Fusion Nuclear Science - Pathways Assessment

C. Kessel, (PPPL) DOE detailee

FESAC, March 7, 2011

There is an increasing awareness of the missing half of fusion research in the US

Fusion nuclear science development is necessary to take any significant step toward fusion energy

ITER shows the strong connection of plasma physics with engineering and technology in the burning plasma regime

Additional steps are needed to close the substantial gaps between ITER and our vision of a DEMO/power plant

Materials science and technology permeates all areas of fusion energy development, and serves as a critical first step in fusion nuclear science

A broad program in fusion engineering science is needed, that begins with basic R&D and leads to fully integrated systems for fusion. This is the only way we can prepare to build a fusion nuclear device in the US

The FNS-PA activity is providing the scientific research information for FES to develop this program

FES has provided guidance for this activity

The aim is to continue a process to define our research in materials science, both nuclear and non-nuclear, and in the fusion nuclear science required for DEMO

Build on Priorities, Gaps, and Opportunities and ReNeW reports

- Identify research requirements to the point of enabling FES to craft calls for proposals and design programs

Center of attention should be on the research that is required before a major new facility, but that can help define that facility

- Plasma/surface interactions
- Nuclear effects on materials and structures
- Harnessing fusion power

Materials science questions (defined broadly – nuclear, non-nuclear, PFC/PMI) is accepted in the Office of Science as the frontier that must join burning plasma physics in establishing fusion's credibility

- Cross-office/agency synergies and IFE are critical and necessary

Possible pathways to DEMO, with their gaps/benefits/risks, what are the implications

Basic Parts of Activity

- Detailed DEMO description for rollback
  - Use a relatively detailed parameter description of DEMO based on power plant studies. While not precise, they provide the long term direction for research and can be corrected as we understand more

- Roll forward R&D specification
  - Based on ReNeW and other activities, begin the next level of detail by describing actual R&D items to be done over next 5-10 years in a number of topical areas spanning FNS

- Examine missions along a pathway to DEMO
  - Establish metrics that show the progress toward DEMO
  - Examine some steps (devices) along the pathway and understand benefits and risks

The FNS-PA core group*

<u>Community members:</u>

M. Abdou (UCLA)
V. Chan (GA)
R. Fonck (Univ. WI)
R. Kurtz (PNNL)
S. Milora (ORNL)
W. Meier (LLNL)
B. Merrill (INL)
J. Minervini (MIT)
N. Morley (UCLA)
F. Najmabadi (UCSD)
H. Neilson (PPPL)
R. Nygren (Sandia)
M. Peng (ORNL)
D. Rej (LANL)
R. Stambaugh (GA)
M. Tillack (UCSD)
G. Tynan (UCSD)
J. VanDam (Univ. TX, USBPO)
D. Whyte (MIT)
S. Willms (LANL)
B. Wirth (Univ. TN)

<u>DOE members</u>:

S. Eckstrand
C. Kessel (PPPL)
M. Koepke
G. Nardella
A. Opdenaker
E. Stevens
E. Synakowski

*a number of local people help our members

Goals of the FNS-PA activity

- Identify research and development activities in a series of topical areas representing and supporting fusion nuclear science

- Motivate these R&D activities by rolling back from DEMO definitions
  - Critical review of assumptions, constraints and analysis – in progress

- Rolling forward from scientific needs studies (ReNeW), what can be started now?
  - Partially reported at FNS-PA meetings, topical group efforts in progress

- Establish what is to be done, why it must be done, how it will be done (facilities) and when it needs to be done

- Establish where there are synergies with non-fusion, and international (non-US) activities, including ITER

Goals of the FNS-PA activity, cont'd

Topical areas:

Materials science and technology

Plasma facing components and plasma material interface

Power extraction and tritium sustainability

FNSF/DEMO detail design studies

$^{+}$Enabling technologies

*Plasma duration and sustainment

Reliability, maintainability, availability, and inspectability

Safety and environment

These will break into subtopics before R&D specifics are identified

These are not issues/needs, they are actually technical activities

Goals of the FNS-PA activity, cont'd

- Primary focus is on R&D in the next 5-10 years, although longer term R&D should be evident
  - Pre-requisite R&D leading up to conceptual design of a FNS facility
  - R&D will continue toward the more challenging needs of DEMO

- Identify mission elements along the pathway to DEMO that allow the most efficient FNS facility step(s) and minimization of technical gaps to DEMO – beginning to examine this now

  - FNS-PA should supply FES with accurate and clear information on R&D that allows them to make the best choices and to defend our programs
  - R&D described well enough to define initiatives and proposal calls
  - Cross-office partnerships (DOE) are valuable to leverage resources and gain support
  - A "stand alone" US infrastructure to address all FNS issues is unlikely, international cooperation is critical and necessary

Detailed DEMO Rollback

US DEMO definition is essentially a power plant, we are demonstrating to the utilities, who will operate the plant, that they can generate electricity reliably and profitably

There are a few areas where DEMO can step back; ~ 75% size and electric power, and as low as 50% availability initially

BUT, the technologies and physics are established, and can only change incrementally and predictably from DEMO to the first full power plant

The DEMO description for rollback is based on ARIES power plant studies
ARIES-RS, ARIES-AT, ARIES-ST, ARIES-CS,…

It will cover many areas; plasma, neutronics, Divertor/FW, TF/PF magnets, H/CD, materials, thermal conversion, device build, tritium….

Parameter values are:
Identified, Justified, Present status, R&D needs

Example DCLL Demo reference parameters

He/W Divertor		Value	Justification	Current Status	R&D Needs
	coolant material	helium	He has safety and performance advantages over other coolants. Neutron streaming is an issue, but can be managed.	High-pressure He loops for fusion exist in various countries, including the US. The technology is mature due to implementation in the fission industry.	operating experience with fusion-relevant materials and components is needed to establish reliability.
$p_{He,div}$	coolant pressure	~10 MPa	Tradeoff between improved heat transfer vs. higher primary stresses. Desirable to use same pressure as the blanket and power conversion system.	10 MPa is well within established norms for He-cooled systems.	NA
$T_{in,div}/T_{out,div}$	coolant inlet/outlet temperature	600/700 C	High temperature desired for high Brayton cycle efficiency. Low temperature is constrained by steel.	HTGR and VHTR outlet as high as 1000 C planned. The issue for us is materials limits, including heat exchanger, and compatibility.	
	armor material	pure W	High temperature capability, resistance to erosion	Studies over the past 10 years have demonstrated the advantage of using W. Materials programs are ramping up to provide more data.	New fabrication techniques may offer improved properties. R&D on joining and machining needed.
$T_{W,min}$	minimum allowable W armor temperature	800 C	DBTT concerns (avoid excessive cracking).	Uncertain. Need lower values for a robust system.	Materials development for lower DBTT. Fracture mechanics studies needed to determine whether this limit is appropriate.
$T_{W,max}$	maximum allowable W armor temperature	2190 C	2/3 the melting point, to retain some level of strength. Recrystallization of armor is considered acceptable.	2/3 melting is probably conservative. Need further studies of the consequences of extreme temperature in the armor.	Testing of prototypical elements under nornal and off-normal conditions is required to demonstrate performance and reliability.
$q_{peak, div}$	Peak steady state surface heat flux in the divertor	5-15 MW/m^2	highly uncertain due to physics uncertainties. Transient values unknown.	EU has demonstrated >15 MW/m^2 in He-cooled W finger mockups	transients, cycling, high-temperature demonstration

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$p_{He,div}$	coolant pressure	~10 MPa	Tradeoff between improved heat	10 MPa is well within	NA

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Topical areas (after each face-to-face meeting, a topical group is formed, made up of core and outside members)

	face-to-face meeting
• Materials science and technology (Kurtz/Wirth)	12/3/10
• Plasma facing components and plasma material interactions (Nygren/Tynan/Whyte) • Power extraction and tritium sustainability (Abdou/Morley/Willms)	1/24-25/11
• FNSF/DEMO detailed design activities • Enabling technologies	3/9-10/11
• RAMI • Safety and environment • Plasma duration and sustainability (establish requirements) – V. Chan will lead	Examining how these areas influence others, in progress

Topical Areas Description

materials science and technology - This topic is intended to address single to few-several effects phenomena.

This area includes all materials; structural solids, liquid metals, insulators, etc. and includes both non-nuclear and the effects of neutron damage and modeling of the effects of microstructure and damage on materials properties.

plasma facing component and plasma material interactions - This topic is intended to address the plasma facing components themselves as well as their functioning in the more integrated system of the first wall, divertor, and other PF components.

The conditions includes high heat and particle fluxes, material erosion/redeposition/migration, dust production, etc.

The PMI area is broken into evolution of PFC materials and PFC configuration.

power extraction and tritium sustainability - This topic is intended to address the integrated blanket science which includes the entire FW, breeding blanket, shield and vacuum vessel together.

This includes all the multi-functionality of the separate parts of the build and its integration including heat removal, breeding, neutron shielding, vacuum maintenance. This can be at least conceptually understood by examining the Test Blanket Module for ITER, where a miniature version of a blanket must be constructed, albeit without the severe neutron effects expected in an FNSF or DEMO.

FNSF/DEMO and subsystem design studies - This topic is intended to include design at all stages, from the early systems analysis to identify operating points, to detailed component design integrated in a self-consistent device design.

This area provides necessary support to other FNS areas by giving information on plasma or material boundary conditions, in-service environments, detailed design constraints, operation constraints, and so forth. This is necessary to focus the more basic R&D on the appropriate critical issues.

RAMI - This topic is intended to include the features in the acronym and apply to complete devices, however these features appear to be important at different times along a pathway to DEMO.

Maintainability is likely to be important early as a critical constraint on device design with the first FNS facility, and remain a design driver thru to DEMO. Availability is a characteristic "parameter" we are trying to increase to a level necessary for DEMO. Reliability is at first strictly the result of conservative design combined with vigilant quality assurance of all processes (design through procurement, fabrication and final assembly), while later it becomes a characteristic "parameter" as statistical data is obtained thru systematic testing of components. Inspectibility is likely to be important at all phases of development since it encompasses diagnostics and the ability to determine the state of systems (including failures).

Enabling technologies - This topic is intended to include the many critical technologies for a successful device and includes 1) magnets, 2) H/CD sources, 3) fueling, pumping, particle control, 4) diagnostics and control, 5) plant cryo-systems, 6) balance of plant (outside tokamak core) thermal systems, etc.

Safety and environment - This topic is intended to include both "cultural" and hard R&D areas.

In addition to the licensing and qualification aspects, this also includes the management of waste, choice of materials, constraints on maintenance and operations, and establishment of failure modes and accident probabilities. The ITER TBM program has a licensing aspect that is very useful to understand this aspect.

Plasma duration and sustainment - This topic is intended to include the plasma requirements for a successful FNSF and DEMO.

We are not identifying R&D here, only establishing what we see as requirements of the plasma, and would include plasma on time, plasma duty cycle, plasma performance via NWL, allowed disruptivity or elimination of disruptions, non-inductive plasma current, maximum heat flux and transient heat flux in divertor, etc.

All topical areas will be keeping track of plasma science issues/requirements/boundary conditions that arise in their deliberations.

The R&D activities are a subject for the plasma science program to address, but we would like to make clear the “need” for research in these areas.

PFC/PMI area will be establishing its physics oriented R&D

Materials science and technology topical area: Rick Kurtz / Brian Wirth to lead

Core members

- Mohamed Abdou, UCLA
- Vincent Chan, GA
- Stan Milora, ORNL
- Neil Morley, UCLA
- Richard Nygren, SNL
- Martin Peng, ORNL
- Don Rej, LANL
- Mark Tillack, UCSD
- Dennis Whyte, MIT

Non-core members

Patrick Calderoni, INL

Rion Causey, SNL (retired)

Brian Gleeson, University of Pittsburgh

Phil Heitzenroder + Charles Neumeyer, PPPL

Peter Lee, Florida State University

Joe Minervini, MIT ←

Bruce Pint, ORNL

Shahram Sharafat, UCLA

Lance Snead, ORNL

Bob Swindeman, ORNL (retired)

Gary Was, University of Michigan

Scott Willms, LANL ←

Subtopics in Materials Science area, and people assignments

- First-Wall/Blanket/Vacuum Vessel Structural Materials – **Kurtz**, Wirth, Gleeson, Rej
- Plasma Facing Materials – **Nygren**, Tillack, Whyte, Peng, Tynan
- Breeding & Power Extraction Materials – **Abdou**, Morley, Was
- Insulating & Diagnostic Materials – **Snead**, Heitzenroder, Neumeyer
- Magnet Materials – **Minervini**, Lee
- Chemical Compatibility Issues – **Pint**, Gleeson, Was
- Tritium Materials Issues – **Willms**, Calderoni, Causey
- Design, Licensing, High-Temperature Materials Issues – **Sharafat**, Swindeman, Milora

Rough Guidance on Identifying R&D

- Time frame of research should be near term, approximately 5-10 (maybe 15) years
- Goal of all research is to make the FNSF(s) and DEMO successful, that is support its design, construction, and operation
- Research should indicate/reflect the path beyond the 5-15 year time frame, follow-on research is not too nebulous
- R&D should provide a story of how you are resolving an issue, or how this R&D in combination with a series of steps obtains the required solution
- R&D may require backup options because of its level of uncertainty, what are they and what is that R&D….reserve this for the most critical issues
- Facilities can play a major role in how we think about what R&D can be done, so this factor should emerge from what we are stating needs to get done; there is a facility, there is an upgraded facility required, there is a new facility required

Rough Guidance on Identifying R&D, cont'd

- Initially pursue a US only strategy, however, keep in mind where you know there are international efforts along the same lines, we will return to this later
  - Establishing R&D necessary is the right first step, how the R&D is done and US's capability is next
  - Some difficulty in accurately establishing international facilities, capabilities, and commitments
  - Serious collaborations would require a level of commitment from US
- Indicate where there is synergy, you are aware of, within DOE programs, or within another largely government funded areas (high energy physics, NSF, NASA,…)
- Identify "chunks" of R&D, that can be started near term and funded, this is related to the "size" of the R&D you are identifying which ultimately includes the facilities required to do it, time it takes to complete, and overall scale of work
- Break the topical area into subtopics, and sub-subtopics if necessary in order to get to a level where the R&D can be identified

Examples of R&D specification (facilities, where can R&D be done)

Linear Divertor Plasma Simulators | **Reactor**

		PISCES-B	NAGDIS-II	DIONISIS	PISCES-A DPE/TPE*	PSI-II	PILOT	MAGNUM Goals*	PMTS Goals**	ITER
Discharge		Refl. Arc	Pen.	RF-Plasma	Refl. Arc	Pen.	Arc Casc.	Arc Casc.	RF-Plasma	Divertor
Power	(kW)	5–15	10.5	3	5–10	6.5	45	270	**300**	
p_{target}	(Pa)	0.01–1	0.1–4	0.1–4	0.01–1	0.01–0.1	1–10	< 10	0.01–1	0.1–1*
E_i or T_i	(eV)	10–300	50	10-500	10–200	< 15	0.1–5	0.1–10	3–100	10–300
T_e	(eV)	3–50	10	1-5	3–20	< 30	0.1–5	0.1–10	3–100	< 100
n	(m^{-3})	10^{17}–$2\cdot10^{19}$	$6\cdot10^{19}$	0.1-$1x10^{18}$	10^{17}–10^{19}	10^{19}	$4\cdot10^{21}$	10^{20}	10^{18}–10^{20}	> 10^{19}
Ion flux	($m^{-2}s^{-1}$)	10^{21}–$2\cdot10^{23}$	10^{22}	10^{20}-10^{22}	10^{21}–$3\cdot10^{22}$	10^{22}	$5\cdot10^{24}$	10^{24}	10^{22}–10^{24}	> 10^{23}
Power flux	($MW\cdot m^{-2}$)	1–10	0.01	0.01-0.1	2	0.1	30	10	20	5–10
B	(T)	0.04	0.25	0.01-0.1	0.1	0.1	1.6	3	1	5
Beam dia.	(cm)	5	2	5	5	6–15	1.5	10	10	
Length	(m)*	1.5	2.8	1	1	2.5	0.5–1		10	N/A
Heating	(kW)	< 3 dc	~50 rf	~3 rf	< 1 dc	5	10 dc	50 dc + rf	**110 rf**** Maxwellian	SOL* Thermal
				PMI capabilities				PMI capabilities		
Gas species		D, He	D, He	D, He	D, T*, He	D, He	D, He	D, He	D, He	D, T, He
Targets		Be, C, W	W, C	Mo, W, C	Be*, W, C	W, C	W, C	W, C	W, C, etc.	Be, C, W
Pulse length	(s)	steady	steady	steady	steady	steady	10	steady	steady	400–3000*
Ion Incidence		Normal	Normal	Normal	Normal	Normal	???	???	???	Oblique
Impurity PMI		Be, C								Be, C, W
S.S. Surface Temperature	(deg C)	20-1000		20-500	20-1000					
Transients		YAG	YAG	YAG					Infrared	ELM
Damage				<10MeV Ion Beam					Irradiated samples	Neutron
Max. Fluence (/ day)	(m^{-2})	~10^{27}	~10^{26}	~10^{26}	~10^{26}	~10^{26}	~10^{26}	~10^{28}	~10^{28}	10^{26}–10^{27}

**Helicon + EBW + Whistler + ICRF

In service	Not operational	Near condition	Meets Condition		Below condition	*Added by ORNL

TABLE I: Existing Linear Divertor Plasma Simulators

Example of R&D Specification (R&D items)

Example of SiC insert in blanket

Functional materials in this context includes insulators, armors, tritium breeders, neutron multipliers, corrosion/permeation barriers, etc Basic science that needs to be strengthened or initiated (SiC examples only, the list is long…)

1.Fabrication of reduced thermal, electrical conductivity SiC structures, without degrading mechanical properties
2.Thermomechanical behavior/cracking of inserts under significant thermal gradients
3.Interplay of creep and swelling and thermal expansion in complex ceramic structures
4.PbLi contact, wetting and infiltration in SiC structure porosity
5.SiC tritium transport and barrier characteristics
6.Novel techniques to investigate helium and other conducting transmutation product buildup in SiC

Example of Tungsten initiative

I. Computational Modeling
  - Ductilizing solutes, dislocation nucleation & mobility, grain boundary chemistry & cohesion, near surface He effects

II. Test Methods & Characterization Protocols
  - Deformation & fracture, thermal creep

III. Fundamental Studies of Cleavage Fracture

IV. Intergranular Fracture & Grain Boundary Embrittlement

V. Alloy Development
  - Solute softening, nanostructured alloys, composites & ductile phase toughening

VI. Processing & Joining Technology

VII. Irradiation Effects

VIII. Surface & Dimensional Stability

Enabling technologies

- Enabling technologies - This topic is intended to include the critical technologies for a successful FNSF and DEMO devices and includes
  - 1) magnets – J. Minervini will lead this
  - 2) H/CD sources – small group identified (R. Wilson, R. Callis, S. Wukitch, L. Grisham, D. Rasmussen, R. Parker)
  - 3) fueling, pumping and particle control systems (L. Baylor)
  - 4) plant cryo-systems → ITER demonstration
  - 6) balance of plant (outside tokamak core) thermal systems, etc. → outside activity scope
  - 7) diagnostics (and control?) – small group identified (K. Young, R. Boivon, J. Terry, D. Johnson)

- We need to identify how we can get to the needed research in these areas. In some cases we may be able to say that ITER provides sufficient data, or not. Only the most critical issues should be included.

How to establish the most efficient step(s) or pathway from ITER to DEMO - missions

This is a complex problem – we are presently working through this

We know we can not build lots of devices because of the cost

From the scientific point of view, many devices is the preferred approach because it allows small technical steps (risk) with the ability for course correction

So how can we assess a pathway to DEMO in terms of devices that close technical gaps while determining the minimum number of such devices

→ Establish metrics to judge a device along the pathway to DEMO

→ Begin with a many device solution and establish what those steps might be

→ Begin to collapse low risk technical features of these devices, effectively combining missions to reduce the number, while trying to keep the technical risk as low as possible

Metrics for measuring a step (this is a confinement device) along the pathway to DEMO

- Device life neutron fluence
- FW/blanket maximum neutron fluence to replacement
- Electrical consumption and output, or Q_{engr}
- Plasma fusion gain
- Plasma duration
- Plasma performance
- Plasma duty cycle (on time)
- Tritium sustainability, ranging from none (you purchase it), to over-supply)
- Neutron flux
- PFC/FW/divertor/blanket lifetimes
- Mean Time Between Failures (MTBF) and Mean Time To Replace (MTTR)
- Availability

What's the plan….

Topical areas and expert groups all formed by mid March

All expert group work due in early June. Groups may have a face-to-face meeting of their own as they deem necessary.

All other topics also must have report done by early June (plasma sustainment, enabling tech groups,…)

June and July, assembling and writing report → target is August 2011, the report should be technically reviewed

After March 9,10 face-to-face meeting, will determine what additional meetings are required

Development of DEMO rollback, missions along pathway, Safety/RAMI topics, and other topics may require a dedicated meeting

Conference calls will continue at ~ every 2 weeks