# Fusion Nuclear Science – Pathways Assessment, Overview

C. Kessel, PPPL

FESAC meeting, Gaithersburg, MD
7/28/2011

# Progress in activity

- Kick-off meeting, July 2010
- Some early discussions at FNST meeting, UCLA, August 2010
- Charter and topical groups established, to identify required R&D over next ~ 5-10 years, roll forward
  - Report outline
  - Some guidance on R&D specification
- Completed 4 face-to-face meetings
  - Materials science and technology – Dec 2010
    - Topical group meeting – May 2011
  - Power extraction and tritium sustainability & PFC/PMI – Jan 2011
  - Enabling technologies & design activities & safety and environment – March 2011
  - All topical groups report on writing and structure – July 12-13, 2011
- Conference calls
- Construction of a DEMO parameter table, roll back vision
- Exercise to examine “missions” along a path to DEMO

# Report outline – targeting Aug-Sept delivery

1. Introduction

2. DEMO projection table of parameters

3. FNS Topical area R&D specification
    1. Material science (some sections)
    2. Power extraction and tritium sustainability (some sections)
    3. PFC/PMI (2 of 3 drafts)
    4. Safety, environment and RAMI (draft)
    5. Magnets, heating and current drive, fueling/pumping/particle, diagnostics (draft)

4. Facilities list and timelines (collect facility info from the sections above)

5. Plasma duration and sustainment (draft)

6. Leveraging opportunities (known or strong potential collaborations)

7. FNSF & DEMO design activities

8. Pathway to FNS facilities and DEMO, missions and metrics

# People involved – FNS-PA core group

**chair:**

C. Kessel (PPPL)

**members:**

- 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)

# People involved – additional topical group members (listed only once)

**Materials science**
B. Gleeson, UP
P. Lee, FSU-NHMFL
R. Causey, SNL ret
I. Zatz PPPL
S. Sharafat, UCLA
L. Snead, ORNL

**Power extraction and tritium**
Dai-Kai Sze, UCSD
Alice Ying, UCLA
Mohamed Sawan, UW
Clement Wong, GA
Pattrick Calderoni, INL
Bruce Pint, ORNL
Yutai Katoh, ORNL
Sergey Smolentsev, UCLA
Jake Blanchard, UW
Siegfried Malang, (ret.)
Art Nobile, LANL

**PFC configuration**
R. Majeski, PPPL

**PFC evolution**
R. Doerner UCSD
J.P. Allain Purdue
T. Rognlien LLNL

**Magnets**
Leslie Bromberg, MIT
Joel Schultz, MIT
M. Takayasu, MIT
D. Larbalestier, FSU-NHMFL

**Fueling/pumping**
L. Baylor, ORNL

**H/CD**
R. Wilson, PPPL
L. Grisham, PPPL
D. Rasmussen, ORNL
R. Parker, MIT
R. Callis, GA

**Safety, environment**
L. Cadwallader
P. Humrickhouse
M. Shimada

**Diagnostics**
K. Young, PPPL
Réjean Boivin, GA
David Johnson, PPPL & US ITER
Jim Terry, MIT

**Plasma duration (GA)**
T. Luce
A. Garofalo
J. Wesley
T. Evans
Stangeby
T. Petrie
G. Jackson
D. Humphreys
C. Petty
J. Kinsey
T. Strait
Van Zeeland
R. Nazikian

**(MIT)**
M. Greenwald, E. Marmar, A. Hubbard, P. Bonoli

**(PPPL)**
J. Menard, C. Skinner, R. Maingi, M. Zarnstorff

# DEMO/power plant parameter table

Purpose of this is to provide the longer term vision, or where we think we need to go…..it is a vector direction, and carries some uncertainty

We may not reach the most aggressive visions we have for power plants, but we know the direction of our assumptions are generally correct

When we look back from a DEMO/power plant, we see that our R&D is moving in a direction that is consistent with our vision, regardless of whether it achieves our parameter projections or not

Plasma parameters – both moderate and aggressive

Dual Coolant Lead Lithium blanket (ferritic steel, He coolant, LiPb breeder/coolant) – nearer term

SiC, LiPb breeder coolant – more aggressive

Table contains parameters describing:  Divertor, FW, blanket, vacuum vessel, power cycle, neutronics, TF/PF magnets, H/CD, fueling and pumping

Contains description, present status, and R&D needs

# Topical area R&D examples so far: materials science and power extraction/tritium

# Materials science topical group

- Led by R. Kurtz and B. Wirth

- Subtopics
  - Structural materials
  - PFC
  - Breeding/blankets
  - Tritium
  - Insulating, diagnostics
  - Corrosion, compatibility
  - Design criteria, licensing and safety, high temperature

- This groups focus is single effect to few effect material science, including non-nuclear and neutron irradiation effects

Some of the subgroups needed a timeline structure to help them focus their R&D specification

- ITER TBM (goal of 3 dpa/30 appm He) [5 years]
  - He cooled ceramic breeder
  - PbLi/He dual cooled liquid breeder
- FNSF (goal of 3-50 dpa, 30-500 appm He) [5-15 years]
- DEMO (goal 100-150 dpa, 1000-1500 appm He) [>15 years]

# Near-Term (5 years) Structural Materials Research I

- RAFM Steels
  - Fabrication and joining technology development (partnership with U.S. industry) for advanced fabrication technologies
  - Thermo-mechanical effects (fatigue, creep, creep-fatigue, etc.)
  - Low-dose irradiation effects on alternate microstructures (HIP, cast, etc.)
  - Nondestructive evaluation technique development, and development of flaw acceptance criteria
- ODS or Nanostructured Ferritic Alloys
  - Fracture toughness and material anisotropy
  - Joining technology (solid-state welding technologies)
  - Fabrication (scale-up) technology
  - Nanocluster stability under irradiation

# Near-Term (5 years) Structural Materials Research II

- Tungsten Alloys
  - Improve ductility and fracture toughness (DBTT < ~ 800°C)
  - Increase recrystallization temperature ($T_{rc}$ > ~ 1200°C)
  - Thermo-mechanical effects
  - Oxidation resistance
  - Low-dose irradiation effects on mechanical and thermo-physical properties
- Vacuum Vessel Steels
  - Assessment of potential candidates needed.
  - Close collaboration between design and materials communities to determine geometry, operating conditions, activation requirements, loading conditions, cooling water chemistry, min thickness for shielding, mechanical properties and effects of irradiation, fabrication and joining issues (e.g. no PWHT).

# Long-Term (5-15 years) Structural Materials Research I

- RAFM Steels, ODS Alloys, Tungsten Alloys
  - Data from a fusion-relevant neutron source and non-nuclear testing facilities needed to understand single-effects and multiple-effects phenomena.
  - Materials degradation phenomena such as He embrittlement, irradiation creep, volumetric swelling, and phase instabilities begin to be manifested at > 10 dpa so intermediate (3-50 dpa) and high-dose (50-150 dpa) neutron irradiation effects need to be characterized.
  - Development of a material property data base sufficient to support design, licensing, safety and code qualification requirements for FNSF and DEMO.

# Long-Term (5-15 years) Structural Materials Research II

- SiC Composites
  - He effects (100 appm He/dpa)
  - Effect of transmutations on phase stability and electrical and thermal conductivities.
  - Irradiation creep data of composites with He.
  - Composite swelling in thermal and stress gradients is needed.
  - Joining of SiC in useful shapes and irradiation testing.
- Vanadium Alloys
  - Influence of interstitial impurities on tensile, creep and fracture properties.
  - Development of a suitable MHD insulator coating.
  - The effects of He and H on swelling and mechanical (creep) properties.
  - Non-hardening embrittlement mechanisms driven by impurity-solute segregation, phase/structural instabilities, He, H, etc.

# Critical Resource Needs I

- Research Scientists and Engineers
  - Many specialized skills will be needed – physical metallurgists, ceramists, electron microscopy experts, mechanical property specialists, fracture mechanics, materials evaluation specialists (SANS, PAS, APT, etc.), corrosion scientists, nondestructive evaluation specialists, theory and modeling experts (multiscale materials modeling).
  - 2003 FESAC Development Plan estimated ~60 FTE/y at peak activity.
  - Existing talent pool rapidly shrinking!
- Materials Science Facilities
  - Materials evaluation equipment – TEM, SEM, FIB, Auger, APT, etc.
  - High-temperature materials testing – creep, fatigue, fracture, thermal-shock and fatigue.
  - Compatibility testing – flow loops for corrosion testing, oxidation.
  - Physical property measurements – thermal, electrical, optical, etc.
  - Material fabrication and joining of small to large-scale components.
  - Hot cells for handling and testing of activated materials.

# Critical Resource Needs II

- Non-Nuclear Structural Integrity Benchmarking Facilities
  - Facilities for testing various components such as blanket modules are needed to investigate the potential for synergistic effects that are not revealed in simpler single-variable experiments or limited multiple-variable studies.
  - Provides data to refine predictive models of materials behavior.
  - Gives reliability and failure rate data on materials, components and structures to validate codes for designing intermediate step nuclear devices and DEMO.
  - Test bed to test and evaluate nondestructive inspection techniques and procedures.
- Other Facilities
  - Extensive computational resources will be needed at all phases of fusion materials development to support model development but, in particular, large-scale structural damage mechanics computational capability will be needed to guide and interpret data obtained from component-level test facilities.

# Critical Resource Needs III

- Fission Reactors
  - The capability to perform irradiation experiments in fission reactors is essential for identifying the most promising materials and specimen geometries for irradiation in an intense neutron source.
- Fusion Relevant Neutron Source
  - Overcoming radiation damage degradation is the rate-controlling step in fusion materials development.
  - Evaluation of radiation effects requires simultaneous displacement damage (up to ~150 dpa) and He generation (up to ~1500 appm).
  - International assessments have concluded that an intense neutron source with ≥ 0.5 liter volume with ≥ 2 MW/m$^2$ equivalent 14 MeV neutron flux to enable testing up to a least 10 MW-y/m$^2$, availability > 70%, and flux gradients ≤ 20%/cm is essential to develop and qualify radiation resistant structural materials for DEMO.

# Power extraction and tritium sustainability: blanket science

Immediate research needs 1-5 years

Led by N. Morley, M. Abdou, and S. Willms

1. PbLi Based Blanket Flow, Heat Transfer, and Transport Processes (Smolentsev, Morley, Calderoni)
2. Plasma Exhaust and Blanket Effluent Tritium Processing (Willms, Nobile, Abdou)
3. Helium cooling and Thermomechanics of high heat flux surfaces for FW/ Blanket (Wong)
4. Ceramic Breeder Thermomechanics and Tritium Release (Ying)

Subtasks under each main category

Each Subtask (1-2 page) described in terms of four main topics:
Justification and Status,
R&D Task Description,
Facility Needs, and
Dependencies

Have used the US TBM blankets as the focus: DCLL and ceramic breeder designs

# Power extraction and tritium sustainability

1. PbLi Based Blanket Flow, Heat Transfer, and Transport Processes

**Task 1:** Develop understanding of the pressure drop and distribution of flow and temperature in PbLi blankets at prototypic temperatures with prototypic materials (1-2 page)

**Task 2:** PbLi Corrosion, transport, deposition, and chemistry control with prototypic materials conditions (1-2 page)

**Task 3:** Control of tritium and activation products in PbLi blankets (1-2 page)

**Task 4:** Measurement of PbLi behavior at high temperature, in-field, in pile. (1-2 page)

# Power extraction and tritium sustainability

**Medium term research needs 5-10 years**

1. Multiple thermomechanical effects and mockup testing of PbLi and ceramic breeder blanket systems heating and pulsed mechanical loading
2. TBM scale loops and modules
3. Fuel Cycle Development Facility (HD integrated development facility)
4. Tritium Breeding and Processing Facility (Small integrated tritium breeding/extraction facility)
5. ITER TBM/FNSF design and safety/licensing R&D
6. Irradiation effects on blanket material and component functions (small unit cells)

**During ITER operations, 10-20 years**

1. ITER TBM modules experiments and PIE
2. Continued FNSF design and safety/licensing R&D
3. Or early FNSF experiments if the facility is ready

# Plasma duration and sustainment

- This topical area is not intended to identify specific R&D, but only to highlight what emerge as critical plasma physics areas that affect the fusion nuclear science mission's success (make it vulnerable)
  - The FNS mission requires a steady state neutron source with sufficient plasma performance and duration to provide the level of neutron fluence necessary
  - What can our confinement facilities do in these areas

- Steady state plasmas that provide the fusion nuclear environment
- Benefits of enhanced plasma performance to the FNS and DEMO
- Particle fueling, pumping, and control
- Disruption (off-normal) events avoidance and mitigation
- Power and particle transient loading
- Energetic particle losses

- This section is being circulated to PPPL and MIT personnel to comment on physics issues and facility statements

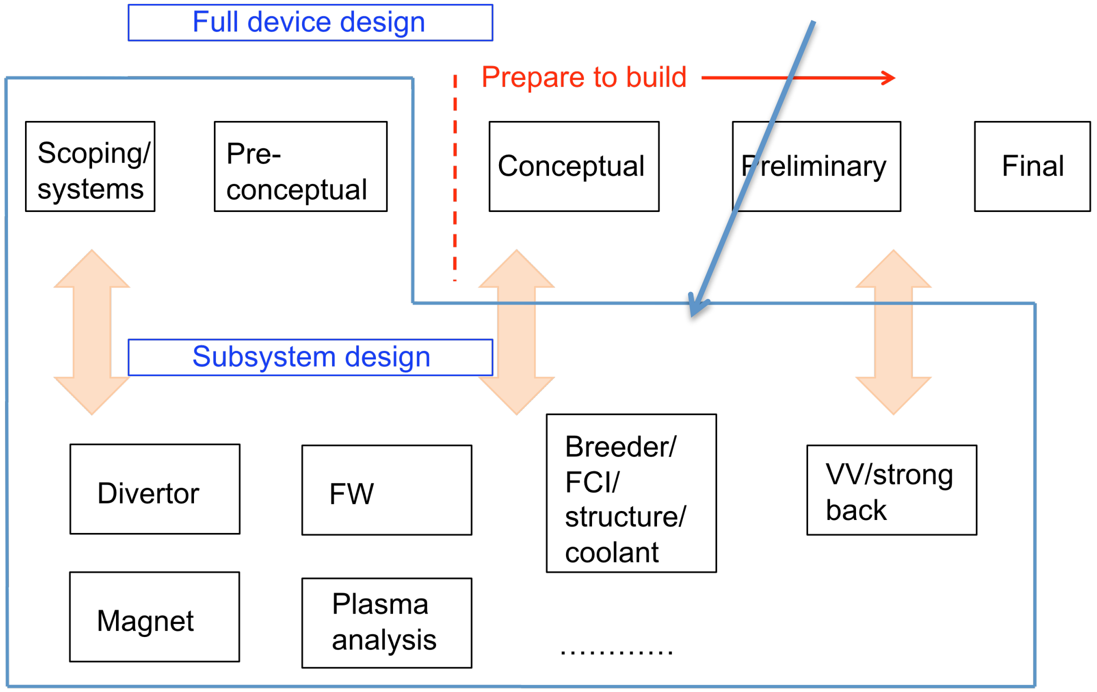
# Design activities

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, and its integration 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.

Systems analysis (0D analysis of plasma, engineering, costing)
Detailed plasma analysis
Magnet engineering and design
Neutronics analysis and radial build development
Mechanical/thermal analysis
Thermal hydraulics
Materials properties and compatibility
Heating and Current Drive systems
Maintenance/Remote handling
Pumping/fueling/vacuum systems and particle handling
Tritium extraction, processing
Prepare to build design areas (we will largely neglect these)

We are focused on activities inside this box



Full device design

Prepare to build

Scoping/ systems

Pre-conceptual

Conceptual

Preliminary

Final

Subsystem design

Divertor

FW

Breeder/ FCI/ structure/ coolant

VV/strong back

Magnet

Plasma analysis

…………

# Examination of possible FNS steps/missions along the path to DEMO, still in progress

What steps/missions should a FNS confinement device(s) provide between now and DEMO, that further our

  fusion nuclear nuclear technical basis
  plasma physics technical basis
  prepare us for a demonstration power plant

This question is normally posed in terms of making choices and assigning risk

  Assume 1 device
  Assume 2 devices
  Etc…

But what are the technical requirements?

To isolate the technical aspects, or metrics, we are using a “thought experiment” that assumes many steps/missions, and ignores cost and schedule

  We are trying 6 steps/missions in this exercise
  Examine the step/mission at a systems level

The purpose of confinement devices are to explore, test, and demonstrate integrated performance, the things that are otherwise inaccessible on test stands – these provide a critical part to the R&D path to DEMO

| metrics | step 1 | step 2 | step 3 | step 4 | step 5 | step 6 | DEMO |
|---|---|---|---|---|---|---|---|
| Life of plant fluence, MW-yr/m$^2$ | 0.75-1.5 | 3.0-6.0 | 4.5-9.0 | | | 2-4 x 20 | 6-8 x 20 |
| FW/blanket fluence to replace, MW-yr/m$^2$ | 0.75<br>7.5 dpa | 1.5-3.0<br>15-30 dpa | 1.5-4.5<br>15-45 dpa | | | 20<br>200 dpa | 20<br>200 dpa |
| $Q_{engr}$ | 0 | 0 | 0 | | | < 4-7 | 4-7 |
| $Q_p$ | 1-1.5 | 2-2.5 | | | | 20-40 | 20-40 |
| Plasma duration | 1 day | 1 day | days | | | 0.5-1 year | 1 year |
| Plasma performance $\beta_N H_{98}/q_{95}$ | 0.825 | 0.840 | Attempts to > 0.8 | | | 0.8-2.85? | 2.85 |
| Plasma on-time / year | 10% | 20% | 30% | | | 20-50% | 50-80% |
| Tritium sustain | 0 | TBR > 0.5, OB only | TBR $\geq$ 1.0 IB/OB | | | TBR $\geq$ 1.0 | >100% |
| Life of plant | 10-20 | 10-20 | 10-20 | | | 20+ | 40+ |
| Ave neutron flux, peak OMP | ~0.5, 0.75 | ~1.0, 1.5 | ~1.0, 1.5 Larger for higher $\beta_N$ | | | 2.5-3.0, 3.8-4.5 | ~2.5-3, 3.8-4.5 |
| $q_{peak,\ OB\ div}^{steady}$ MW/m$^2$ | ~7 | ~11 | | | | | ~10 MW/m$^2$ |

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6. Leveraging opportunities (known or strong potential collaborations)

7. FNSF & DEMO design activities

8. Pathway to FNS facilities and DEMO, missions and metrics