that are vital in filling the gaps identified in this report and that can hold their own in the international arena.

Initiatives and Facilities - Missions

- As part of answer to charge 3, a lengthy set of “mission elements was derived.
  - These are research activities which could fill the fine-scale knowledge gaps previously identified
  - Often more than one activity per gap
- As discussed, fine-scale gaps were consolidated into 15 significant categories
- From these, a set of major initiatives or facilities is proposed
  - Each makes a dominant contribution to at least one, but typical more than one gap
  - In some cases alternate approaches are described
  - In other cases, a staged or sequential approach is required
  - New proposals might combine missions
  - Chapter 5 describes the relationship between the proposed initiatives and the gaps and outlines programs by which each gap could be filled

Initiatives and Facilities (2)

Recommendation 4: The development of a long-term strategic plan should include careful consideration of the following nine major initiatives.

- **I-1** Initiative toward predictive plasma modeling and validation: This activity describes a concerted and coordinated program that would combine major advances in advanced physics based plasma simulations, especially multi-scale, multi-physics issues combined with a vigorous effort to validate these models against large and small-scale experiments. A critical element would be the development and deployment of new measurement techniques.

- **I-2** Extensions to ITER AT capabilities: This initiative would entail new or enhanced drivers (heating, current drive, etc.), control tools and diagnostics capable of carrying out a comprehensive AT physics program. The aim would be to achieve an understanding of burning AT regimes sufficient to base Demo on.

Initiatives and Facilities (3)

_ **I-3** Integrated advanced burning physics demonstration: This facility would be a dedicated sustained, high-performance burning plasma experiment with a goal to achieve an understanding sufficient to base Demo on. It is predicated on the condition that extensions to the ITER AT program and predictive understanding from the international superconducting tokamaks will not achieve an understanding sufficient for extrapolation to Demo.

_ **I-4** Integrated experiment for plasma wall interactions and plasma facing components: This very-long pulse or steady-state confinement experiment would perform research on plasma wall interactions and plasma facing components in a non-DT integrated facility. It would attempt to duplicate and study, as closely as possible, all of the issues and (non-nuclear) problems that PWI/PFCs would face in a reactor.

_ **I-5** Advanced experiment in disruption-free concepts: This would be a performance extension device for a concept that had demonstrated promise for fusion applications by projecting to high performance and efficient steady state, and which was significantly less susceptible to off-normal events compared to a tokamak. A stellarator would be the mostly likely candidate for such a facility.

Initiatives and Facilities (4)

- **I-6** Engineering and materials physics modeling and experimental validation initiative: This would be a coordinated and comprehensive research program consisting of advanced computer modeling and laboratory testing aimed at establishing the single-effects science for major fusion technology issues, including materials, plasma-wall interactions, plasma-facing components, joining technologies, super-conducting magnets, tritium breeding, RF and fueling systems.

- **I-7** Materials qualification facility: This initiative would involve testing and qualification of low-activation materials by intense neutron bombardment. The facility generally associated with this mission is the International Fusion Materials Irradiation Facility (IFMIF), however alternates have been discussed.

Initiatives and Facilities (5)

- **I-8** Component development and testing program: This would entail coordinated research and development for multi-effect issues in critical technology areas. Examples are breeding/blanket modules and first wall components but this initiative could include other important components like magnet systems or RF launchers. This program would most likely be carried out as enabling research in direct preparation and support of planned nuclear fusion facilities such as ITER, CTF or Demo.

- **I-9** Component qualification facility: This facility is aimed at testing and validating plasma and nuclear technologies in a high availability, high heat flux, high neutron fluence DT device. It would qualify components for Demo and establish the basis for licensing. In fusion energy development plans, this machine is called a Component Test Facility (CTF).

Relationship of Initiatives to Gaps

How Initiatives Could Address Gaps

Legend

Major Contribution	3
Significant Contribution	2
Minor Contribution	1
No Important Contribution	

	G-1 Plasma Predictive capability	G-2 Integrated plasma demonstration	G-3 Nuclear-capable Diagnostics	G-4 Control near limits with minimal power	G-5 Avoidance of Large-scale Off-normal events in tokamaks	G-6 Developments for concepts free of off-normal plasma events	G-7 Reactor capable RF launching structures	G-8 High-Performance Magnets	G-9 Plasma Wall Interactions	G-10 Plasma Facing Components	G-11 Fuel cycle	G-12 Heat removal	G-13 Low activation materials	G-14 Safety	G-15 Maintainability
I-1. Predictive plasma modeling and validation initiative	3	2		2	2	3	1		2						
I-2. ITER – AT extensions	3	3	3	3	3		2		2	2	1	1		1	1
I-3. Integrated advanced physics demonstration (DT)	3	3	3	3	3	1	3	2	3	3	1	1	1	1	1
I-4. Integrated PWI/PFC experiment (DD)	2	1		1	2		2	1	3	3	1	1		1	1
I-5. Disruption-free experiments	2	1		2	1	3		1	1	1					
I-6. Engineering and materials science modeling and experimental validation initiative							1	3	1	3	2	3	3	2	1
I-7. Materials qualification facility							1			3	2	1	3	3	
I-8. Component development and testing			1				2	1		3	3	3	2	2	2
I-9. Component qualification facility	1	1	2	1	2		3	2	2	3	3	3	3	3	3

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