

ReNeW Thrust 13 Draft:

Establish the Underlying Science and Innovative Technology Needed for Fusion Power Extraction and Fuel Sustainability

Developed by Theme IV and some Theme III panel members

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Power extraction is THE goal of a fusion energy system

- For any fusion energy system to proceed to DEMO, we must:
 - guarantee fuel sustainability (i.e. tritium self-sufficiency) concurrent with high-temperature power extraction
 - while keeping the system safe, reliable, maintainable, environmental attractive, and compatible with plasma operation
- The main in-vessel and supporting components that contribute to these essential functions are:
 - the breeding blanket with integrated first wall facing the plasma
 - the divertor
 - the vacuum and tritium processing systems
- Thrust 13 is about understanding the behavior of the materials and components in the fusion nuclear environment -- usually referred to as **Fusion Nuclear Science and Technology (FNST)**
- This represents a challenge that requires important advances in many scientific fields and engineering disciplines

Unique Attributes of Fusion Power Extraction

- a. Very high surface heat flux and potentially high peaking factors,
- b. Complex volumetric heating source
plasma products (neutrons, particles, radiation) .. nuclear reactions ..
- c. Strong impact of EM field (both static and dynamic) on structures and heat transfer
- d. Large temperature and stress gradients
multitude of complex physical phenomena,
- e. Compatibility with the fuel cycle (tritium production and extraction),
- f. Complex geometry, and
- g. evolving material properties (e.g., .. radiation effects).
- h. Location of components inside VV sets tough requirements on limits for space, failure tolerance & reliability**
- i. Compatibility with plasma configuration, operation & control**

What are the challenges?

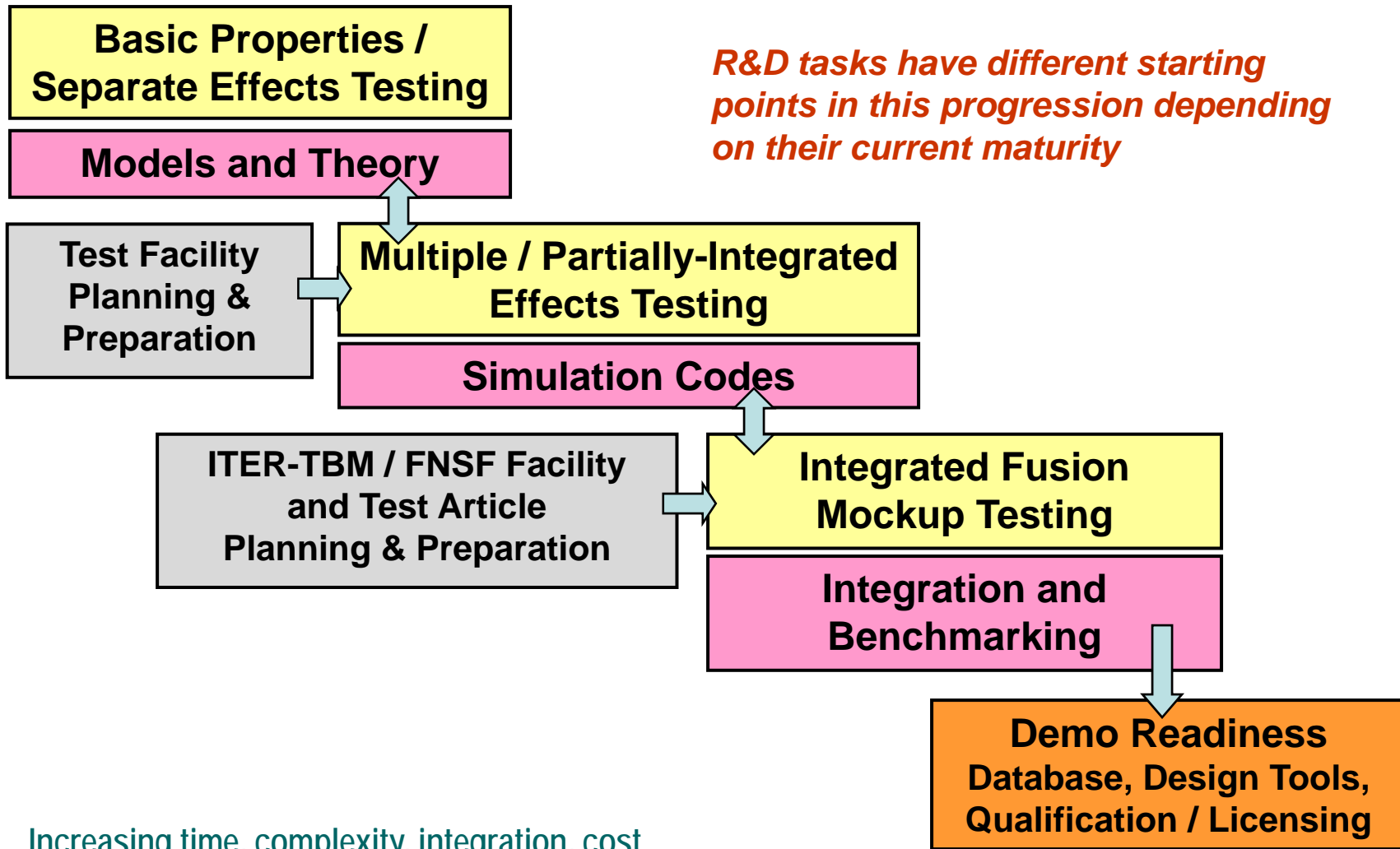
- *How do we control the generation and transport of tritium and transmutation products?*
- *How does the interaction of conducting liquid metal coolants with complex electromagnetic fields and intense heating impact tritium production and power extraction systems?*
- *What techniques can improve the heat transfer capabilities of helium for high heat flux removal?*
- *What are the key synergistic phenomena that govern power extraction and fuel cycle component performance?*
- *What are the failure mechanisms and frequencies?*
- *How can the performance and life-time limits be extended?*
- *All of these in a in a real practical fusion energy system*
 - **Compatibility with plasma operation, plasma maintenance hardware, and vacuum vessel environment**
 - **Real materials... Manufacturable, Maintainable, Affordable**
 - **Safe and licensable**

Elements of Thrust 13

Main Goal: Create, model, and test the many technologies needed for fusion relevant, high temperature power extraction and conversion, tritium breeding, and tritium control and recovery from the plasma chamber.

- Fundamental Research (on Heat Transfer, LM-MHD, Chemistry, Thermomechanics...)
 - basic properties, separate effects testing, theory and models
- Multiple Effects Testing
 - investigate performance, design and material options, and uncover pre-irradiation synergistic failure modes
 - develop engineering diagnostics capabilities and remote maintenance approaches
- Fusion “Break-in” in ITER-TBM
 - conduct beginning-of-life fusion environment tritium breeding and power extraction experiments with prototypic materials, temperatures, diagnostics, and designs
- Fully Integrated Testing
 - resolve key knowledge gaps to a Demo stemming from effects of significant neutron flux, fluence, and nuclear heating in concert with all other fusion environmental conditions
- Aggressive reliability growth and diagnostic development
 - building upon the knowledge accrued during all stages of development and testing described above.

Linkages of Main Thrust Elements

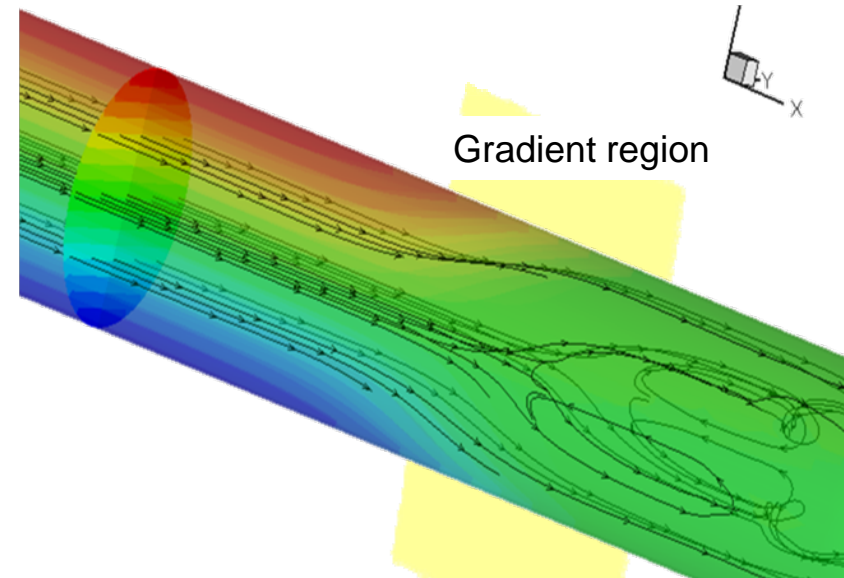


Fundamental FNST Research

- An intensive program of laboratory scale experiments and model development addressing gaps in understanding and database

Example areas:

- PbLi alloy tritium chemistry, transport characteristics, isotope / impurity control
- PbLi compatibility with SiC flow channel insert material and ferritic/martensitic steel
- Liquid metal MHD interactions that dominate liquid metal blankets and free surface divertors flow and transport
- Heat transfer and enhancement in high-temperature helium-cooled divertor concepts.
- Tritium chemistry, transport and removal techniques from high temperature helium
- Ceramic-breeder pebble-bed response to thermomechanical load and cycling
- Interaction database of beryllium and liquid metal alloys with water and air

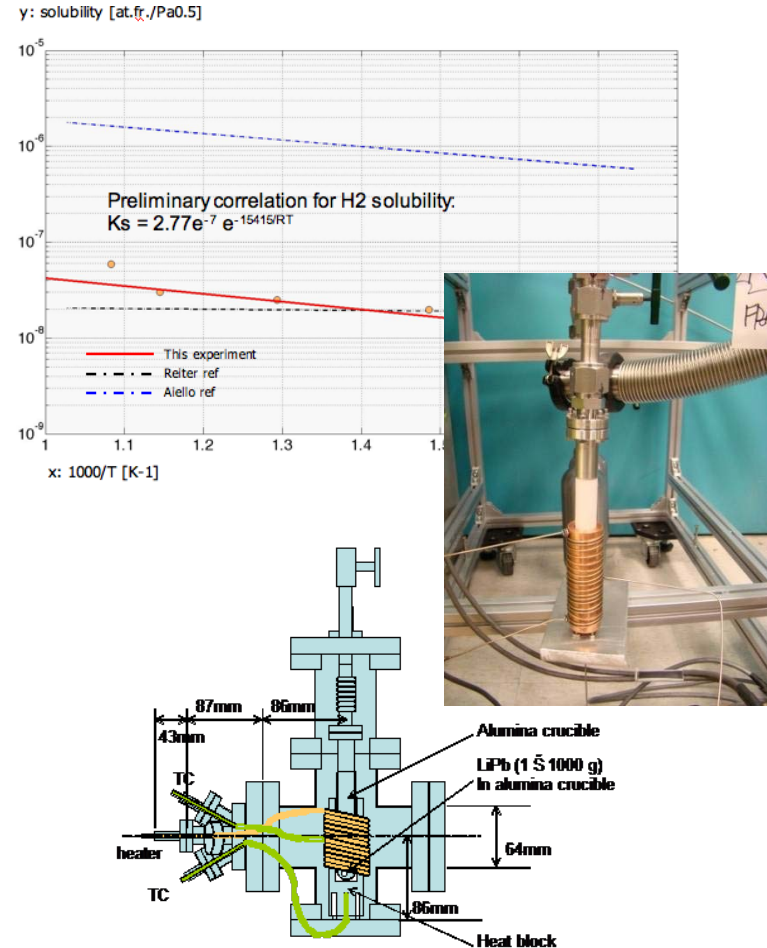


3D MHD simulation of LM coolant streamlines in a pipe disturbed by a magnetic field gradient

- Formation of instabilities and recirculating regions can strongly influence both heat and tritium transport behavior and generate strong flow resistance.
- MHD forces generally exceed viscous and inertial forces by 5 orders of magnitude in fusion blankets.

Fundamental FNST Research (2)

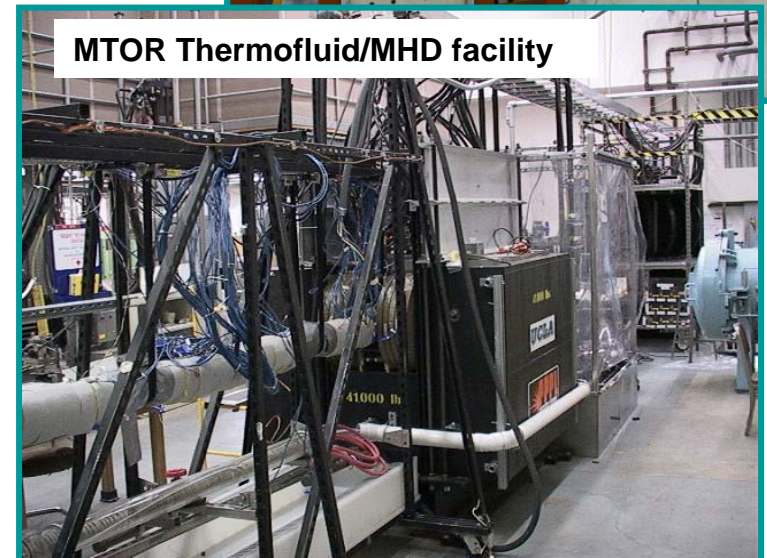
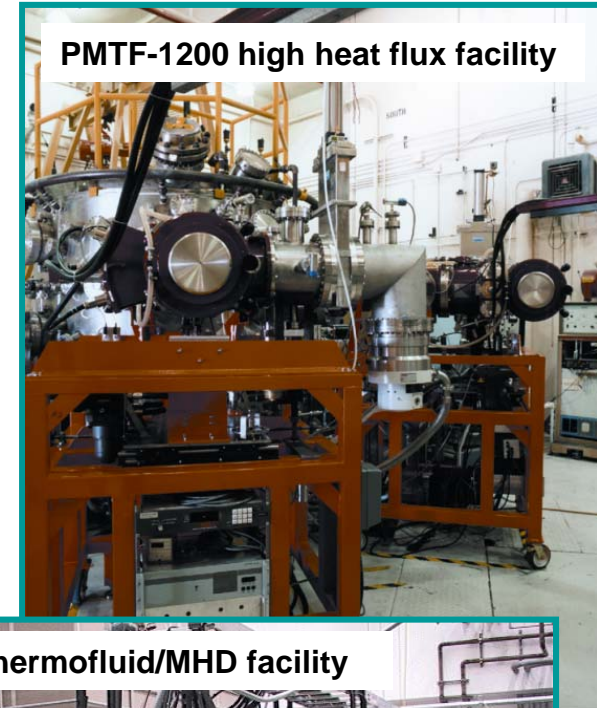
- Scope
 - Functions and Elements of the Blanket, FW, Divertor, heat transport and tritium systems (mainline and alternates)
 - Database, basic phenomena exploration, model development in:
 - Thermofluid/Heat transfer properties
 - Chemistry and reaction rates
 - Thermomechanical properties
 - Diagnostic capabilities
 - Multiple university/lab research programs
- Time scale
 - Consistent 10 year effort
- Other Benefits
 - Innovation, invention, discovery
 - Basic validation of existing designs and models
 - Reinvigoration of FNST in the US



Past tritium solubility measurements in PbLi have a wide discrepancy, by orders of magnitude. New experiments must provide better accuracy and help identify sensitivities that can drastically change the results

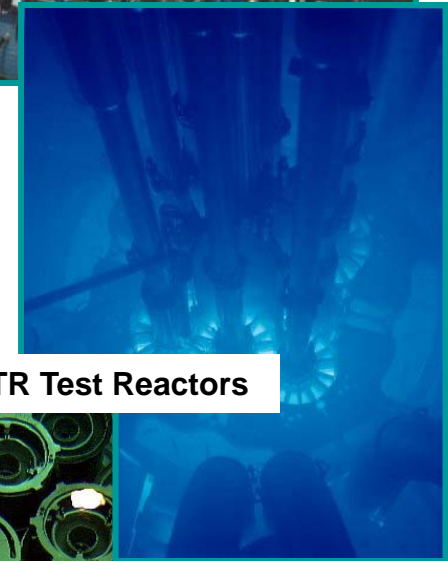
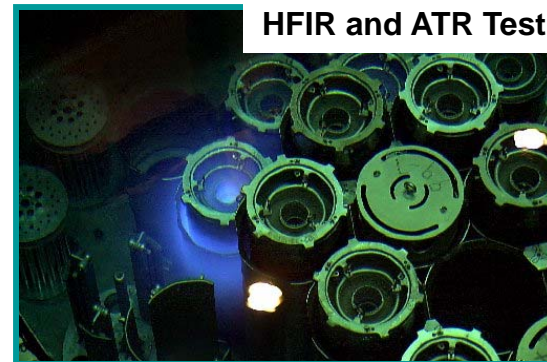
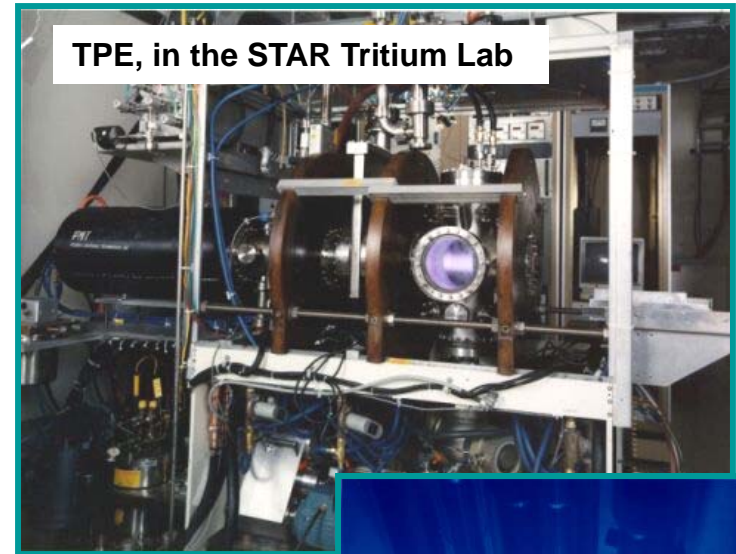
Multiple-Effects, Synergistic Phenomena

- Synergistic phenomena will dominate the behavior, failure modes and reliability of first designs and prototypes. Examples...
 - LM Thermofluid/MHD + FCI Thermomechanics
 - Neutron irradiation driven heating and breeding in blanket unit cells
 - Multiple effect tritium/thermal/chemical effects
- Utilize test facilities to
 - explore multiple-effect phenomena,
 - investigate specific design and material combinations
 - uncover synergistic failure modes
- Partially-integrated thermal, nuclear, electromagnetic, and plasma loading conditions
 - Magnetic/Thermal,
 - Plasma/Thermal, Tritium/Thermal,
 - Neutron/Thermal/Tritiumthat can accommodate prototypic sizes and materials (Be, Li, PbLi, T)
- Sufficient single effects database a prerequisite



Multiple-Effects, Synergistic Phenomena (2)

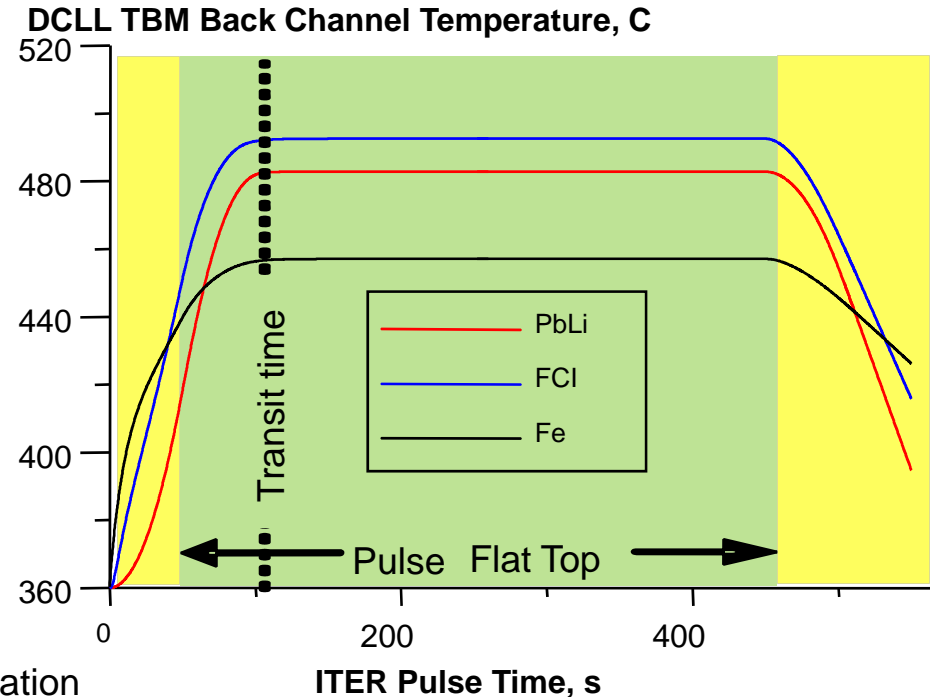
- Scope
 - Mockups of the Blanket, First Wall, Divertor, heat transport and tritium systems (mainline and alternates)
 - Upgrade and construction of needed user test facilities (3-4 total)
- Time scale
 - Planning and scoping - Immediate
 - Operations, Consistent 10 yr effort
- Additional Benefits
 - Model validation in more complex operational regimes
 - Testing fabrication and diagnostic capability
 - Initial reliability growth and qualification information
 - Enabling continuous power and tritium extraction



Fusion “Break-In” in ITER-TBM

Utilize the ITER burning plasma to conduct beginning-of-life fully integrated tritium breeding and power extraction experiments with prototypic materials and at prototypic temperatures

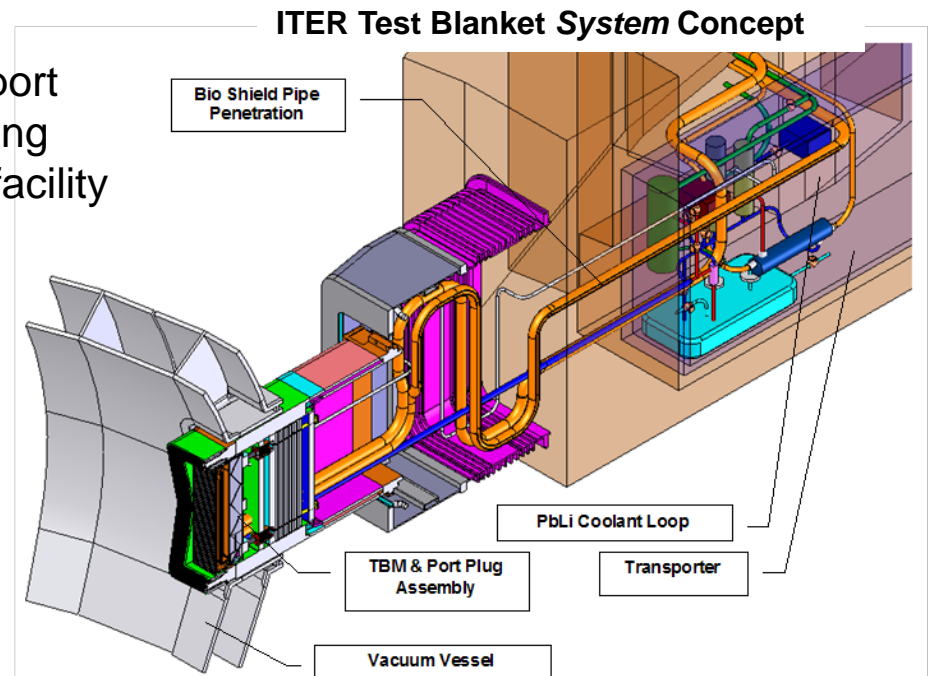
- Study “Prompt” phenomena that reach near steady state during the ITER burn
 - Tritium production profiles
 - Nuclear heating profiles
 - MHD thermofluid behavior
 - Thermomechanical state and temperature profiles
 - Disruption responses
- Investigate phenomena that reach a cyclic equilibrium over many pulses
 - Tritium concentration and permeation
 - Corrosion and activated product transport
 - Impact of early life radiation damage in ceramics, especially insulators like the flow channel insert
- Value strongly dependent on developing suitable measurement capability and sufficient prior understanding



Material temperatures at the back exit channel of a proposed DCLL TBM as a function of ITER burn duration. Transit time is the average time necessary for PbLi coolant/breeder to pass through the TBM

Fusion “Break-In” in ITER-TBM (2)

- Scope
 - Construction of auxiliary support loops to enable US TBM testing (equivalent in scale to a test facility previously described)
 - Fabrication of several TBM Mockups
 - PIE on exposed TBMs
- Time scale
 - Modest planning with TBM-PC – immediate
 - Operations ~2022
 - Afore-described R&D prerequisite
- Additional Benefits
 - Model validation in full fusion environment: e.g. neutronics, thermofluid, EM,...
 - Continue reliability growth database in 1st fusion environment
 - Establish test procedures, qualification procedures, diagnostics testing
 - Share information internationally / concept , design, material screening



Performing tritium breeding and power extraction experiments in ITER, using experimental modules with relevant materials, coolants, and support systems, at prototypic temperatures

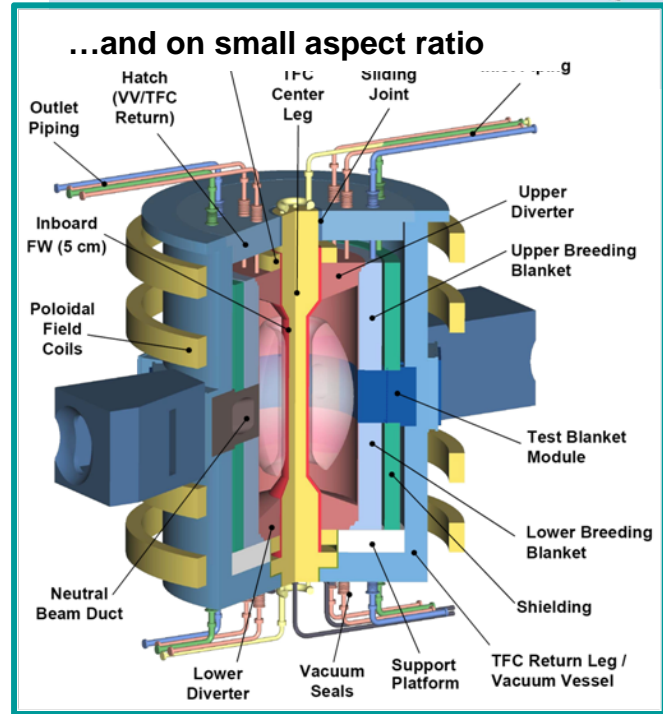
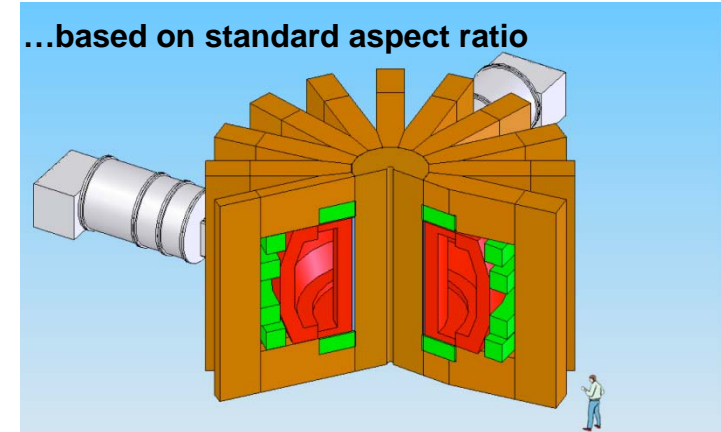
Fully-Integrated Fusion Environment Testing

- Resolve key power extraction component and tritium fuel cycle knowledge gaps to a Demo
 - stemming from effects of significant neutron flux and fluence in concert with all other fusion environmental condition.
 - with prototypic materials, components, coolants, and temperatures for long periods of operation

- A test program is envisioned to include
 - highly instrumented experimental modules geared towards understanding phenomena and behavior (test modules)
 - base blanket system to breed T, but also for reliability statistics and aggressive series of Test, Analyze and Fix iterations
 - prototypic divertor and divertor testing capability

All based on the materials, concepts, coolants that extrapolate to Demo needs

Tokamak-based FNSF concepts...



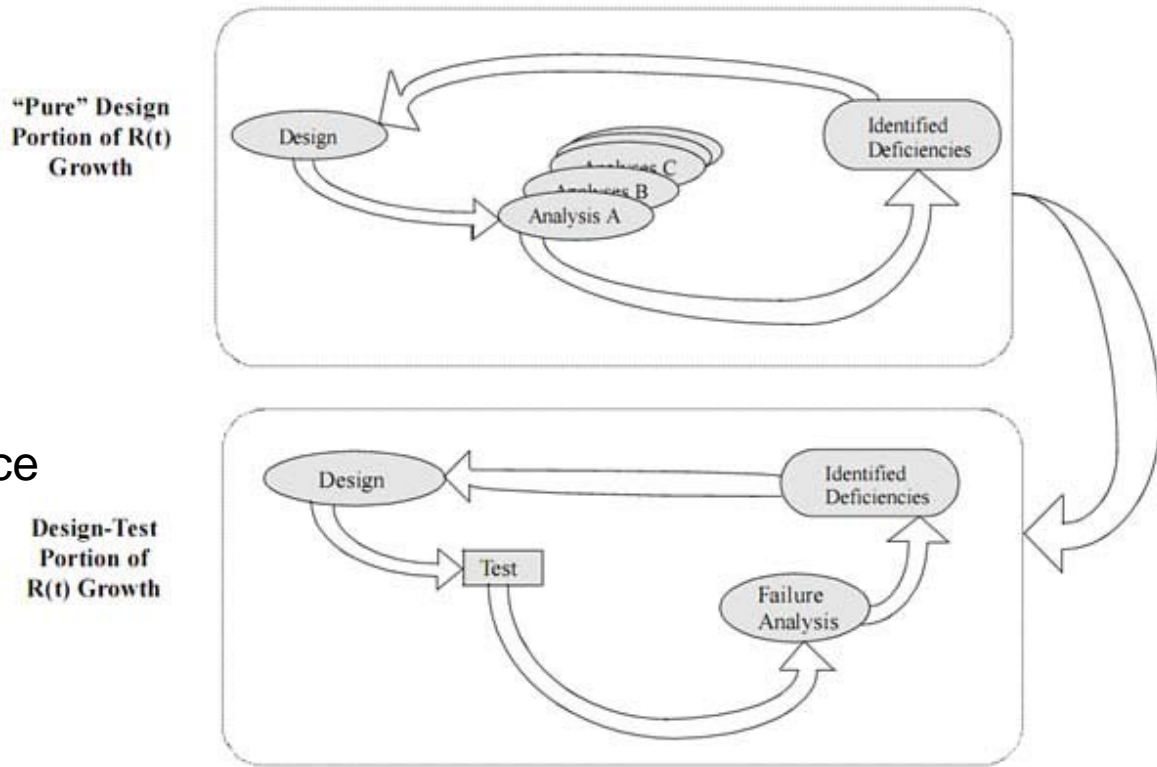
Fully-Integrated Fusion Environment Testing (2)

- Scope
 - Planning of FNSF Facility
 - Fabrication/Operation of FNSF and test components and systems
 - Extensive PIE
- Time scale
 - Modest planning, facility identification – soon, to account for long lead time
 - Detailed design and construction depends on planning and progress in other areas (Afore-described R&D prerequisite)
- Benefits
 - Resolve key power extraction component and tritium fuel cycle knowledge gaps to a Demo
 - Fully establish the engineering feasibility, fuel sustainability, and performance verification of the plasma chamber components and fuel processing systems
 - Model validation in full fusion environment, assure Demo be designed based on predictive capability
 - Middle-life reliability growth database suitable to design and license to Demo
 - Test environment for plasma maintenance systems and plasma diagnostics suitable to proceed to Demo

Reliability Growth

Initiate an aggressive reliability growth and maintainability improvement program

- Build upon the knowledge/data accrued during ALL stages of development and testing
- Include data from in-service performance in present-day and future confinement machines to help develop needed reliability data.



Such a program will be instrumental in the design of FNSF and Demo, which will need to meet extremely demanding availability requirements.

Engineering Science Diagnostics

- Successful experiments require diagnostic capability compatible with a challenging environment
 - High temperature
 - Strong chemical activity
 - RF, X-ray, neutron and energetic particle irradiation
- Engineering diagnostics are required for control and investment protection in test facilities through Demo
 - Temperature, strain, potential, current, flow, pressure, neutron flux and energy, concentrations
....
- A diagnostic development effort is needed during ALL stages of development and testing to enable the Demo design and operation

Desired:

- Measurements all things at all times
- Clear interpretation
- Simple assembly and integration
- No disturbance of phenomena



So far, only Spock has this capability

Relationship to other “technology” thrusts

- Strongly coordinated with Thrust 14 that focuses on accompanying material science and material engineering issues
- Thrust 15 should serve as an integrator of research and model development in Thrusts 13 and 14
 - Bringing results into evolving designs and integrated simulation tools
 - Providing guidance towards highest leverage R&D issues
- The first wall and divertor power extraction and tritium control are intimately connected to PFC and PMI issues (Thrusts 10-12).
 - high temperatures and neutron damage are likely to change PFC surface tritium retention, recycling, diffusion and impurity generation
 - Heat transfer of gas and liquid metal coolants for divertor and first wall structures
 - the potential use of liquid metal free surface divertors, or the occurrence of melt layers during off-normal plasma events will have strong implications on the edge plasma and surface erosion

(**We have included first wall and divertor power extraction, including heat sink design and testing with prototypic materials, in Thrust 13**, but we note that some of this work appears in thrusts 10-12 as well – where should it live?)

Relationship to “plasma” thrusts

- Physics and internal component issues, like Fueling efficiency, tritium burn fraction, size and materials used in antennae, coils, shells, *etc.* all impact fuel sustainability
 - these issues must be approached jointly between the plasma requirements, technological limitations and the impact on fuel sustainability
- Leading candidate structural materials for power extraction and fuel cycle components are based on ferritic/martensitic steels that have non-unity relative magnetic permeability, and large amounts of LM
 - Error field effects from the use of these materials in the plasma chamber, as well as from MHD currents arising from flowing LM coolants
 - Field penetration and response times of sensors
- Many of fusions most difficult problems: disruption, VDEs, ELMs prediction, control, mitigation and survivability require integrated physics/technology research and solutions (Thrust 2, and PMI thrusts)
 - Research on power extraction is important to help define the solution space
 - Should a Fusion Nuclear Science Facility (FNSF,CTF, FDF,VNS...) include addressing such issues as a primary mission element?

Thrust 13 Summary Points

Establish the Underlying Science and Innovative Technology Needed for Fusion Power Extraction and Fuel Sustainability

- Fusion development in general, including many aspects of plasma physics research, requires authoritative information on engineering science and technology in order to help:
 - Enable next step devices, and evaluate technological readiness
 - Solve difficult problems (disruptions, ELMs, tritium inventory, component failure modes, etc.) jointly through both physics and technology advancements and innovations
 - Identify and pursue *practical* paths toward a successful Demo
- New knowledge and capabilities are needed in engineering science and technology. Progress will occur through an integrated program of:
 - well-instrumented benchmark experiments, first in labs, later in dedicated facilities and integrated fusion test environments
 - supported at all stages by validated computational models and reliability growth and diagnostic development efforts

Thrust 13 Summary Points (2)

Establish the Underlying Science and Innovative Technology Needed for Fusion Power Extraction and Fuel Sustainability

- The gap from ITER to Demo is large in many areas including power extraction and tritium fuel cycle fundamental behavior and component feasibility
 - Many of these complicated components have never been built or tested but will dominate the feasibility, safety and reliability of a Demo (ITER in-vessel and cooling technology does not extrapolate)
 - The ITER environment is suitable to begin fusion environment testing of Demo relevant technologies, but is not sufficient to resolve them
- To address the scientific and technology gaps in the development a bold thrust to understand and develop the power extraction and fuel cycle components is required:
 - including aggressively pursuing a testing capability for ALL in-vessel components in an integrated, moderate-fluence fusion environment