Prior FNST Studies and Perspective on FNST Pathway

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With major input from many experts and colleagues over many years

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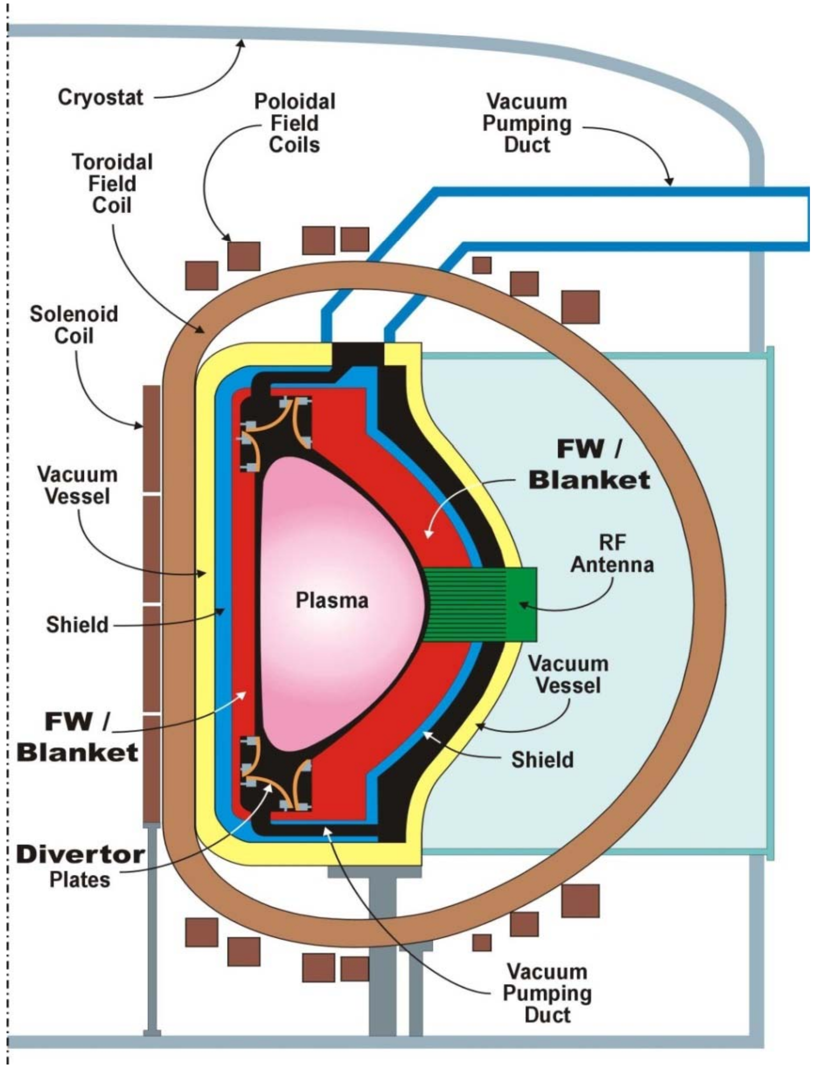
Fusion Nuclear Science and Technology (FNST)

FNST is the **science**, **engineering**, **technology** and **materials** for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium.

Inside the Vacuum Vessel "Reactor Core":

- **Plasma Facing Components**
  divertor, limiter and nuclear aspects of plasma heating/fueling
- **Blanket (with first wall)**
- **Vacuum Vessel & Shield**



Other Systems / Components affected by the Nuclear Environment:

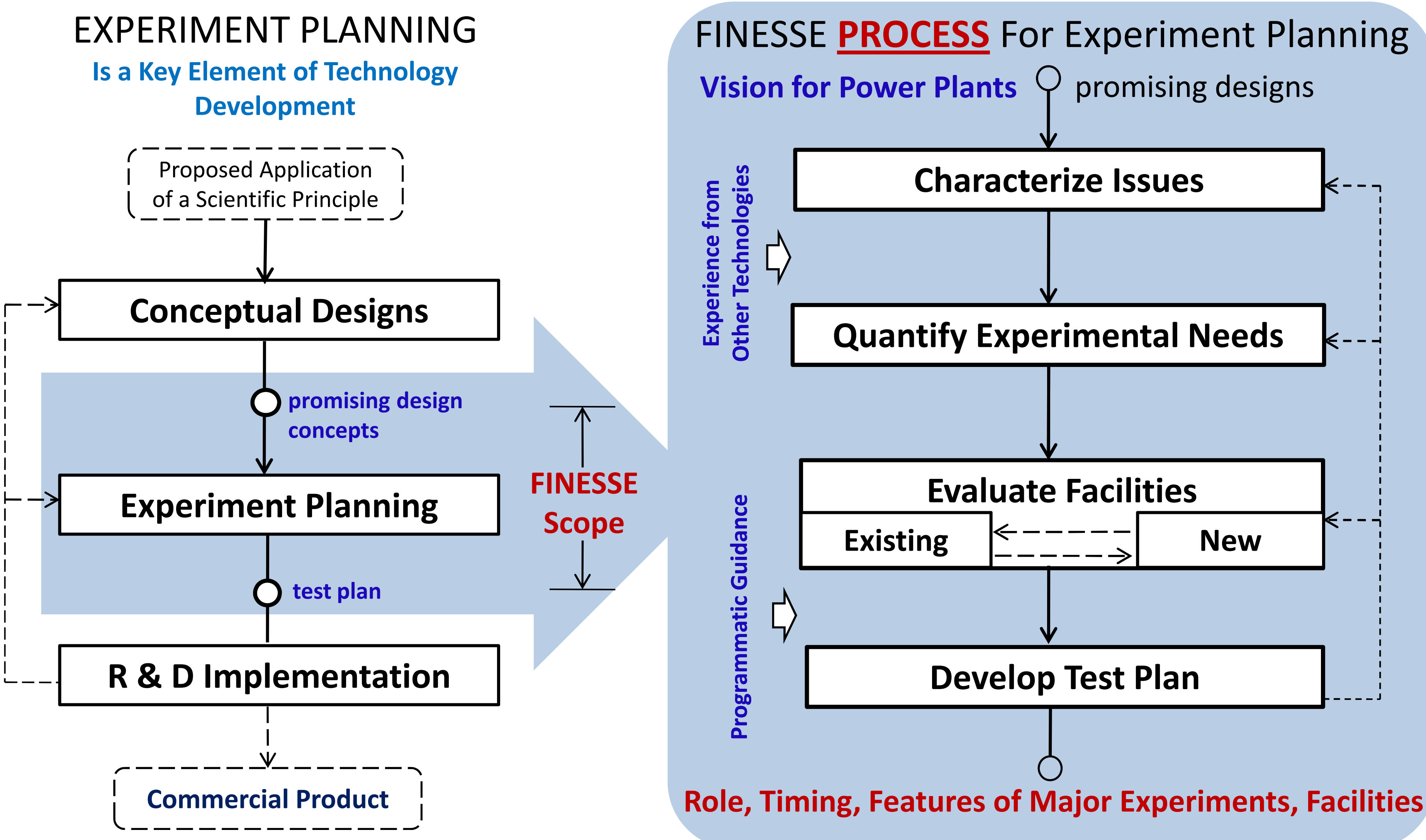
- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems

Extensive FNST Studies over the past 25 years included Technical Planning and Development Pathway

- **Started** with FINESSE (1983-87), **evolved** in IEA study (1994-96), and **improved** in FNST community efforts the past several years.
- **Involved fusion scientists, engineers (blanket, PFC, PMI, Materials, Tritium, Safety), and plasma physicists .**
- **STRONG participation of experts in Technology development from Aerospace and Fission industries.**
- **Very strong international participation.**
- **Over 200 man-year of efforts domestically and internationally.**
- **Developed processes for "Experiment Planning" based on ROLLBACK Approach and utilized experience from other technologies.**
- **A study (2005-2007) to develop a technical plan and cost estimate for US ITER TBM provided 1-understanding of the detailed R&D requirements (specific tasks, cost, and time) and 2- insights into the practical and complex aspects of preparing to place a test module and conduct experiments in the fusion nuclear environment.**
- **Technical Reports and Journal Publications on website: www.fusion.ucla.edu**

FNST Studies Developed a PROCESS for Technical Planning Using Rollback from Power Plants/DEMO and Analogy to Other Technologies

NUCLEAR FUSION, Vol.27, No.4 (1987)



- **Considered issues before experiments and experiments before facilities**
- **The idea of FNSF emerged from the last step of "Develop Test Plan"**

How To Select "Promising Designs for Technical Planning"?

- FNST studies utilized vision of reactors for major parameters (wall load, plasma operating mode, etc.) and overall configuration features.
- FNST studies concluded it could not just use designs of nuclear components from reactor studies (because point designs make one specific choice to explore it).
- FNST studies selected and developed designs best suited for R&D strategy.
  - e.g. Blanket comparison and selection study (BCSS) selected two classes of concepts: Liquid Breeders and Solid Breeders as the basis for R&D planning. (Reason: both classes have feasibility issues, can not select before testing in the fusion environment)
  - e.g. unrealistic assumption: tritium fractional burnup in the plasma.

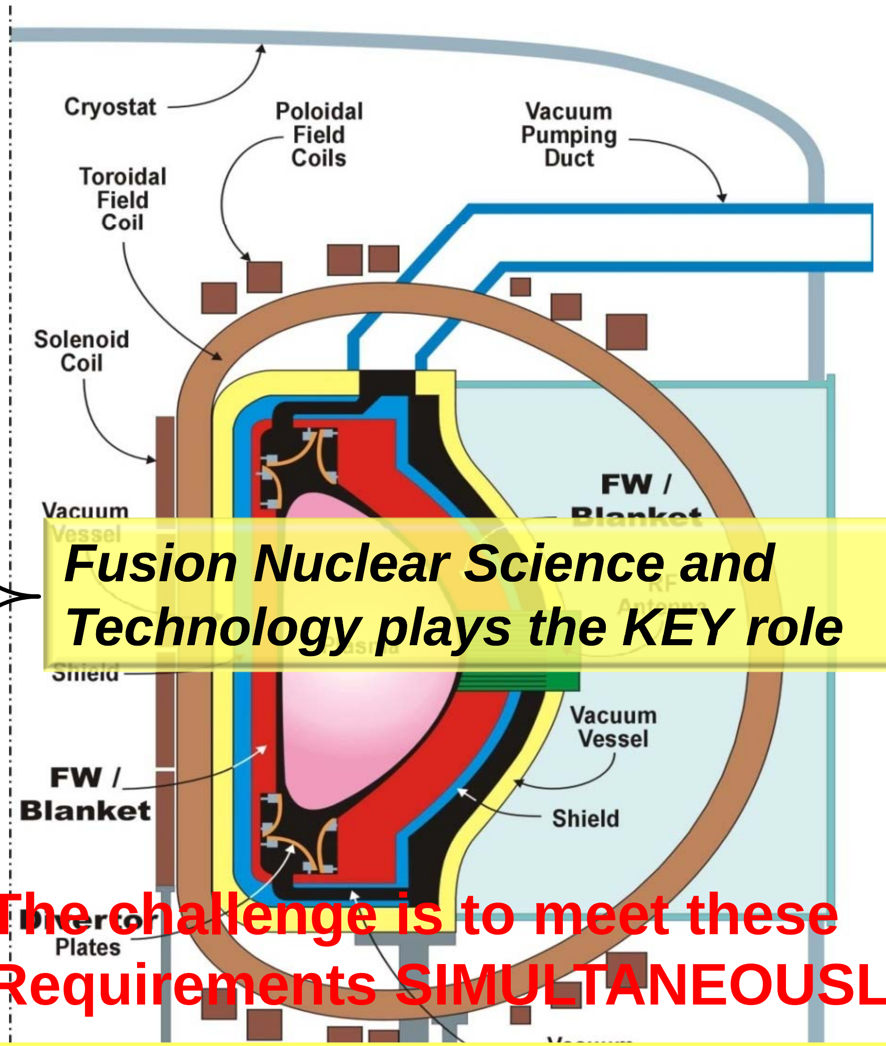
Engineering Scaling for Experiments Must Be Based on Power Plant Parameters (not on DEMO)

- Engineering scaling is the process to develop meaningful tests at experimental conditions and parameters less than those in a reactor.
- DEMO fusion power is smaller than in power plants because of cost considerations. Therefore, wall load in DEMO is lower than in power plant.
- e.g. Power Reactors: 3-4 MW/m^2 DEMO: 2-2.3 FNSF: 1-1.5

Experiments in FNSF must be designed to show nuclear components can extrapolate to power reactor. Hence engineering scaling in FNSF should be based on 3-4 MW/m^2

Principal Requirements for a Fusion Energy System

1. **Confined and Controlled Burning Plasma (feasibility)**
2. **Tritium Fuel Self-Sufficiency (feasibility)**
3. **Efficient Heat Extraction and Conversion (feasibility)**
4. **Reliable System Operation (feasibility/attractiveness)**
5. **Safe and Environmentally Advantageous (feasibility/attractiveness)**



Fusion Nuclear Science and Technology plays the KEY role

The challenge is to meet these Requirements SIMULTANEOUSLY

Besides plasma confinement, the overall goal for fusion development should be: "demonstrate tritium self sufficiency while simultaneously extracting high temperature heat in a safe, reliable, maintainable and practical system."

Top-Level Technical Issues for FNST (set 1 of 2)

(Details of these issues published in many papers by many authors, Last update: December 2009)

Tritium

1. **"Phase Space" of practical plasma, nuclear, material, and technological conditions in which tritium self sufficiency can be achieved**
2. **Tritium extraction, inventory, and control in solid/liquid breeders and blanket, PFC, fuel injection and processing, and heat extraction systems**

Fluid-Material Interactions

3. **MHD Thermofluid phenomena and impact on transport processes in electrically-conducting liquid coolants/breeders**
4. **Interfacial phenomena, chemistry, compatibility, surface erosion and corrosion**

Materials Interactions and Response

5. **Structural materials performance and mechanical integrity under the effect of radiation and thermo-mechanical loadings in blanket/PFC**
6. **Functional materials property changes and performance under irradiation and high temperature and stress gradients (including HHF armor, ceramic breeders, beryllium multipliers, flow channel inserts, electric and thermal insulators, tritium permeation and corrosion barriers, etc.)**
7. **Fabrication and joining of structural and functional materials**

Top-Level Technical Issues for FNST (set 2 of 2)

Plasma-Material Interactions

8. Plasma-surface interactions, recycling, erosion/redeposition, vacuum pumping
9. Bulk interactions between plasma operation and blanket and PFC systems, electromagnetic coupling, and off-normal events

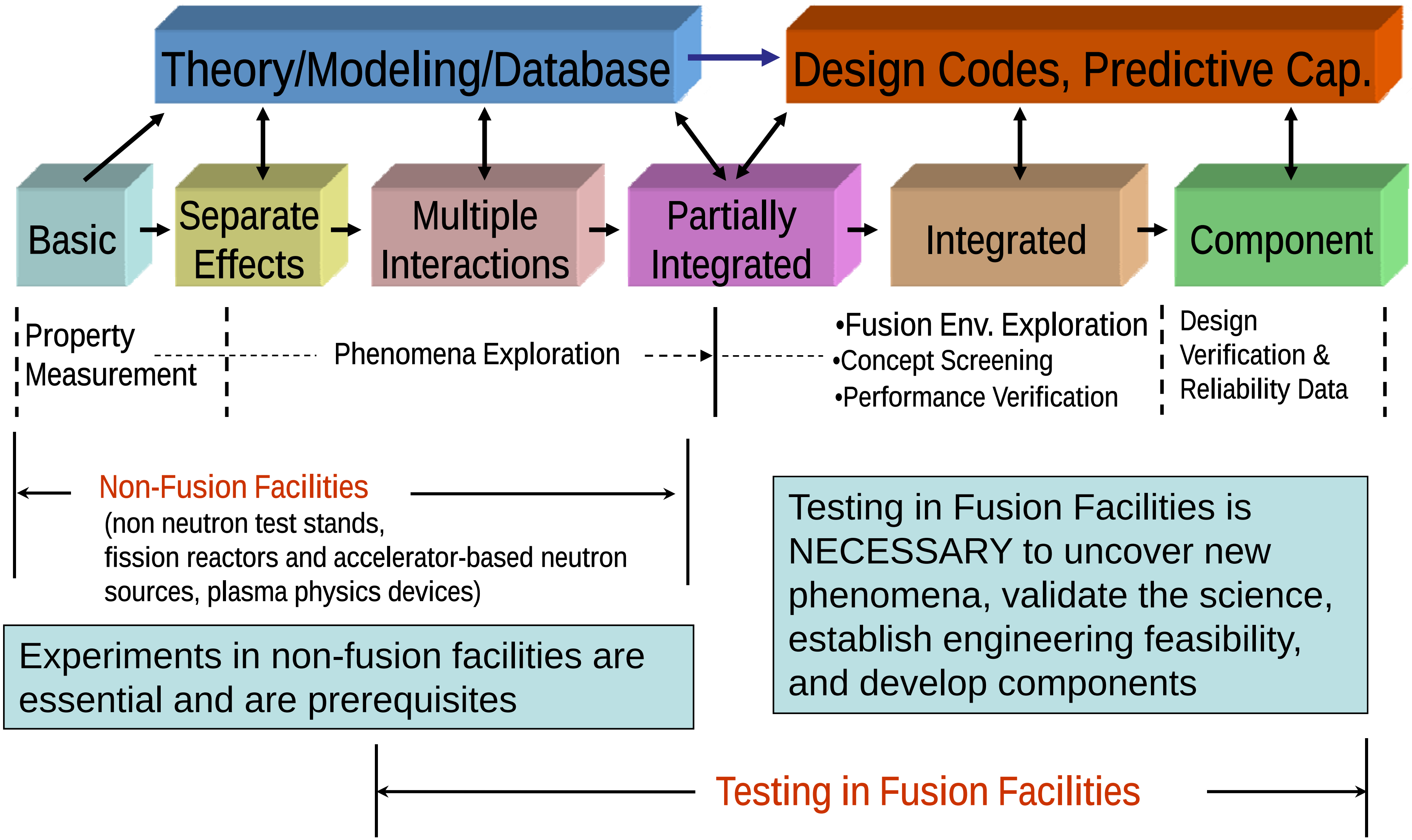
Reliability, Availability, Maintainability (RAMI)

10. Failure modes, effects, and rates in blankets and PFC's in the integrated fusion environment
11. System configuration and remote maintenance with acceptable machine down time

All issues are strongly interconnected:

– they span requirements
– they span components
– they span many technical disciplines of science & engineering

Science-Based Framework for FNST R&D involves modeling and experiments in non-fusion and fusion facilities



FNST Studies Detailed the Types of Experiments in Non-Fusion Facilities

Example of Figures from NUCLEAR FUSION, Vol.27, No.4 (1987)

Solid Breeders

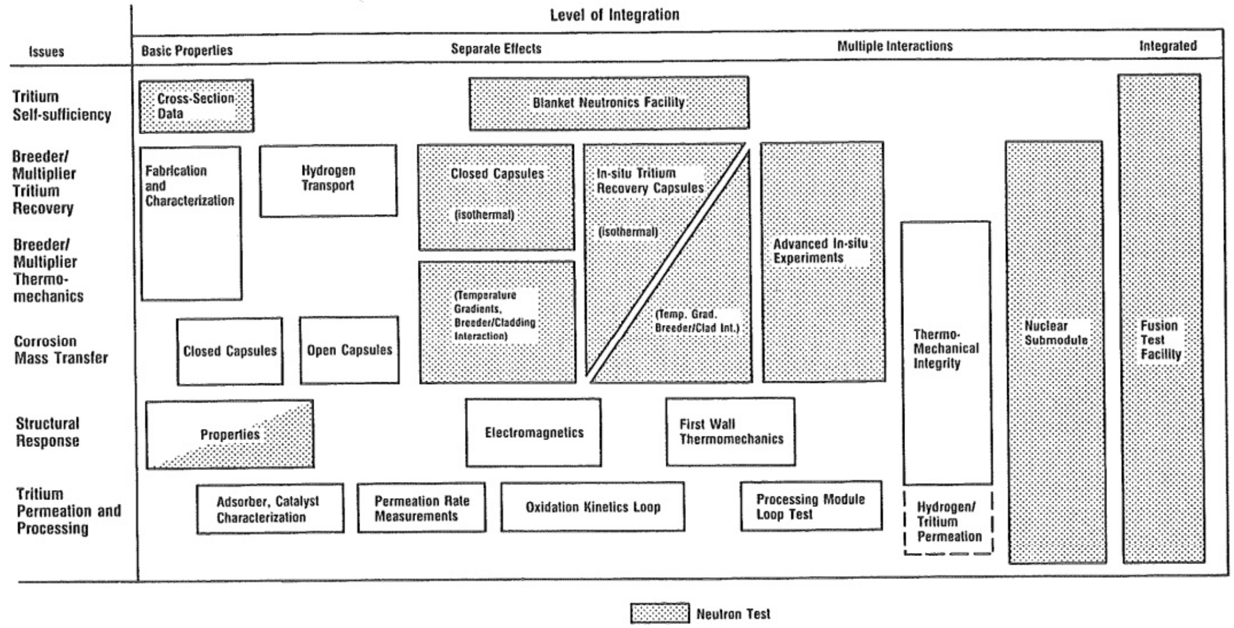


FIG. 5. Types of experiments and facilities for solid breeder blankets (some experiments and/or facilities already exist).

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Liquid Breeders

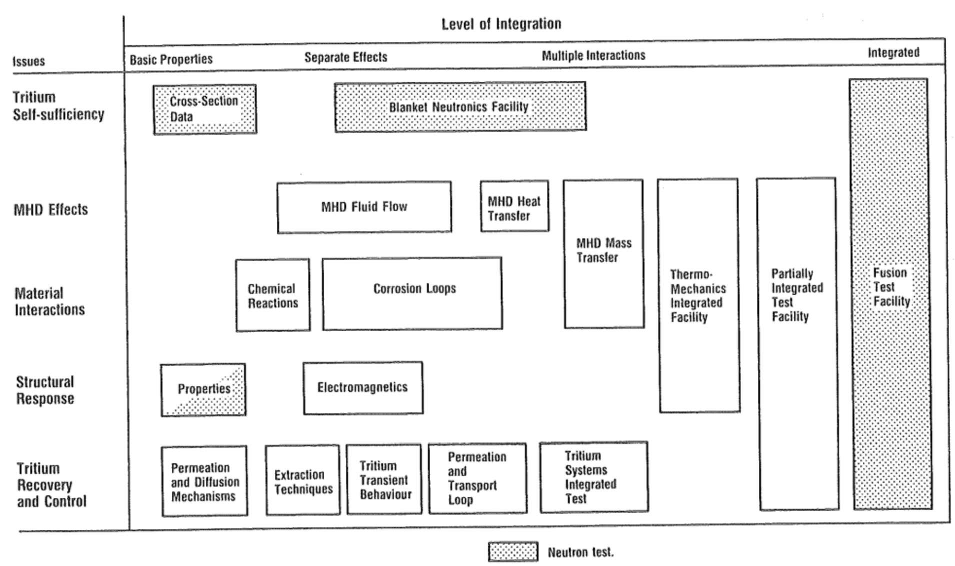

FIG. 8. Types of experiments and facilities for liquid breeder blankets (some experiments and/or facilities already exist).

FNST Studies Defined in Detail
the Types of Experiments in Non-Fusion Facilities (continued)

Example of Figures from NUCLEAR FUSION, Vol.27, No.4 (1987)

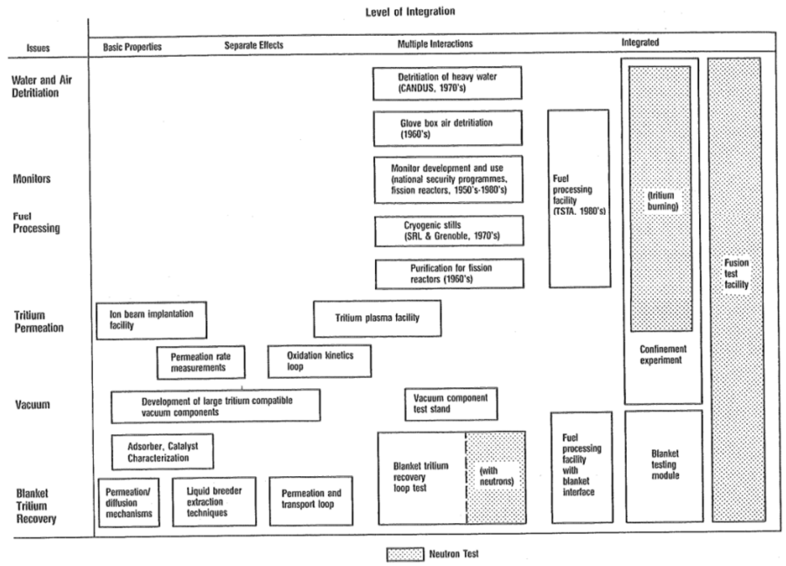

FIG. 15. Types of experiments and facilities for tritium processing and vacuum systems (some experiments and/or facilities already exist).

Tritium Processing

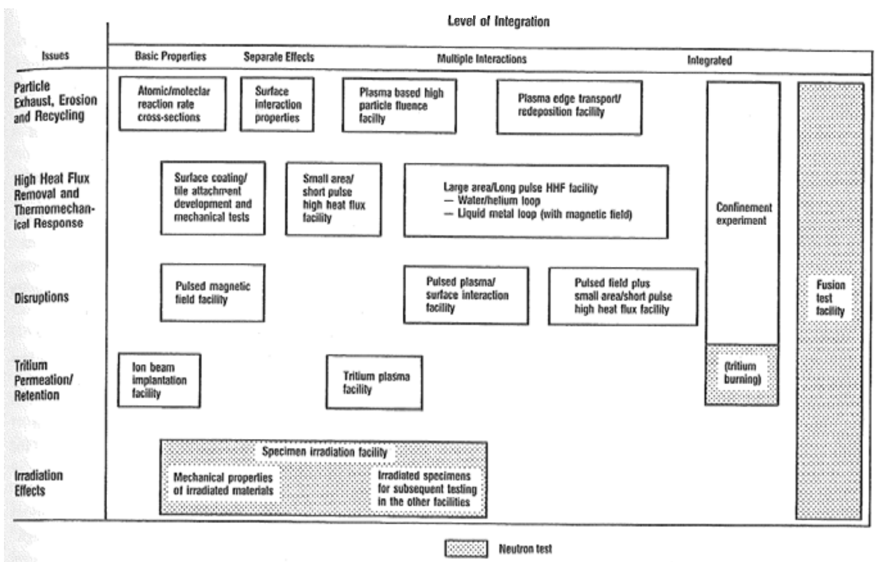

FIG. 16. Types of experiments and facilities for plasma interactive components (some experiments and/or facilities already exist).

PFC

FNST Studies also Defined in Detail the Test Sequence for major R & D Tasks in Non-Fusion Facilities

Example of Figures from NUCLEAR FUSION, Vol.27, No.4 (1987)

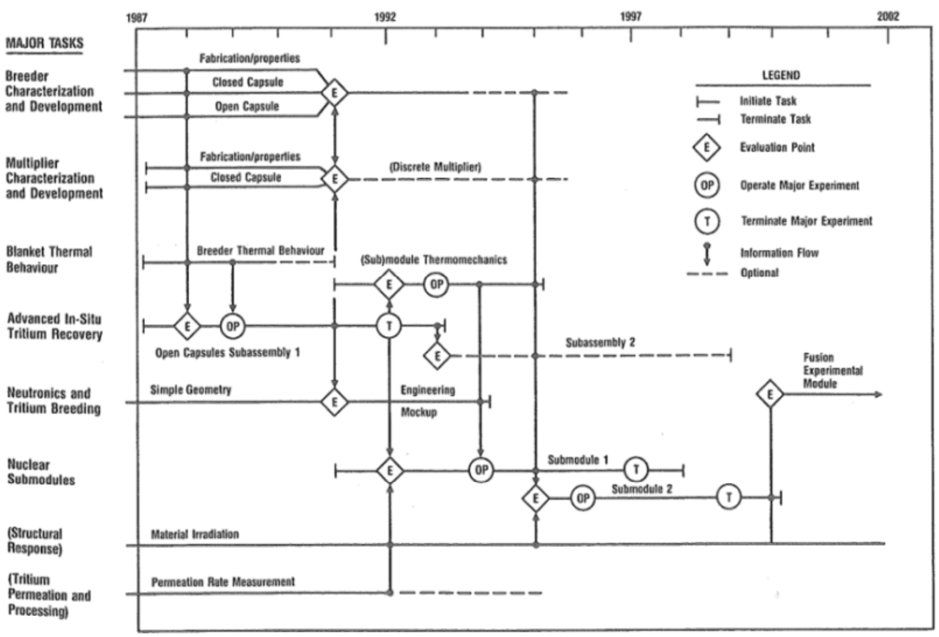

FIG. 7. Test sequence for major solid breeder blanket tasks.

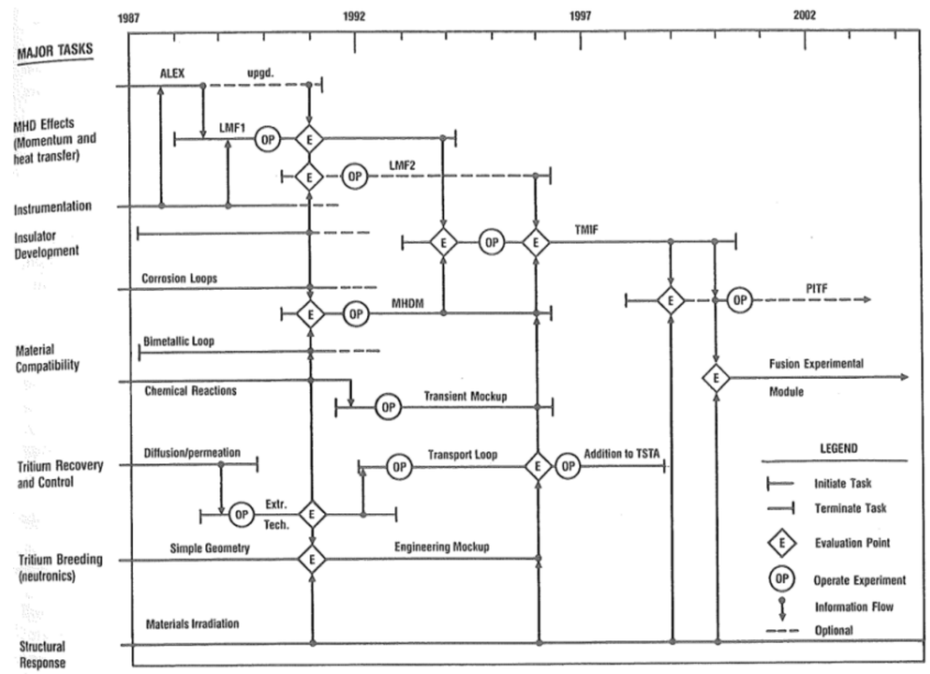

FIG. 11. Test sequence for major liquid breeder blanket tasks.

Solid Breeders

Liquid Breeders

The FNST community updated these plans in 2001.
The changes were modest.
The time line had to be shifted by ~ 20 years.

FNST Studies Science-Based FNST Pathway to DEMO

Non-fusion facilities

Preparatory R&D

Modeling and experiments in non-fusion facilities

- Basic property measurement
- Understand issues through modeling and single and multiple-effect experiments

None of the top level technical issues can be resolved before testing in the fusion environment

FNST Testing in Fusion Facilities

Scientific Feasibility	Engineering Feasibility	Engineering Development
Stage I	Stage II	Stage III
0.1 - 0.3 MW-y/m²	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**
≥ 0.5 MW/m² **burn > 200 s**	**1-2 MW/m²** **steady state or long burn** **COT ~ 1-2 weeks**	**1-2 MW/m²** **steady state or long burn** **COT ~ 1-2 weeks**
Sub-Modules/Modules	Modules (10-20m²)	Modules/Sectors (20-30m²)
• Establish scientific feasibility of basic functions under prompt responses and under the impact of rapid property changes in early life	• Establish engineering feasibility of blankets/PFC/materials (satisfy basic functions & performance, up to 10 to 20% of MTBF and of lifetime)	• RAMI: Failure modes, effects, and rates and mean time to replace/fix components and reliability growth • Verify design and predict availability of FNST components in DEMO

DEMO

- Details of requirements on wall load, energy fluence, plasma mode, etc. are derived based on engineering scaling and described in several papers
- Other important requirements, e.g. surface heat flux, **B** also defined
- The stages **are consecutive steps** in scientific/technological development, they can be carried out in **one or more facilities**
- Facility operation has to add other considerations, e.g. DD phase, availability

Why FNSF should be Low Fusion Power, Small Size, low Q

- **The idea of FNSF emerged in the 1980's from considering the following question:**
  - ***Should we combine the plasma physics mission with the FNST mission in one facility or two separate facilities?***
- **The answer in FINESSE was TWO SEPARATE facilities:**

  One for plasma physics (ITER), and Another for FNST (FNSF)

Primary Reason

a. **Plasma physics testing requires large fusion power (high Q/ignition) but short operating time.**

b. **FNST requires small fusion power but long operating time.**

- ***Combining a and b results in extremely large tritium consumption (>300 kg) and high-cost , high-risk device.***

FNSF should be low fusion power, small size

- **To reduce risks associated with external T supply and internal breeding shortfall**
- **Reduce cost (note Blanket/FW/ Divertor will fail and get replaced many times)**
- **FNST key requirement 1-2 MW/m^2 on 10-30 m^2 test area**
- **Cost/risk/benefit analysis lead to the conclusion that FNSF fusion power <150 MW**
- **For Tokamak (including ST) this led to recommendation of:**
  - **Low Q plasma (2-3) - and encourage minimum extrapolation in physics**
  - **Normal conducting TF coil (to reduce inboard B/S thickness, also increase maintainability e.g. demountable coils).**

FNST studies over the past 25 years used rollback approach.
It was very useful. It provided foundation for moving forward

In the last 2 years, the FNST community started also using a roll-forward approach in partnership with the broader community and facility designers to explore FNSF options and the issues associated with the facility itself

Findings:

- Rolling forward reveals practical problems we must face today like
  -- Vac Vessel -- MTBF/MTTR -- standard A, ST, other configuration?
  -- level of advanced physics -- level of flexibility in device configuration

- Sensitivity to exact details of the DEMO becomes less important – Instead: we find out we must confront the practical issue of how to do things for the first time – nuclear components never before built, never before tested in the fusion nuclear environment.

- Debate about “how ambitious FNSF should be” becomes less important because WE DO NOT KNOW what we will find in the fusion nuclear environment.

  -- How many stages FNSF can do? Maybe one FNSF can do all 3 stages. Or, we may need 2 or 3 consecutive FNSF facilities. (remember fission did 63!!)

  -- What critical flaws may be found in initial operation of FNSF? Maybe we cannot get past stage 1? e.g. MTBF too short, MTTR too long, cannot contain tritium?

  -- Maybe we will get an early answer to “is tokamak a feasible option for power plant?”

FNSF Strategy/Design for Breeding Blankets, Structural Materials, PFC & Vacuum Vessel

Day 1 Design

- Vacuum vessel – low dose environment, proven materials and technology
- **Inside the VV** – all is "experimental." Understanding failure modes, rates, effects and component maintainability is a crucial FNSF mission.
- Structural material - reduced activation ferritic steel for in-vessel components
- Base breeding blankets - conservative operating parameters, ferritic steel, 10 dpa design life (acceptable projection, obtain confirming data ~10 dpa & 100 ppm He)
- Testing ports - **well instrumented, higher performance blanket experiments (also special test module for testing of materials specimens)**

Upgrade Blanket (and PFC) Design, Bootstrap approach

- Extrapolate a factor of 2 (standard in fission, other development), 20 dpa, 200 appm He. Then extrapolate next stage of 40 dpa…
- Conclusive results (real environment) for testing structural materials,
  - no uncertainty in spectrum or other environmental effects
  - prototypical response, e.g., gradients, materials interactions, joints, …

Suggestions/Recommendations

- **We used the rollback approach for the last 25 years. Now we need to move forward.**
- **Assign a group of FNST experts** to summarize and update FNST studies as to R&D required, and requirements on FNSF mission/major parameters, major features
- **Start "roll forward" process to identify the best option for FNSF**
  - Address practical issues of building FNSF "in-vessel" components of the same materials and technologies that are to be tested.
  - Evaluate issues of facility configuration, maintenance, failure modes and rates, physics readiness (Quasi-steady state? Q ~ 2-3?). These issues are critical and they vary with proposed FNSF facility. (e.g. standard A vs. ST)
  - Address role and mission of initial phase DD operation in FNSF.
  - Need a Mechanism/Process for comparing various options for FNSF facility
- **Find a way to engage experts in RAMI** in the fusion program and particularly in pathway development assessment (experts should have experience in technology development and have analytical capabilities). RAMI considerations can be a **deciding factor** in evaluating different options for FNSF mission and designs and can be the "Achilles Heel" for fusion.
- **Enhance fundamental FNST R&D now**
  - Such fundamental R&D does not strongly depend on variations in details of vision for DEMO or pathway. Results from R&D will help us improve the vision and pathway.