Challenges and Strategy for Development of FNST: Blanket/FW & Tritium Fuel Cycle

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for U.S. Burning Plasma Research
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This Talk:

- Will not list detailed R&D items. We have done this many times. Many documents available
- **The focus is on the critical go/no-go problems for which HOW and WHERE to perform the R&D is a challenge, yet there is not a credible strategy being adopted, communicated, nor pursued**
- What is presented here is derived from Many comprehensive studies performed over 3 decades. Efforts on these studies were hundreds of man-years because of “free” participation by Aerospace, Nuclear, and other industries, internal funds from many national labs and universities, Japan and EU (plus much enthusiasm!). These studies cannot be redone today. The results of these studies have been reported in scholarly journals and comprehensive reports.
- **Scientific bases and more details on the complex issues and strategy elements addressed in this talk are provided in selected references listed at the end of this presentation**

Outline

Introduction/Definitions

I. KEY Challenges/Issues and Required R&D

1. Multiple Effects/Multiple Interactions
2. RAMI (Reliability/Availability/Maintainability/Inspectability)
3. Tritium Fuel Cycle and Tritium Self-Sufficiency
4. External T Supply and Required T Startup Inventory

II. Scientific Framework and Strategy for Fusion Development

1. Role and Features of required non-fusion and fusion facilities
2. FNST Requirements on FNSF Parameters and Features
3. Timing and Stages of FNSF(s), How many FNSF(s) do we need?
4. Solving the paradox of short MTBF/long MTTR and what to do about dpa

III. More on a Plasma-Based Fusion Environment Test Facility (FNSF)

1. What type of facility should FNSF be and what main features and parameters should it have?
2. Options for FNSF Facility: Tokamaks (standard and low aspect ratios, type of magnets), GDT/mirrors

Summary

Fusion Nuclear Science & Technology (FNST)

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

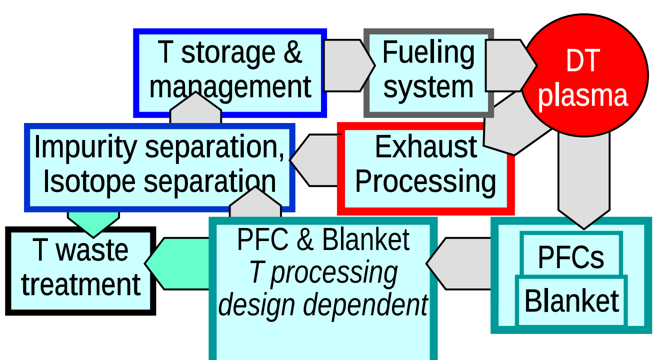
In-vessel Components ("Core")

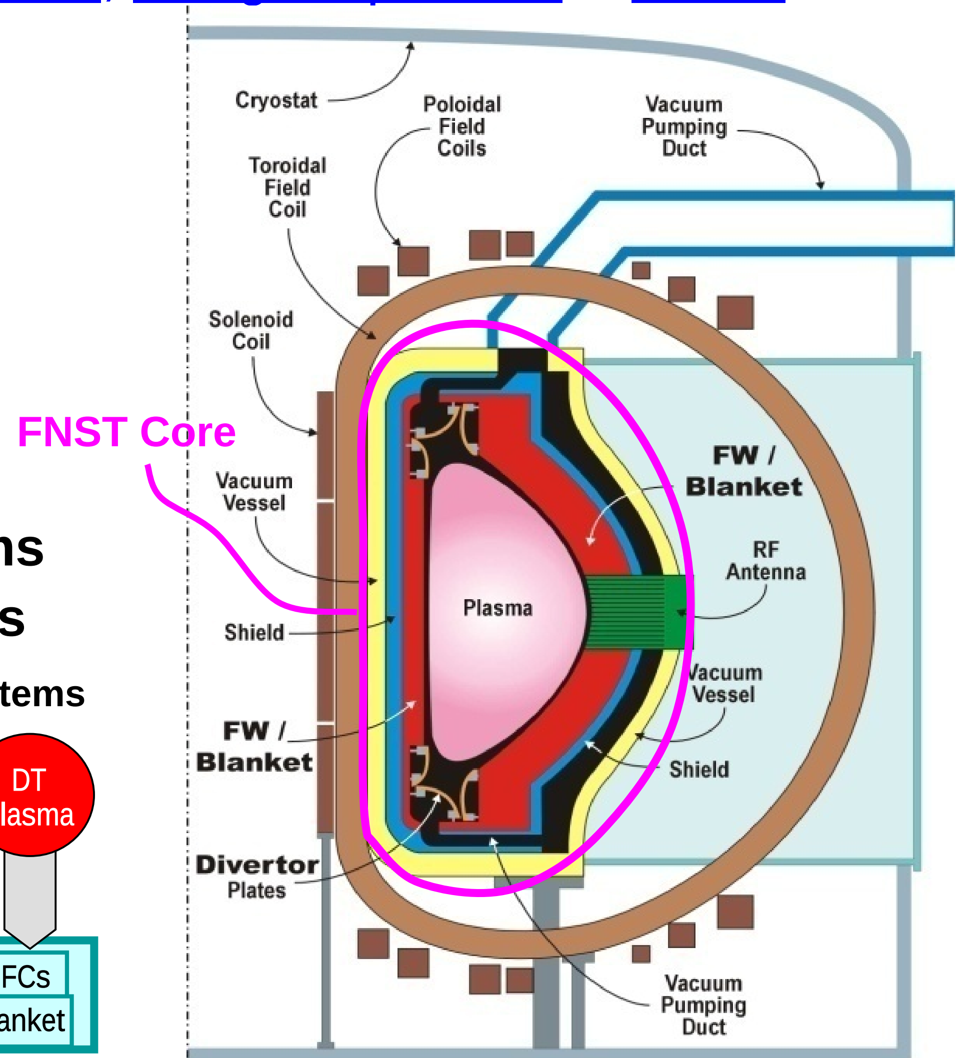
- **Blanket** and **Integral First Wall**
- **Divertor/PFC**
- **Vacuum Vessel** and **Shield**

Other Nuclear Systems

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

Tritium Fuel Cycle pervades entire fusion system





Fusion Nuclear Environment is Complex & Unique

Neutrons *(flux, spectrum, gradients, pulses)*

- Bulk (volumetric) Heating
- Tritium Production
- Radiation Effects
- Activation and Decay Heat

Heat Sources *(thermal gradients, pulses)*

- Bulk (neutrons)
- Surface (particles, radiation)

Particle / Debris Fluxes *(energy, density, gradients)*

Magnetic Fields *(3-components, gradients)*

- Steady and Time-Varying Field

Mechanical & Electromagnetic Forces

- Normal *(steady, cyclic)* and Off-Normal *(pulsed)*

Multiple functions, materials, and many interfaces in highly constrained system

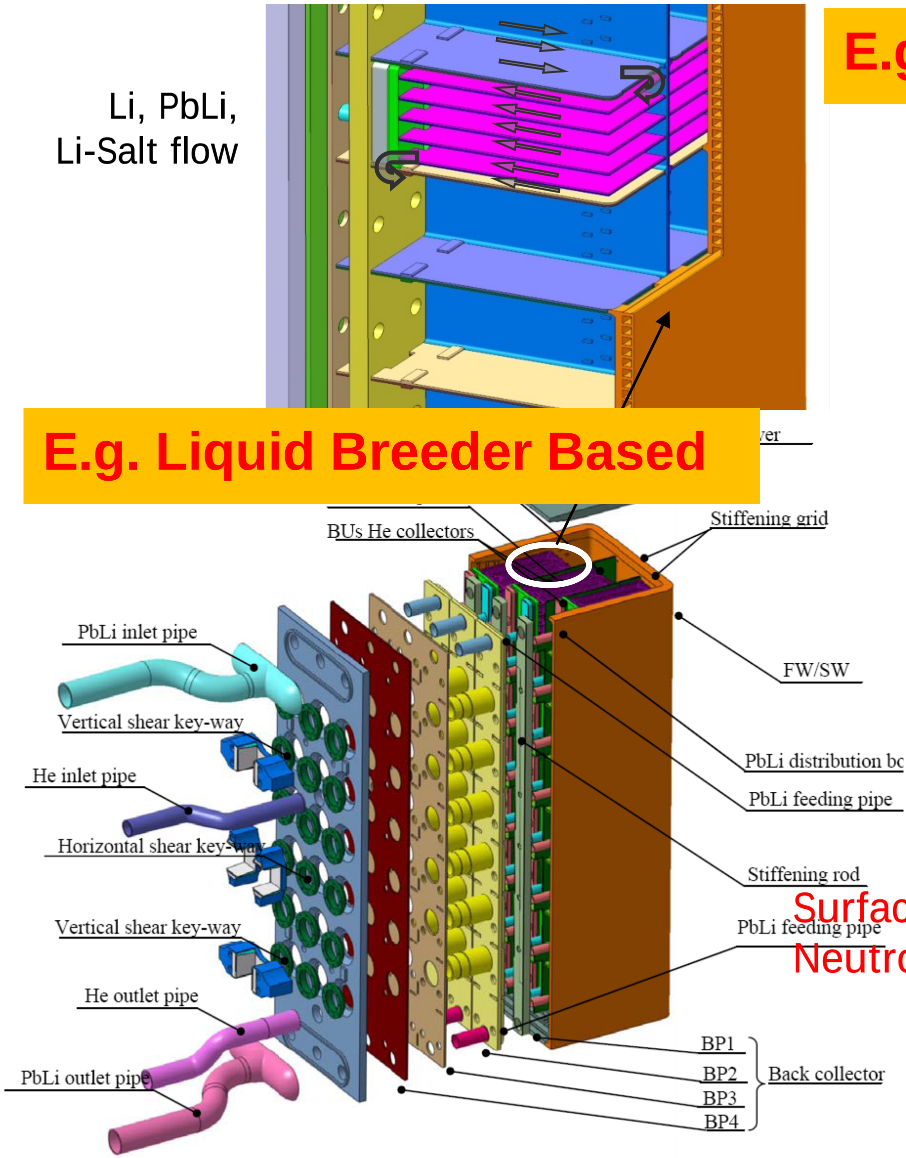
Combined Loads, Multiple Environmental Effects

- Thermal-chemical-mechanical-electrical-magnetic-gravitational-nuclear interactions and multiple/synergistic effects
- Interactions among physical elements of components

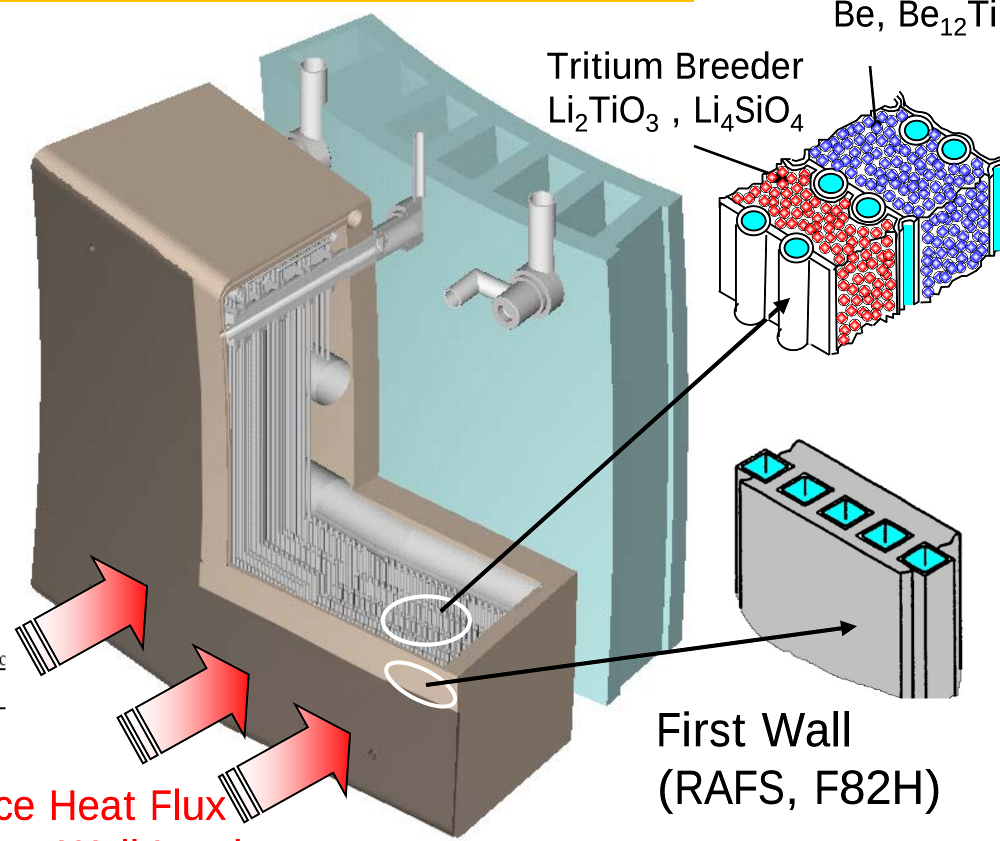
Blanket/FW systems are complex and have many functional materials, joints, fluids, and interfaces

Li, PbLi, Li-Salt flow

E.g. Liquid Breeder Based



E.g. Ceramic Breeder Based



Surface Heat Flux
Neutron Wall Load

Coolants: He, H_2O, or liquid metal or salt

Key challenges that must be carefully considered in planning a credible pathway for FNST & Fusion Development

- **The Fusion Nuclear Environment**: Multiple field environment (neutrons, heat/particle fluxes, magnetic field, etc.) with high magnitude and steep gradients experienced by complex Blanket/FW
  - *lead to yet undiscovered new phenomena due to multiple interactions and synergistic effects*
  - *can not adequately simulate in laboratory facilities or fission reactors*
  - *full simulation to uncover phenomena and quantify behavior requires DT Plasma-based facility (FNSF)*
- **Nuclear heating** in a large volume with steep gradients
  - *drives temperatures and most FNST phenomena*
  - *cannot simulate in laboratory facilities or fission reactors*
  - *can be simulated only in DT Plasma-based facility (FNSF)*
- **Complex configuration** with FW/Blanket/Divertor inside the vacuum vessel. Makes the fusion system not fault tolerant and challenging to maintain. RAMI is a central issue

I. KEY Challenges/Issues and Required R&D

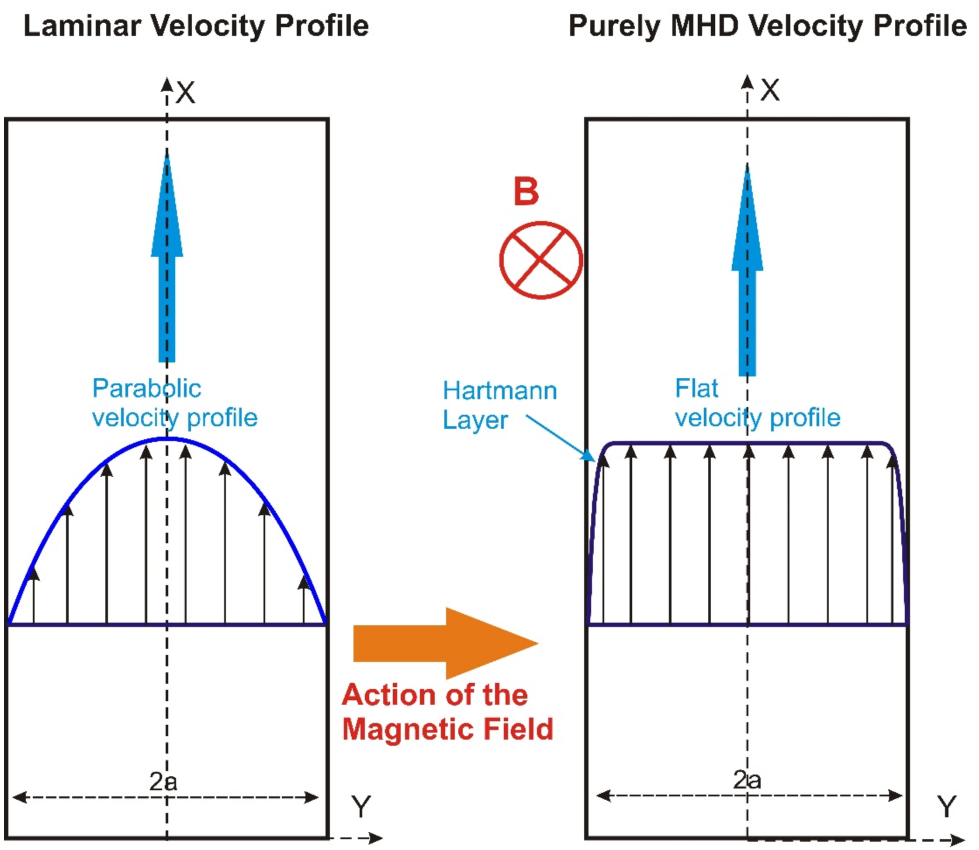
1. Multiple Effects/Multiple Interactions
2. RAMI (Reliability/Availability/Maintainability/Inspectability)
3. Tritium Fuel Cycle and Tritium Self-Sufficiency
4. External T Supply and Required T Startup Inventory

Moving forward with Multiple Effects/Multiple Interactions Experiments and Modelling is NECESSARY to understand and learn the behavior of blankets in the fusion environment

Example: MHD Thermofluids

Fusion Researchers for 30 years studied Liquid Metal MHD Flow Behavior in Blankets as if it were PURELY in the Presence of Magnetic Field (i.e. separate effect). So, the common assumption has been:

Flow is *Laminar*: the flow velocity profile is strongly altered by the action of the Lorentz force leading to **flat laminar core** with **very thin Hartmann and side layers**

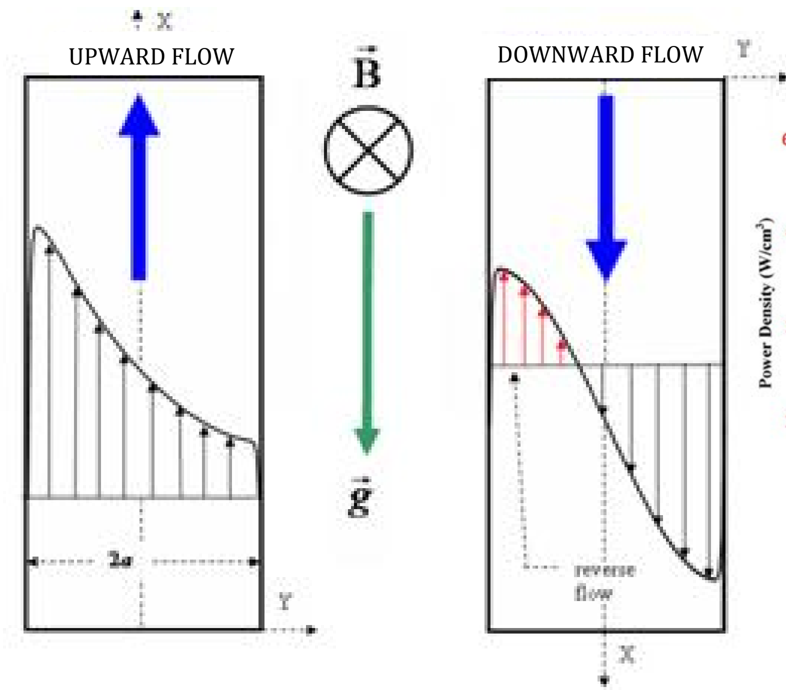


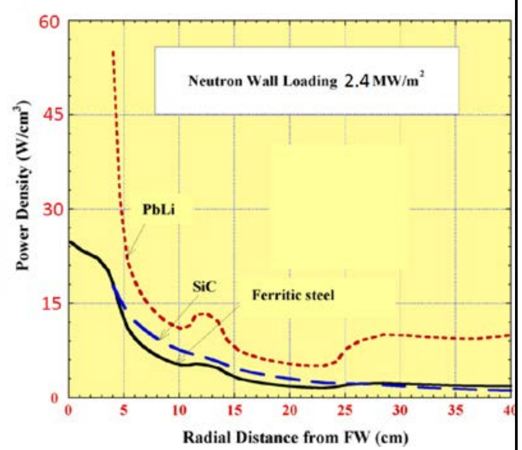
<u>But we just discovered that what we assumed for 30 years is wrong</u>

Discovery: Spatial gradients in nuclear heating & temperature in LM blanket combined with $\vec{g}$ and $\vec{B}$ lead to New Phenomena that fundamentally alter our understanding of the MHD Thermofluid behavior, Tritium Transport/Permeation and Materials Interactions in the blanket in the fusion nuclear environment

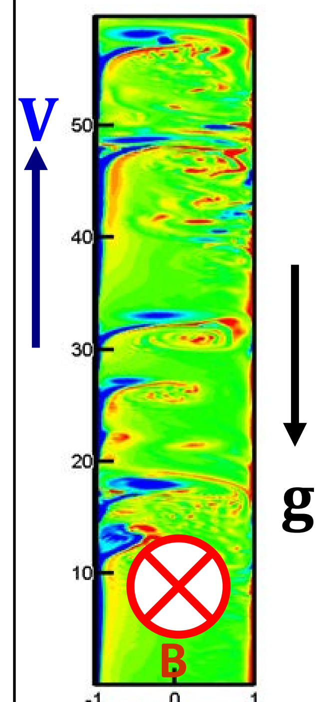
lead to **Buoyant MHD interactions resulting in an unstable "Mixed Convection" flow regime**

Base flow strongly altered leading to velocity gradients, stagnant zones and even "**flow reversal**"





Vorticity Field shows new **instabilities** that affect transport ph eat, T, Corrosion)



This result is from modeling at limited parameters in idealized geometry.

- **Predictions from separate effect tests for the integrated fusion nuclear t are wrong**
- **Blankets designed with current knowledge of phenomena and data will <u>not</u> work**

What do we need to do to investigate "MHD Buoyant interactions/mixed convection flow" and other phenomena?

- Need to perform **multiple effects experiments** in which we can observe & characterize MHD mixed convection phenomena & discover new phenomena
- Need major initiatives to perform **more integrated phenomenological and computational modeling** using high speed computation (e.g. solve simultaneously Energy, Maxwell, and Navier-Stokes equations in a coupled manner, push for high performance parameters e.g. Ha, Gr, Re)

Requirements in Experiments:

1) Simulation of volumetric heating and high temperature with steep gradients
2) Provide flexible orientation of the channel flow w.r.t. gravity
3) Provide sufficient volume inside the magnets to realistically simulate multi-channel flows with multi-material and geometry representation
4) Include representative 3-component magnetic fields with gradients
5) Use Prototypic Materials (e.g. PbLi, RAFM, SiC) and operating conditions (e.g. high T)
6) Develop instrumentation techniques compatible with high-temperature liquid metals

- **Designing Laboratory Facilities that satisfy the above Requirements involves Big challenges** that we must confront. Examples are highlighted in the next 2 slides (from UCLA research)

Multiple effects experiments will necessarily be at <u>scaled down</u> conditions from blankets in DEMO. How do we preserve phenomena?

- By preserving ratios of forces through the use of relevant non-dimensional parameters

Non-Dimensional Parameters
➢ Reynolds Number, $Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{\rho u L}{\mu}$
➢ Hartmann Number, $Ha = \left(\frac{Electromagnetic\ forces}{Viscous\ forces}\right)\hat{}0.5 = BL\sqrt{\frac{\sigma}{\mu}}$
➢ Grashof Number, $Gr = \frac{Buoyancy\ forces}{Viscous\ forces} = \frac{g\beta\Delta T L^3}{\nu^2} = \frac{g\beta\dot{q}L^4}{\nu^2\kappa}$

- Need to consider these parameters in a coupled manner
- **What is the "right combinations" of these Dimensionless Parameters to preserve phenomena? Discovery of the right combinations is R&D by itself.**
- Examples of coupled parameters we should attempt to preserve in the experiments:
  - Ha/Re – determines transition to turbulence in Hartmann layers
  - $r = \sqrt{Gr/Ha\ Re\left(\frac{a}{b}\right)^2}$ - responsible for the shape of velocity and temperature profile in steady mixed-convection flows
  - $Ha/\sqrt{Gr}$ – determines transition from 3D to Q2D in MHD mixed-convection flows

Non-Linear LM MHD Phenomena is difficult to scale from experiment to DEMO
(Blanket scaling problem similar to plasma physics!)

DEMO BLANKET: Ha~10^4, Gr~10^{12}, Re~10^5

EXPERIMENT: Ha~10^3, Gr~10^9, Re~10^5

Grand Challenge

How do we scale results from experiments to predicting Blanket behavior in DEMO?

- Non-linear phenomena (difficult to scale)
- Higher Ha will suppress (or strongly modify) turbulence/instabilities
- Higher Gr will enhance buoyancy/instabilities
- **So, what will be the real behavior in the real blanket where both Ha and Gr are high?**

Summary of FNST Multiple Effects/Multiple Interactions Issues and required R&D

Right now, we do not know and cannot predict how the blanket/FW will work in the fusion nuclear environment. This behavior cannot be predicted by synthesizing results of separate effects; and predictions are wrong.

Pathway Issues and Needed R&D:

- Need to move forward with Multiple Effects/Multiple Interactions Experiments. We must build a number of new laboratory facilities to do the best possible simulation of the combined effects of the fusion nuclear environment and representative blanket mockups.
- A sequence of progressively more powerful facilities is needed ($5M, $20M, $50M). We also need several such facilities with different approaches to simulation to be constructed around the world.

Current status: No such facilities exist in the world. A first-of-a-kind facility is being completed as an upgrade of the MaPLE (Magnetohydrodynamic PbLi Experiment) facility at UCLA, in exemplary partnership with EUROfusion, to study MHD thermofluids multiple-effects, material interactions, and tritium transport & permeation.

- But full simulations in the Lab is impossible because volumetric heating can be simulated only in DT Plasma-based facility. Need to build experimental FNSF
- Extrapolation from lab facilities to FNSF/DEMO is extremely problematic (non-linear phenomena similar to plasma physics issues). Launching Major 3-D Modelling Initiative is a MUST

Reliability/Availability/Maintainability/Inspectability (RAMI) is a serious challenge that has major impact on priorities and strategy for fusion R&D

Availability required for each component needs to be high

Component	#	failure rate (1/hr)	MTBF (yrs)	MTTR/type Major (hrs)	MTTR/type Minor (hrs)	Fraction Failures Major	Outage Risk	Component Availability
Toroidal C[illegible]	16	5×10^{-6}	23	10^4	240	0.1	0.098	0.91
P[illegible] C[illegible]								
Magnet supplies	4	1×10^{-4}	1.14	72	10	0.1	0.007	0.99
Cryogenics	2	2×10^{-4}	0.57	300	24	0.1	0.022	0.978
Blanket	100	1×10^{-5}	11.4	800	100	0.05	0.135	0.881
Divertor	32	2×10^{-5}	5.7	500	200	0.1	0.147	0.871
Htg/CD	4							0.884
Fueling	1							0.998
Tritium System	1							0.995
Vacuum	3							0.998
Conventional equipment - instrumentation, cooling, turbines, electrical plant								0.952
TOTAL SYSTEM	(Due to unscheduled maintenances)						0.624	0.615

Two key parameters:
MTBF – Mean time between failures
MTTR – Mean time to repair

DEMO availability of 50% requires:
- **Blanket/Divertor Availability ~ 87%**
- **Blanket MTBF >11 years**
- **MTTR < 2 weeks**

Extrapolation from other technologies shows expected MTBF for fusion blankets/divertor is as short as ~hours/days, and MTTR ~months
GRAND Challenge: Huge difference between Required and Expected!!

Fundamental Reasons why we have Serious Problems with short MTBF, long MTTR, and very low expected availability in current fusion "confinement" systems

- Location of Blanket/FW/Divertor **inside*** the **vacuum vessel**:

  → ***low fault tolerance*** → ***short MTBF Because*** many failures (e.g. coolant leak) require immediate shutdown, also no redundancy possible.

  → ***long MTTR Because*** repair & replacement requires breaking "vacuum seal" and many connects / disconnects, and many operations in the limited access space of tokamaks, stellerators, and other "toroidal/closed" configurations ** The decision to put the blanket inside the vacuum vessel is necessary to protect the vacuum vessel, which must be robust and cannot be in high radiation/temperature/stress state facing the plasma.*

- Large surface area of the first wall results in high failure rate for a given unit failure rate per unit length of piping, welds, and joints → ***short MTBF***

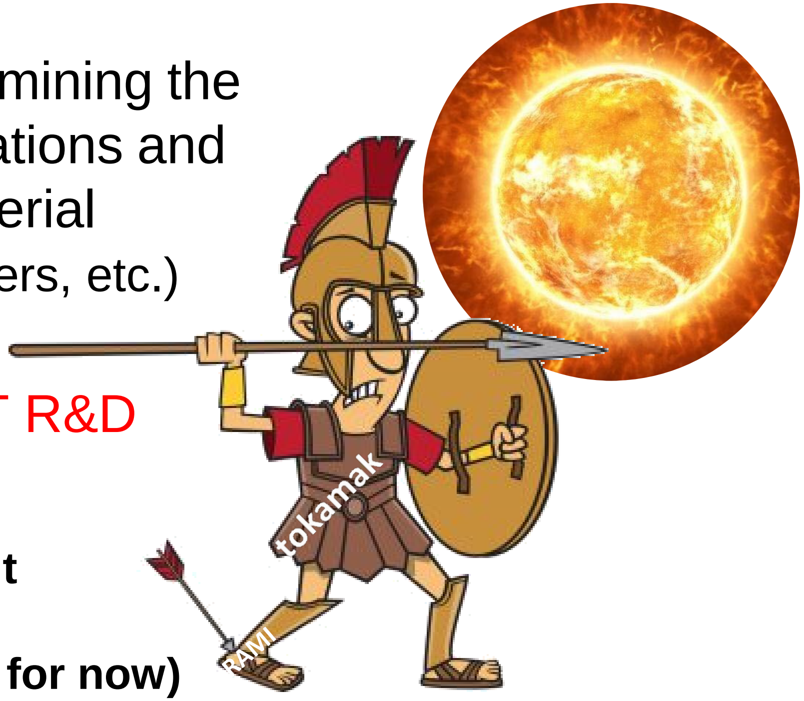
Results show: anticipated MTBF is hours/days (required is years), and MTTR is 3-4 months (required is days), and availability is very low < 5%

Contrast this to fission reactors:

- Can continue operation with ~2% of fuel rods with failures (MTBF ~ years)
- An entire fuel bundle can be replaced in ~ 2 days (MTTR ~ 2 days).
- Fission reactors have been able to achieve 90% availability

Observations and Suggestions for improving the situation with RAMI, the *Achilles' Heel is*sue for fusion

- MTBF/MTTR will be the key issue in determining the feasibility of plasma confinement configurations and the feasibility of blanket concepts and material choices (structure, breeder, insulators, T barriers, etc.)
- Performance, Design Margin, Failure Modes/Rates should be the focus of FNST R&D Not a long dpa life

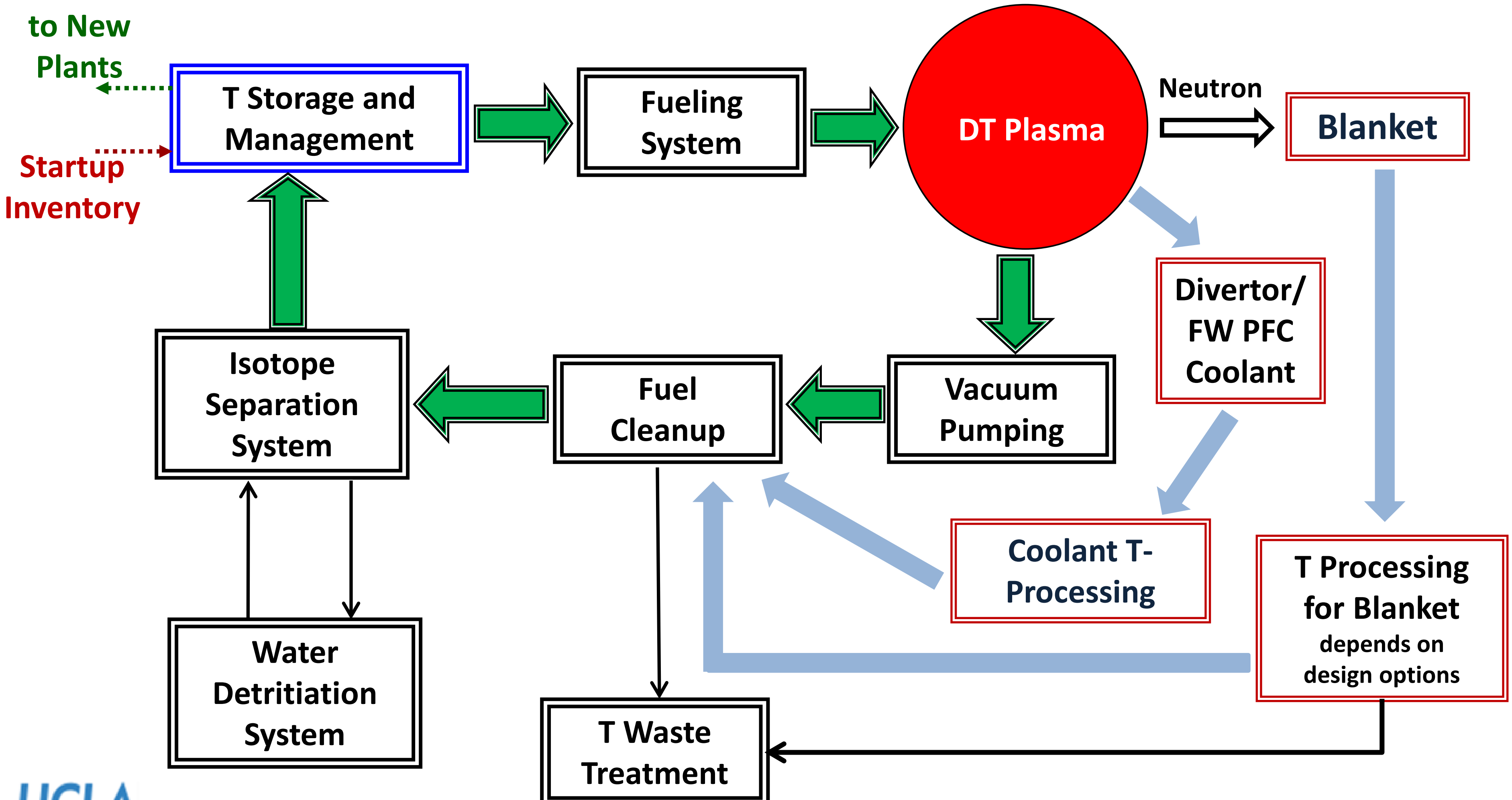


1. **Setting goals for MTBF/MTTR is more important NOW than dpa goals for lifetime of materials (RAFS with 10-20 dpa, 100 ppm He is sufficient for now)**
2. R&D should Now focus on:
   – Scientific understanding of multiple effects, performance and failures so that functions, requirements & safety margins can be achieved, and designs simplified and improved
   – Subcomponent tests including non-nuclear tests
   – Understand that Reliability Growth takes very long time, Build FNSF early as "experimental" facility that focuses only on the FNST components inside the vacuum vessel. Realistic understanding of MTBF/MTTR can be obtained in such FNSF
   – Be prepared for surprises and be ready to change pathway.

Tritium Fuel Cycle: Dynamic models have been developed to calculate time-dependent tritium flow rates and inventories and required TBR

This work helped us make progress working with physicists and technologists
and now reveals more Serious R&D challenges ahead

Simplified Schematic of Fuel Cycle



Tritium self-sufficiency condition:

$$TBR_a \geq TBR_r$$

TBR_a = Achievable tritium breeding ratio

TBR_a is a function of **design, technology, material** and **physics**.

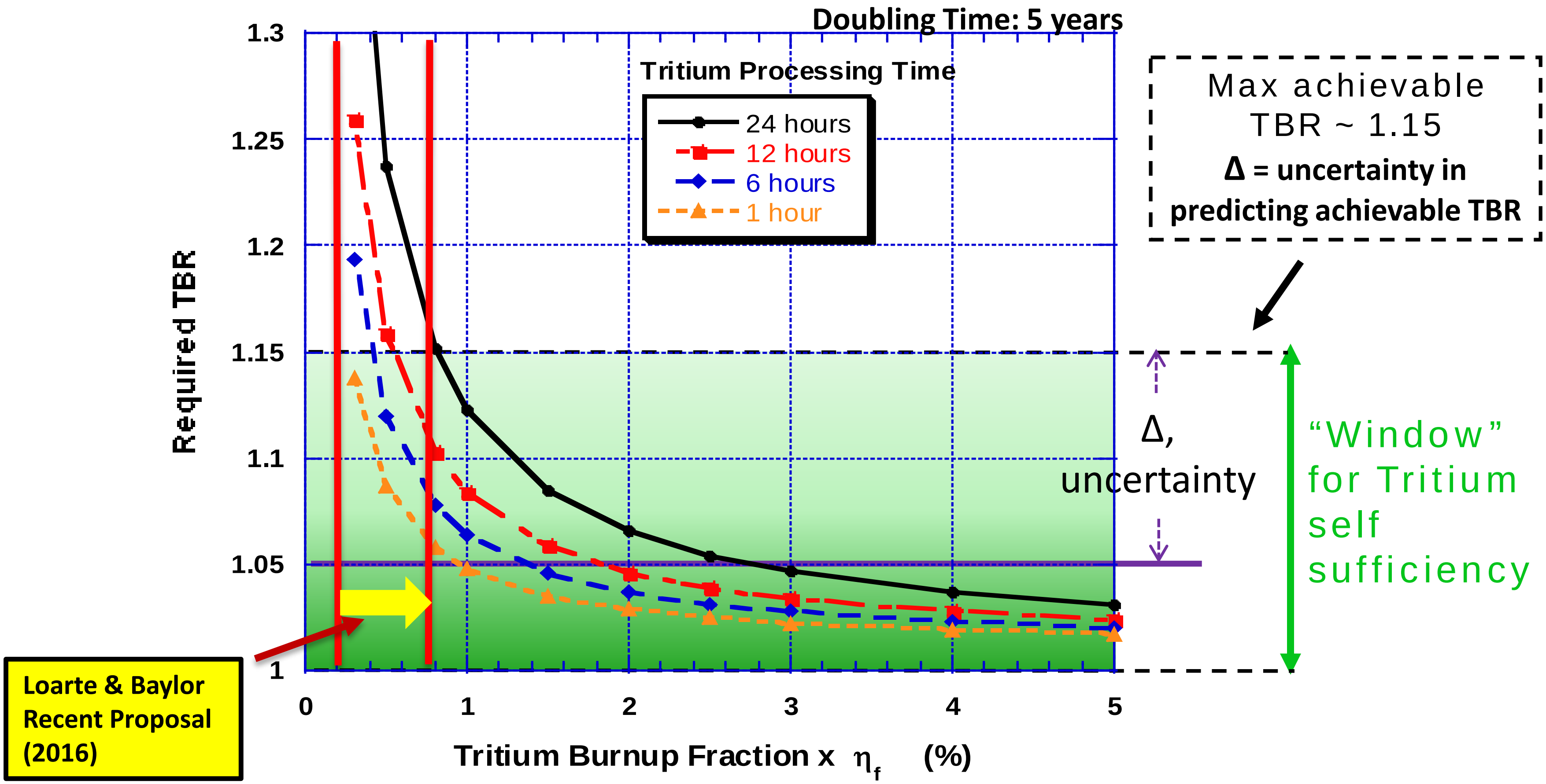
TBR_r = Required tritium breeding ratio

TBR_r *should exceed unity by a margin required to:*

1) *Compensate for losses and radioactive decay (5.47% per year) of tritium between production and use*
2) *Supply tritium inventory for start-up of other reactors (for a specified doubling time)*
3) *Provide a "reserve" storage inventory necessary for continued reactor operation under certain conditions (e.g. a failure in a tritium processing line)*

TBR_r depends on many system physics and technology parameters. To determine TBR_r, one must consider the "dynamics" of the entire T fuel cycle

Need to Demonstrate T Self-Sufficiency early (fundamental requirement). But there are large uncertainties and the required R&D is challenging



State of the art (ITER: f_b ~0.35%, η_f < 50%) achieving T self-sufficiency is Unlikely.

To Change this to likely, we must:

- **Lower Required TBR:** R&D to achieve $f_b \times \eta_f > 5\%$ and $t_p < 6$ hours **(how do we get there?)**
- **Reduce uncertainties in achievable TBR, Δ :** R&D for blanket & conduct "full blanket" (or at least "full sector") tests in DT Fusion Facility. ITER will not do it. So, **Where** and **When**? (**need FNSF**)

EXTERNAL T Supply Issue: Tritium Consumption and Production

Tritium Physical constants

- Half life: 12.32 years; decay rate: 5.47 %/yr - **Relatively short life**
- Some of the T will be lost by radioactive decay during T flow, processing, and storage
- **T available now from non-fusion sources is totally irrelevant to evaluating availability of T for startup of DEMO or FNSF constructed > 20 years from now**

Tritium Consumption in Fusion Systems is Huge

55.8 kg per 1000 MW fusion power per year

Tritium Production in Fission Reactors* is much smaller (and cost is very high)

LWR (with special designs for T production): ~ 0.5-1 kg/year

($84M-$130M/kg per DOE Inspector General)

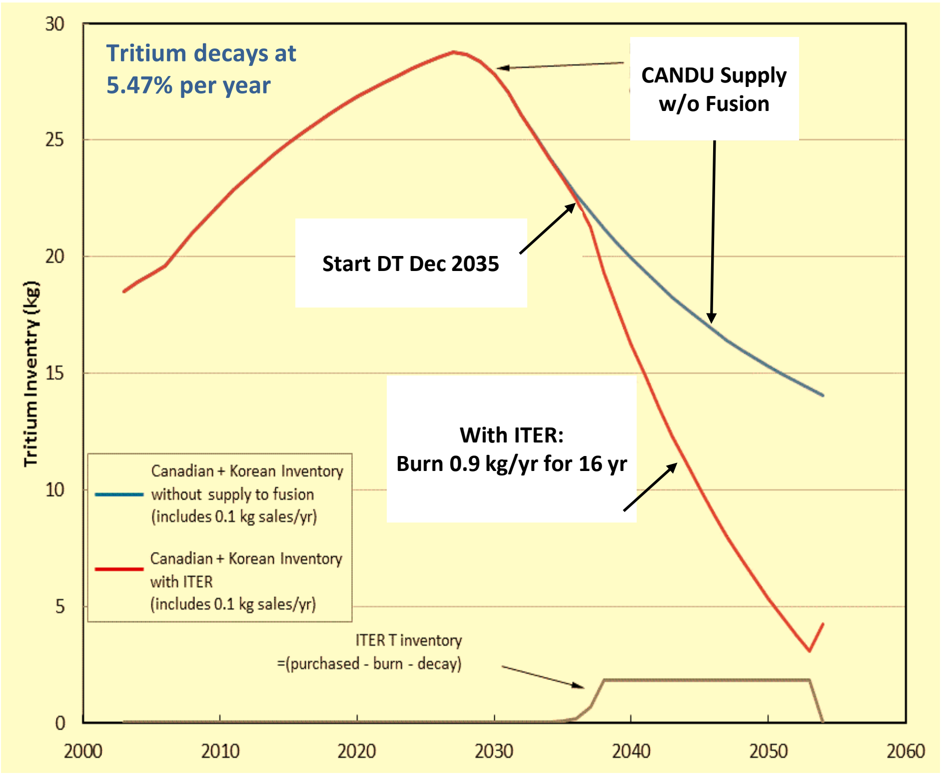
***Typical CANDU produces ~ 130 g per year** (.2 Kg per GWe per full power year) (T is unintended by product)*

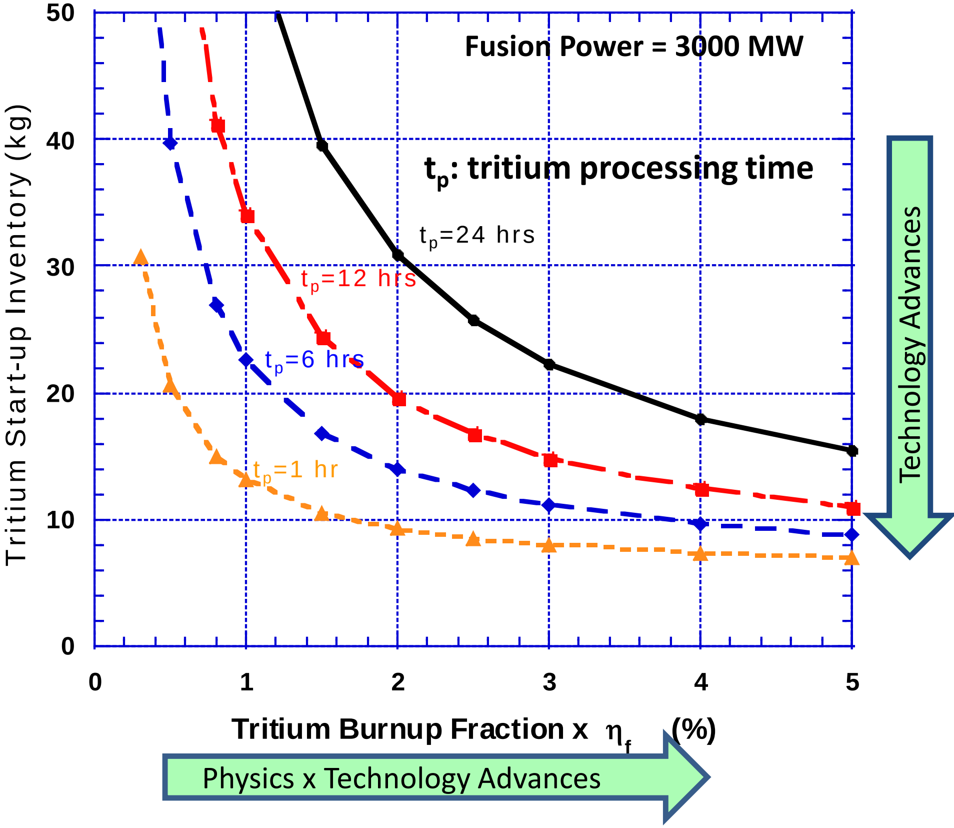
CANDU Ontario: Current supply will be exhausted by ITER DT starting in 2036.
Future Supply from CANDU depends on whether current reactors can be licensed to extend life by 20 years after refurbishment.
There are many political, national policy, and practical issues with both CANDU and LWR

- **Other non-fission sources (e.g. APT (proton-accelerator)) proved totally uneconomical**
- **Start-up with D-D fuel would pose additional tokamak physics and technological problems, and would delay power production by years and is not economically sensible**

** Note: Fission reactor operators do not really want to make tritium because of permeation and safety concerns. They want to minimize tritium production if possible*

Issue: With ITER DT start in 2036, there will be no tritium left to provide "Start up" T inventory for any major DT Fusion facility beyond ITER But the Required T Startup inventory is HUGE unless we do something





Confronting the Consequences of Fusion Tritium Consumption being large and the lack of adequate external non-fusion supply of T to start any fusion device other than ITER is critical for the development of fusion

The world fusion programs cannot depend on external non-fusion supply of T to:

1. Provide startup T inventory for 2 or 3 DEMOs plus other facilities such as FNSF and CFETR
2. Provide replacement for any shortfall in satisfying T self-sufficiency in large power fusion devices

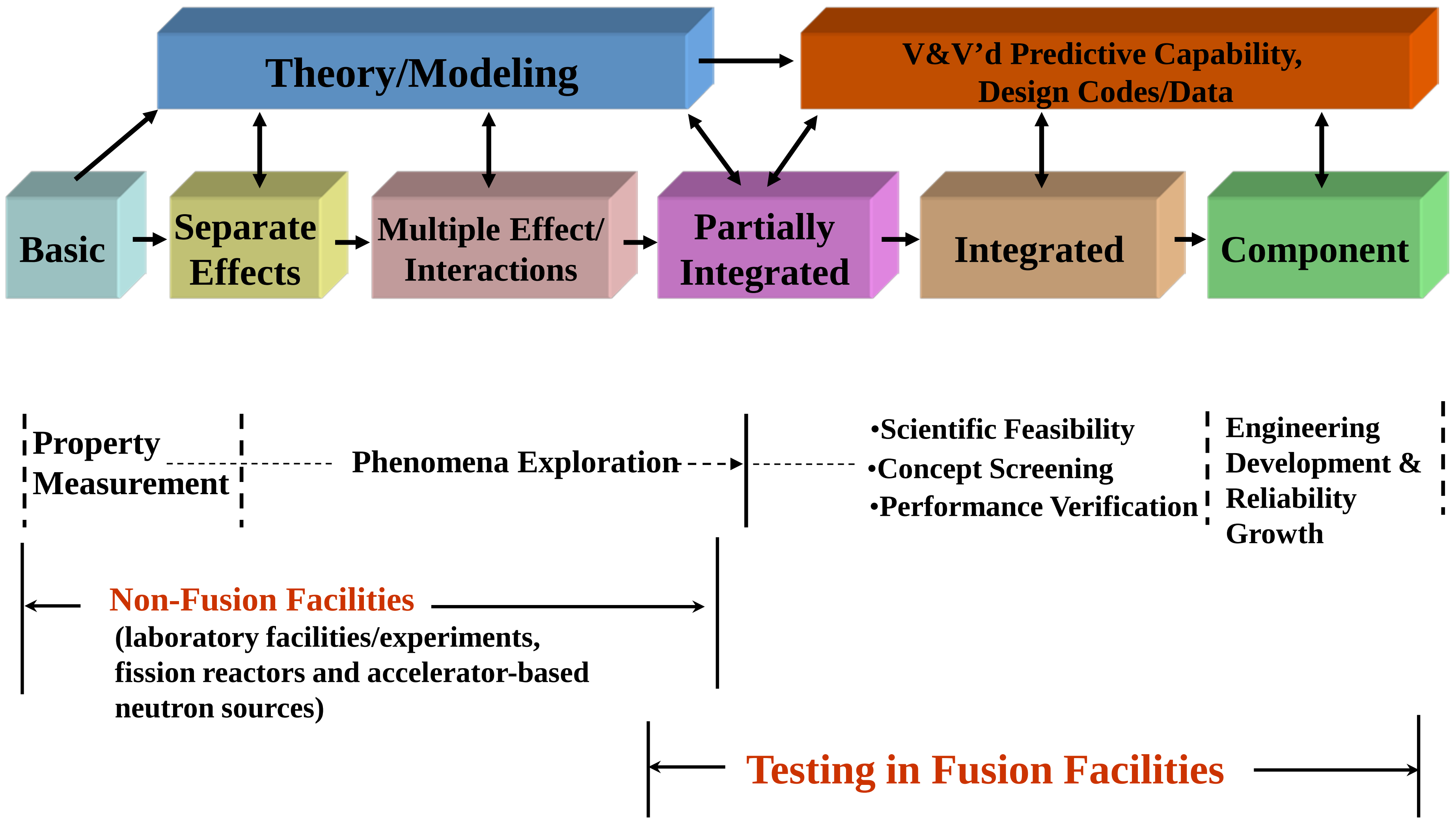
Therefore, Fusion Development Pathway must develop a strategy that confronts this problem. Examples of some key elements of such a strategy:

- Every effort must be done to **minimize the Required Startup T Inventory :** e.g. higher burn fraction, higher fueling efficiency, shorter T processing time, minimization of T inventory in all components
- **Minimize failures in tritium processing systems** and required reserve time
- No DT fusion devices other than ITER can be operated without a full breeding blanket
- Development of breeding blanket technology must be done in low fusion power devices
- Use FNSF to accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO (See calculations in Supporting slides)

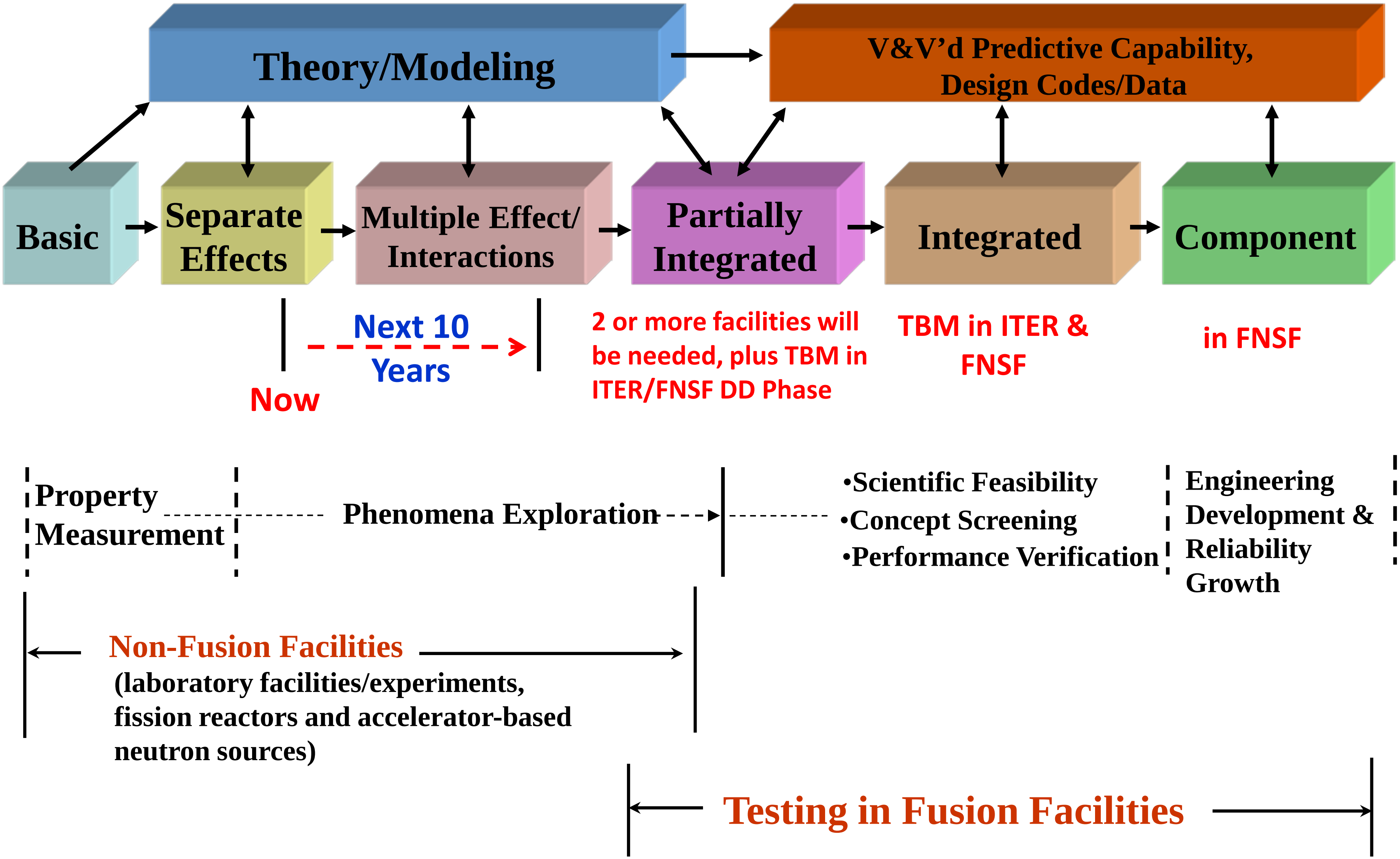
II. Scientific Framework and Strategy for Fusion Development

1. Role and Features of required non-fusion and fusion facilities
2. FNST Requirements on FNSF Parameters and Features
3. Timing and Stages of FNSF(s), How many FNSF(s) do we need?
4. Solving the paradox of short MTBF/long MTTR and what to do about dpa

Science-Based Framework for FNST/Blanket/FW R&D involves modeling & experiments in non-fusion & fusion facilities.



We are now in mostly "Separate Effects" stage. We Need to move to "multiple effects/multiple interactions" experiments and modelling



Necessary R&D Stages of Testing FNST components in the fusion nuclear environment prior 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
	Fluence ~0.3 MW-y/m²	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**
	NWL ≥ 0.5 MW/m² **Plasma 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 (10-20m^2)	Modules/Sectors (20-30m^2)

Stage I – Scientific Feasibility

- Discover and understand new synergistic phenomena
- Establish scientific feasibility of basic functions under prompt responses and under the impact of rapid property changes in early life

Stage II – Engineering Feasibility

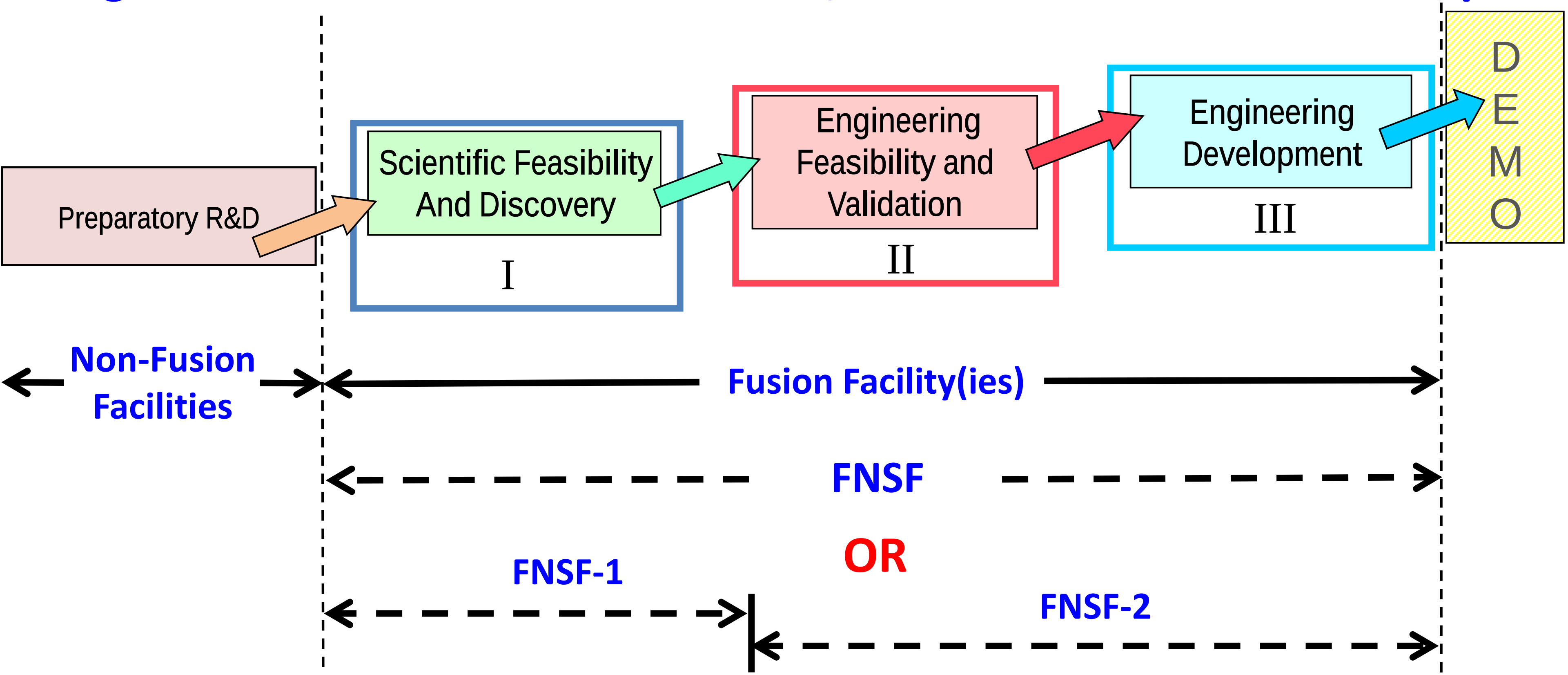
- Establish engineering feasibility of blankets/PFC/materials (satisfy basic functions & performance, up to 10 to 20% of MTBF and of lifetime)
- Show basic RAMI feasibility

Stage III – Engineering Development

- 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

Planning the Pathway to DEMO Must Account for Unexpected Negative Results for Current Blanket/PFC and Confinement Concepts



- Today, we do not know whether **one** facility will be sufficient to show scientific feasibility, engineering feasibility, and carry out engineering development

  OR if we will need **two or more** consecutive facilities.

  May be multiple FNSF in parallel?! (2 or 3 around the world)

We will not know until we build one!!

- Only Laws of nature will tell us regardless of how creative we are. We may even find we must change "direction" (e.g. New Confinement Scheme)

Staged approach Strategy for FNSF and Design for Breeding Blankets, Structural Materials, PFC & Vacuum Vessel

- DD phase has important role : All in-vessel components, e.g. divertor, FW/Blanket performance verification without neutrons before proceeding to the DT Phase

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)**

After first stage, 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 from FNSF (real environment) for testing structural & other materials:
  - no uncertainty in spectrum or other environmental effects
  - prototypical responses, e.g. gradients, materials interactions, joints

III. More on a Plasma-Based Fusion Environment Test Facility

Fusion Nuclear Science Facility (FNSF)

1. What type of facility should FNSF be and what main features and parameters should it have?

   "Now + 1" OR "DEMO – 1"?

2. Options for FNSF Facility: Tokamaks (standard and low aspect ratios, type of magnets), GDT/mirrors

What should the next DT Fusion Facilities (Other than ITER) be?
Three key facts must be considered in deliberating on this question

1. **Even with the aggressive R&D of computational simulation and experiments in non-fusion facilities that we must do, we will still have serious uncertainties in predicting the blanket behavior in the fusion nuclear environment**

   Therefore, the primary goal of the next DT fusion facility (at least the 1st stage) is to perform FNST experiments to discover synergistic effects and learn about blanket/PFC/Materials integrated behavior in the fusion nuclear environment. Must plan to be surprised! The next DT fusion facility cannot be for validation or demonstration.

2. **RAMI is the "Achilles heel" for fusion. RAMI will be the key issue in determining the feasibility of plasma confinement configurations and blanket concepts**
   - Very Low Availability (a few percent) will be a dominant issue to be confronted by the next DT fusion device (regardless of its name FNSF, CFETR, DEMO, etc.)
   - RAMI must be the most critical factor in any planning we do

3. **External Tritium Supply is very limited and expensive AND achieving tritium self-sufficiency in fusion devices has many uncertainties**
   - Next DT fusion device must breed its own tritium and have low fusion power to minimize T startup inventory requirements and avoid risk of breeding short fall

VNS/CTF/FNSF

Is this idea new?

No, it was first proposed in 1984 (in FINESSE) and studied and evolved over many years/decades in many excellent studies, for example:

- FINESSE (1983-86)
- TASKA-M UW-KFK (1983-85)
- IEA HVPNS Study (1995-96)
- UCLA/GA/ORNL/Columbia Univ. joint study on FNSF (2009-2013)

What name for the facility?

The name was changed over the years VNS/CTF/FNSF. FNSF is the name adopted since 2007

(Not to be confused with "FNSF" in the recent FESS study that defined very different type of facility with very different mission)

Why FNSF should be low fusion power, small size

- To reduce risks associated with external T supply and internal breeding shortfall
- Reduce Capital, operating cost, and replacement time (note Blanket/FW/ Divertor will fail and get replaced many times)
- Avoid accumulating “mountains” of Radwaste from failed FNST components
- Satisfy FNST key requirement 1-2 MW/m^2 on 10-20 m^2 test area (or less if cost is much lower)

- Cost/risk/benefit analyses* led to recommendations for Tokamak FNSF:
  - Fusion Power < 100 MW
  - Size comparable to JET (R < 3 m)
  - Low Q plasma (1-3) - and minimize extrapolation in physics from JET
  - Normal conducting TF coils (to reduce inboard B/S thickness, also increase maintainability e.g. by using demountable coils).

Plan FNSF scope, mission, power, and size such that we can build it the soonest (parallel to ITER). Avoid planning FNSF to be very ambitious since this has the risk of ever rising costs and very lengthy schedule delays (learn the lesson of ITER)

**References IEA study: M. Abdou et al., Fusion Technology 23:1-57 (1996); also UCLA/GA/ORNL studies 2010-2013; see www.fusion.ucla.edu*

Imagine We had a facility today in which the fusion nuclear environment is simulated and had enough test volume to do experiments on the fusion nuclear components (in-vessel components: Blanket/FW, T system, remote maintenance)

What would have happened?

- We would have resolved most of these critical go/no-go issues
- We would have had real assessment whether the path we are on now leads to practical fusion
- We would be in a better position to address "fusion is always 40 years away"

What kind of facility is needed?

- The only way to simulate the fusion nuclear environment with sufficient volume is to have DT plasma based facility. But plasma performance requirements are modest: driven, Q ~1-3, fusion power < 100 MW, size comparable to JET

Why do we not have this facility today? Why a fusion program with a mission to build a large, high performance powerful DT plasma with very high Q has not yet built a modest small-size low power DT plasma device? Mystery!!

- **Physicists need to think of driven DT plasma for FNSF as ENABLER of Fusion Nuclear Science and Technology Development (think of "ENABLING Plasma". Do not burden FNSF with ambitious physics or superconducting magnet mission).**

Degree of “prototypicality” between FNSF and DEMO?

- Some researchers have recently advocated that FNSF should be as close as possible to DEMO in order to minimize the gap between FNSF and DEMO
  - But our analysis in comprehensive studies over 30 years provides different conclusion
- The major issue in fusion development now is that
  - We don’t know how FNST components will behave in the fusion nuclear environment
  - R&D to test and qualify the FNST components is likely to require long time with success not assured (we do not even have scientific feasibility yet!)
  - The seriousness of the RAMI issue makes the risks very high
- Our concern now should be how to build a practical FNSF with minimum extrapolation of physics and technology (Be technically credible!)
- The focus of FNSF should be on **prototypical “in-vessel” fusion nuclear components** which are missing from ITER
  - Components outside the vacuum vessel (e.g. S.C. magnets) are already prototypical and tested in ITER at almost the same scale as DEMO - no need to be prototypical in FNSF
- An approach that makes FNSF close to DEMO will have:
  - Much larger size than needed for FNSF testing mission
  - Much larger capital and operating costs
  - Longer replacement time and accumulation of much Radwaste
  - Unacceptable risk

Think of: “Now + 1” NOT “DEMO – 1”

Options for FNSF

Different Confinement concepts were studied as options for FNSF over decades in the studies mentioned previously

- **Mirrors**

  Were highly favored in the 1980's because of (a) "decoupling" of fusion power and power density which allows high wall load with no need for large fusion power, and (b) other features such as easier accessibility/maintainability. But interest declined because of difficulties obtaining high electron temperature

- **Standard Aspect Ratio Tokamak** with driven plasma, low fusion power

  Example of design led by GA : Standard Aspect Ratio (A~3.5) with demountable TF coils,

  R ~2.5 m, P_{fusion}=125 MW at P_{NW}=1 MW/m^2

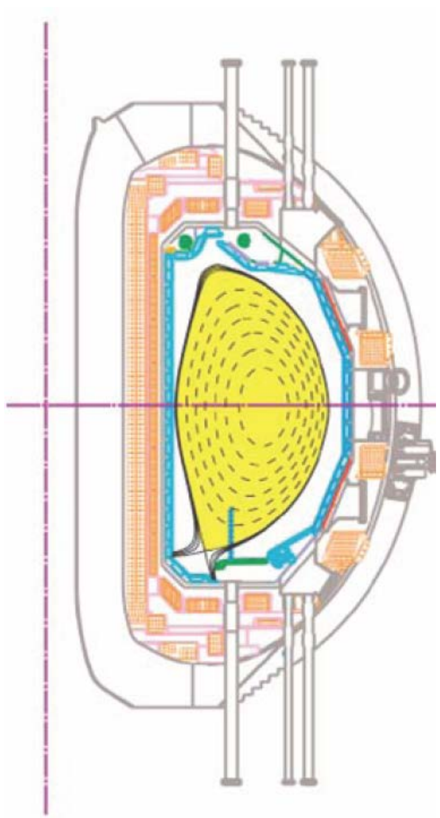
- **Small Aspect Ratio (ST)**

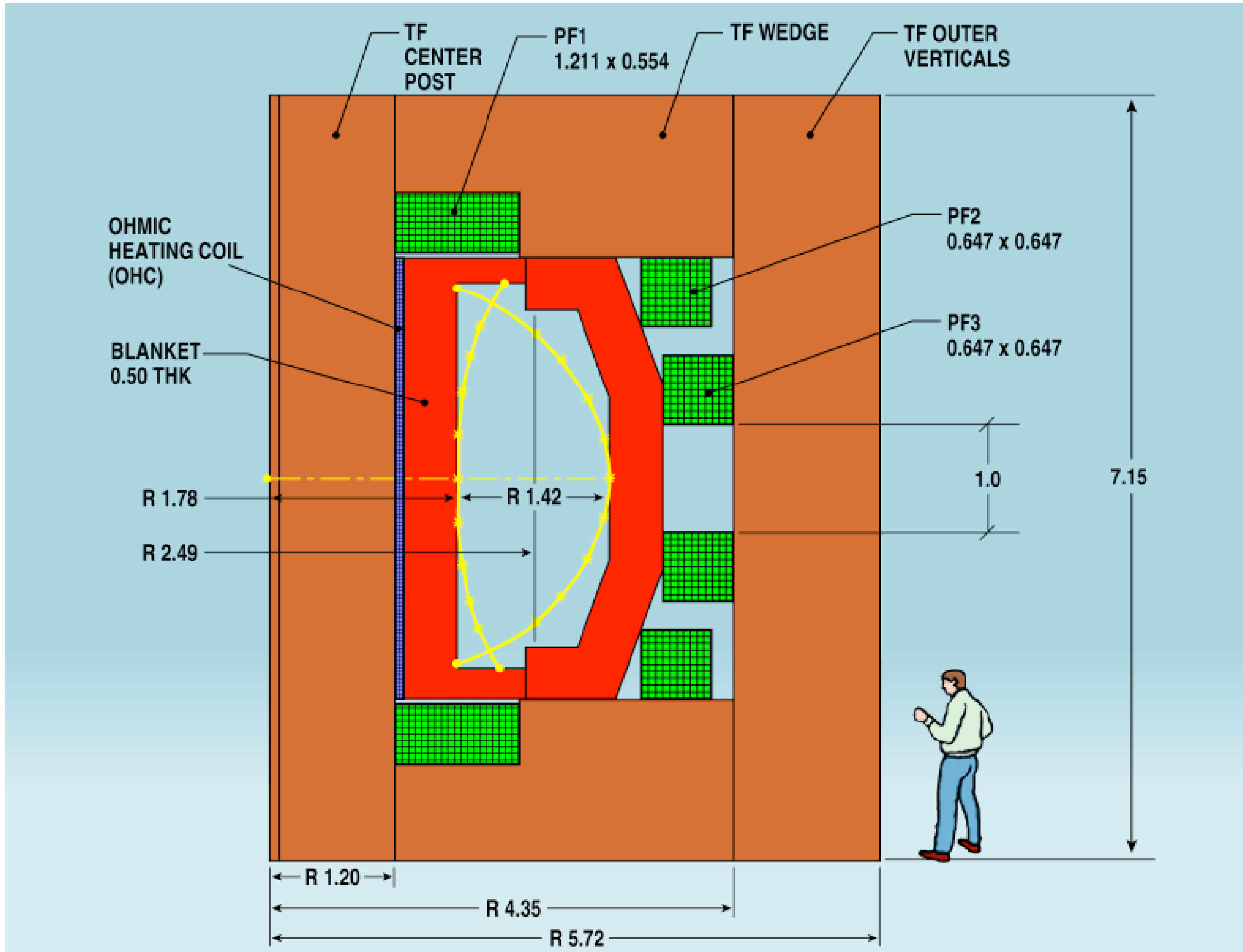
  Example of design by M. Peng et al., ORNL; R=1.2m, A=1.5, κ=3, P_{fusion}=75MW, P_{NW}=1 MW/m^2

- **GDT**

  Several studies, several variants. One studied in IEA HVPNS study had only 0.5 m^2 test area and had issue of too steep gradients in the test space. But improvements were made in subsequent studies

Example of Fusion Nuclear Science Facility (FNSF) Design Option: Standard Aspect Ratio (A~3.5) (GA design) demountable normal TF coils, R=2.5m, P_{fusion} =125 MW, P_{NW} = 1 MW/m^2



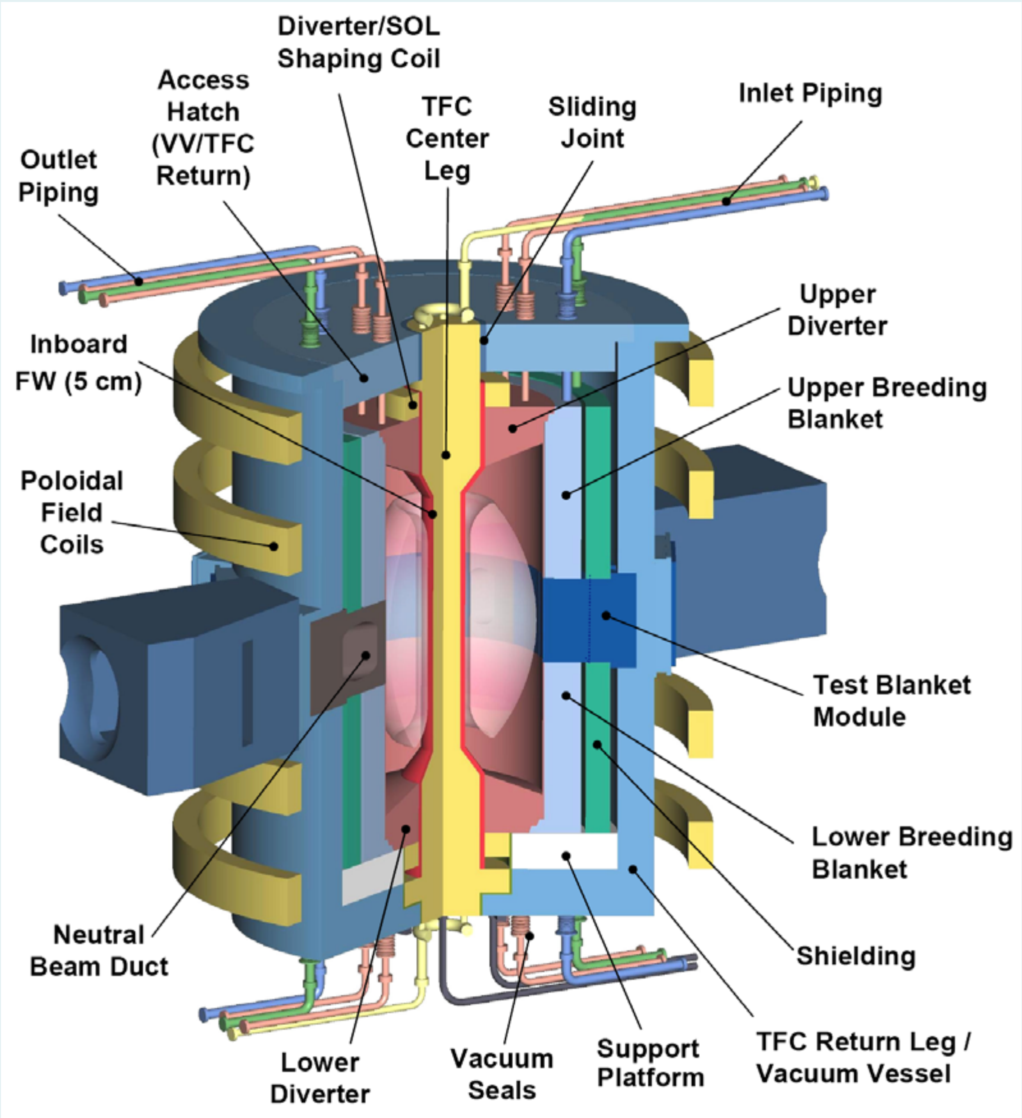


- High elongation, high triangularity double null plasma shape for high gain, steady-state plasma operation

Challenges for Material/Magnet Researchers:

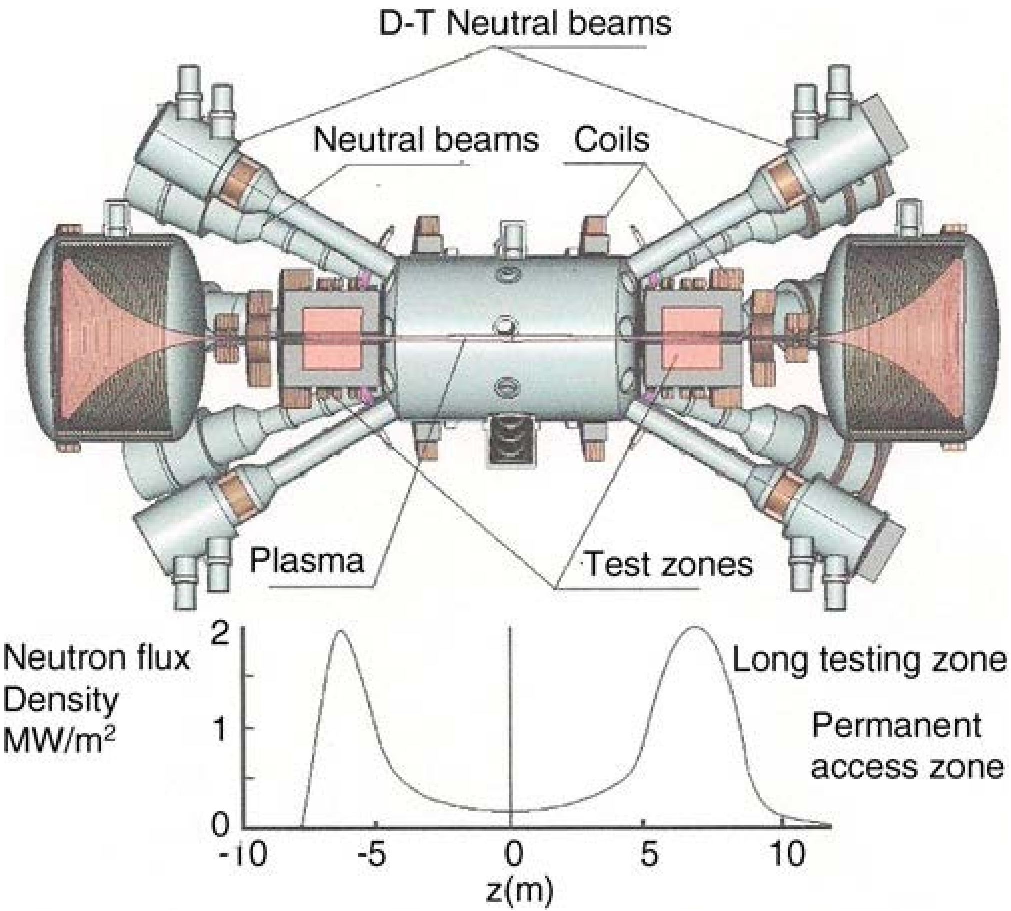
- **Development of practical "demountable" joint in Normal Cu Magnets**
- **Development of inorganic insulators (to reduce inboard shield and size of device)**

Another Option for FNSF Design: Small Aspect Ratio (ST) (Peng et al, ORNL)
Smallest power and size, Cu TF magnet, Center Post
R=1.2m, A=1.5, κ=3, P_{fusion}= 75MW, P_{NW} = 1 MW/m^2



W_L [MW/m^2]	0.1	1.0	2.0
R0 [m]	1.20		
A	1.50		
Kappa	3.07		
Qcyl	**4.6**	3.7	**3.0**
Bt [T]	**1.13**	2.18	
Ip [MA]	**3.4**	8.2	**10.1**
Beta_N	3.8		**5.9**
Beta_T	**0.14**	0.18	**0.28**
n_e [10^{20}/m^3]	**0.43**	1.05	**1.28**
f_{BS}	**0.58**	0.49	**0.50**
T_{avgi} [keV]	**5.4**	10.3	**13.3**
T_{avge} [keV]	**3.1**	6.8	**8.1**
HH98	1.5		
Q	**0.50**	2.5	**3.5**
P_{aux-CD} [MW]	**15**	31	**43**
E_{NB} [keV]	**100**	239	**294**
P_{Fusion} [MW]	**7.5**	75	**150**
T M height [m]	1.64		
T M area [m^2]	14		
Blanket A [m^2]	66		
$F_{n-capture}$	0.76		

GDT-based neutron source for subcomponent and material testing*



Plasma parameters in: D. D. Ryutov et al., *J. Fusion Energy*, **17**, 253, 1998; P. A.Bagryansky et al., *Fusion Eng. Des.*, **70**, 13 2004; P. A. Bagryansky et al., PRL, 114, 205001,2015; Test-zone design in: U. Fischer et al., Jan. 1999. *Fusion Technol.* **35-1T**, 160, 1999 General review in: A.W. Molvik et al., *Fusion Sci. Tech.* **57**, 369, 2010

- **Mirror-to-mirror length 15 m**
- **Mirror magnetic field 15 T**
- **Mirror ratio 20 (4 for the test zones)**
- **NBI power (trapped) 30 MW**
- **Neutron power 2.5 MW over the surface of 2 test zones (1 m long, 20 cm ID each)**
- **Tritium consumption 140 g for CW operation of one year (i.e., the fluence 2MWa/m^2)**
- **No tritium breeding (but the blanket cassettes can be tested)**
- **Both normal conductor and combined solenoids will be used**

**Information provided by Dmitri Ryutov*

Need New Approach to International Collaboration

- **Any DT device which will be built going forward in which the fusion nuclear components are exposed to the fusion nuclear environment for the first time will serve the function of FNSF regardless of name DEMO or CFETR or FNSF. Therefore, there is worldwide common interest in FNST challenges and R&D addressed in this talk regardless of the publicly stated strategy**
- We should think of a new more effective approach to international collaboration much different from the ITER model. For example:
  - 2 or 3 countries each build its own FNSF and share results and experience
  - Other countries can contribute more to R&D for FNSF and DEMO
  - Each Major Country builds its own DEMO when there is enough data, experience, testing, and qualification of fusion nuclear components in the fusion nuclear environment (from FNSF)
- **It is a mistake that US does not have its own TBM in ITER (we are paying for the cost but not getting the full benefits of ITER!). We recommend that the US at least for now maintain collaboration with other parties leading TBM (e.g. Korea, EU, China, Japan)**

Summary (1 of 3)

Overall Problem:

There are critical go/no-go problems for which HOW and WHERE to perform the R&D are a challenge, yet there is not a credible strategy being adopted, communicated, nor pursued

Major Go/No-Go Issues

- The fusion Nuclear environment is multiple-field, with steep gradients in volumetric heating, that result in many multiple effects/synergistic phenomena many of which are yet unknown. Can not adequately simulate in laboratory or other existing facilities, neither predict using existing models
- FNST components (Blanket/FW/Divertor) are inside the VACCUM Vessel in complex "closed" toroidal geometry, making RAMI the "Achilles' heel" for fusion, which together with multiple effects/large surface area, result in predicted extremely low "availability" for any DT device we build (FNSF, CFETR, DEMO, etc.)
- There are Large uncertainties in achieving Tritium Self Sufficiency because of low plasma burn fraction and fueling efficiency, in addition to the inability to narrow the current uncertainties in the achievable TBR without testing a full blanket sector in a plasma-based device
- There are no non-fusion sources to provide the "Start Up" inventory for DEMO, which is currently estimated to be huge

Summary (2 of 3)

What to do about these issues (Key elements of a prudent strategy)

1. **Build a number of multiple-effect Laboratory facilities** with maximum possible simulation of the fusion nuclear environment. These will be only partially effective in uncovering all the key multiple-effect/synergistic phenomena in blankets/FW. In parallel, undertake a **Major Modelling initiative** taking advantage of recent advances of massively parallel computation.
2. **Build a Fusion Nuclear Science Facility (FNSF)** to learn behavior of blankets/FW/Divertor in the fusion nuclear environment, learn about multiple/synergistic-effects phenomena, quantify the potential to attain T self-sufficiency, and possibly produce excess tritium to supply the Required Start up inventory for DEMO; and understand failure modes, rates, effects (RAMI). **Select a version of FNSF that can make it near term (operation parallel to ITER).** Make it small volume, low fusion power, with small requirements for external T supply, simplest, most reliable, driven plasma with current physics basis to enable the FNST mission. Requirements are well defined, but which concept and options for FNSF need a well-led study.
3. Use Tokamaks (and stellerators) as intermediate step in fusion development (continue participation in ITER), but in parallel, **search for other new plasma confinement schemes** that may have better potential for commercialization. In particular, simplicity of configuration, better maintainability, and more manageable RAMI problems. High power density is also desired.

Summary (3 of 3)

What to do about these issues (Key elements of a prudent strategy) (Cont'd)

4. Seek a more effective international cooperation model which is more efficient and reduces redundancy. Need an international cooperation strategy in which the critical R&D facilities, modelling, and research is "distributed" (rather than duplicated) among countries based on mutual benefits even if the development strategy varies among countries.

5. Time has come to **ask for a more effective, more agile management and leadership of the fusion program** with clear roles and effective interactions for universities, national Labs, and industry -- all pursuing a credible strategy for fusion development.

6. Include in the fusion strategy clear elements that enable successful **renewal of "human resources", while preserving "corporate memory/knowledge"** represented by senior researchers and multi-decade literature. Crucial for a program that is taking several human generations.

Thank You!

Extra Slides follow

Selected References with more detailed information about issues, recommended R&D, and strategy elements in this presentation

Abdou, M., Morley, N.B., Smolentsev, S., Ying, A., Malang, S., Rowcliffe, A., Ulrickson, M., "Blanket/First wall challenges and required R&D on the pathway to DEMO", Fusion Engineering and Design, 100:2-43 (2015).

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A.M. Garofalo, M.A. Abdou, J.M Canik, V.S. Chan, A.W. Hyatt, D.N. Hill, N.B. Morley, G.A. Navratil, M.E. Sawan, T.S. Taylor, C.P. C. Wong, W. Wu, A. Ying, "A Fusion Nuclear Science Facility for a fast-track path to DEMO," Fusion Engineering and Design, 89: 876-881 (2014).

M. Abdou and The APEX Team, "Exploring Novel High Power Density Concepts for Attractive Fusion Systems", Fusion Engineering & Design, 45, No.1: 145-167 (1999).

Selected References with more detailed information about issues, recommended R&D, and strategy elements in this presentation (Cont.)

M. Abdou, The APEX TEAM, A. Ying, N. Morley, K. Gulec, S. Smolentsev, M. Kotschenreuther, S. Malang, S. Zinkle, T. Rognlien, P. Fogarty, B. Nelson, R. Nygren, K. McCarthy, M. Youssef, N. Ghoniem, D. Sze, C. Wong, M. Sawan, H. Khater, R. Woolley, R. Mattas, R. Moir, S. Sharafat, J. Brooks, A. Hassanein, D. Petti, M. Tillack, M. Ulrickson, T. Uchimoto, "On the Exploration of Innovative Concepts for Fusion Chamber Technology", Fusion Engineering and Design, 54: 181-247 (2001).

"Tritium Fuel Cycle, Tritium Inventories, and Physics and Technology R & D Challenges for: 1) Enabling the startup of DEMO and future Power Plants AND 2) Attaining Tritium Self-sufficiency in Fusion Reactors", M. Abdou Keynote Presentation at International Symposium on Fusion Nuclear Technology (ISFNT-13), Kyoto, Japan, September 25-29, 2017. [PDF]

W.R. Meier, A.R. Raffray, R.J. Kurtz, N.B. Morley, W.T. Reiersen, P. Sharpe, S. Willms, "Findings of the US research needs workshop on the topic of fusion power," Fusion Engineering and Design, 85: 969-973 (2010).

M. Kovari, M. Coleman, *I. Cristescu, R. Smith, «Tritium resources available for fusion reactors"* 2018 *Nucl. Fusion* 58 026010

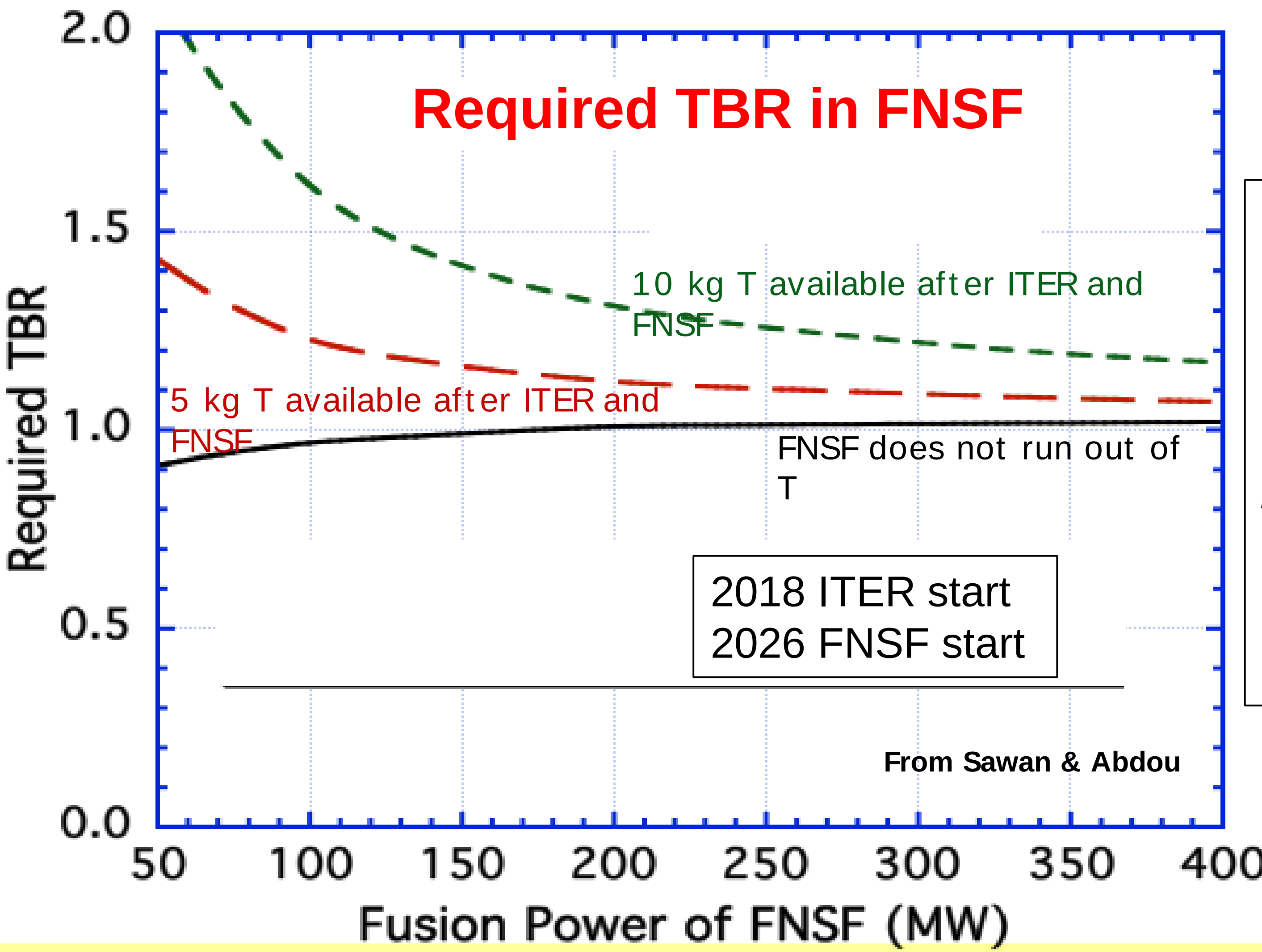
General References

Broader references on FNST are available upon request
Many references are provided already in the Selected References on the previous slides

FNSF should be designed to breed tritium to:

a) Achieve T self sufficiency, **AND**

b) Accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO



Impose a new requirement not originally in the mission of FNSF when it was first proposed in 1984 and in subsequent studies in the 1980's and 90's

Situation we are running into with breeding blankets: What we want to test (the breeding blanket) is by itself An ENABLING Technology

FNST embodies most of the remaining Feasibility and Attractiveness Issues in Fusion Energy Development.

FNST R&D is essential to confront Grand Challenges

Need High Power Density/Physics-Technology Partnership
- -High-Performance Plasma
- - Blanket/FW/divertor Technology Capabilities

Need Low Failure Rate

$$COE = \frac{C \cdot i + \text{replacement cost} + O \,\&\, M}{P_{fusion} \cdot \text{Availability} \cdot M \cdot \eta_{th}}$$

Energy Multiplication

Need High Temp. Energy Extraction Blanket

Need High Availability / Simpler Technological and Material Constraints

$$\frac{(1/\text{failure rate})}{1/\text{failure rate} + \text{replacement time}}$$

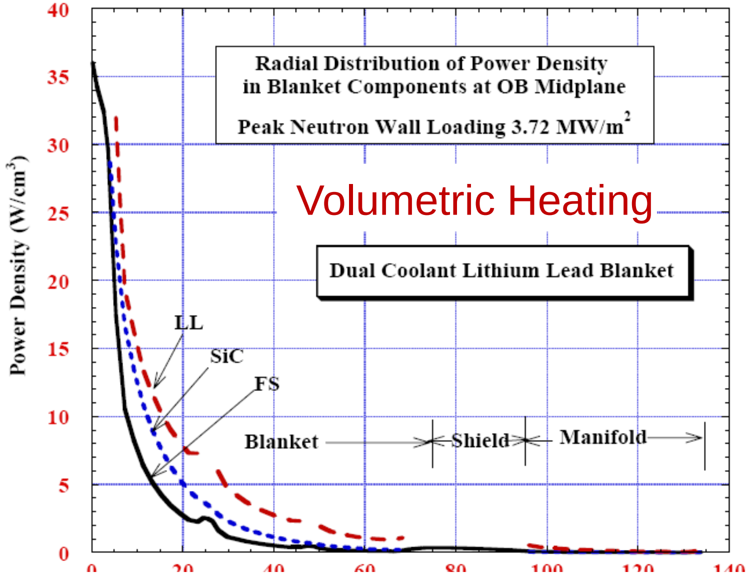
- **Need Low Failure Rate:**
  - Innovative Chamber Technology
- **Need Short Maintenance Time:**
  - Simple Configuration Confinement
  - Easier to Maintain Chamber Technology

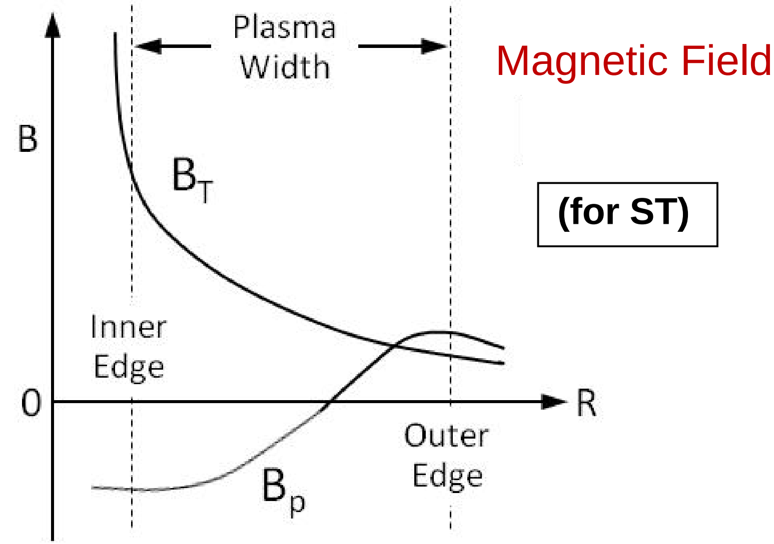
Need for High Power Density *Capability*

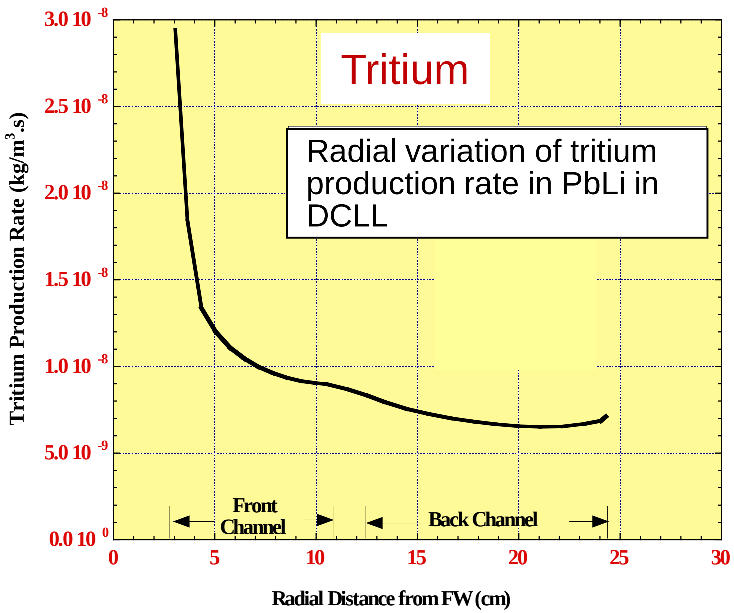
To improve potential attractiveness of fusion power compared to other energy sources (e.g. fission)

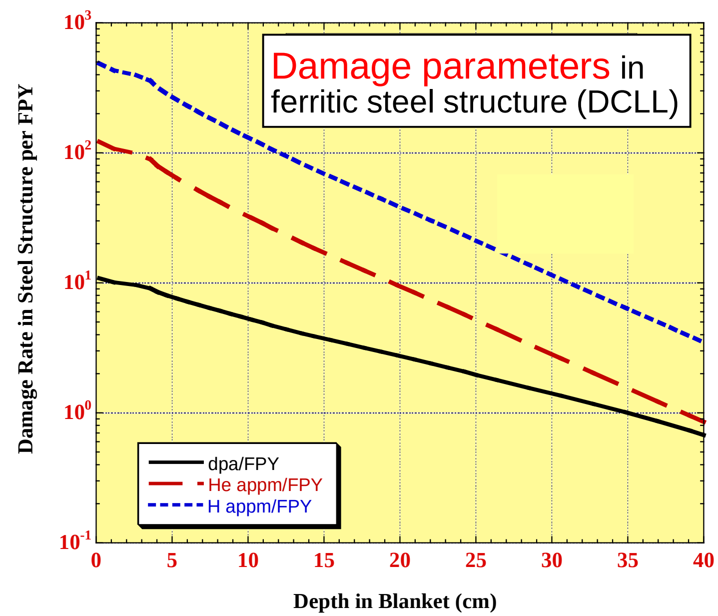
	PWR	BWR	LMFBR	ITER-Type
Average core power density (MW/m^{3})	96	56	240	**0.4**

There are strong GRADIENTS in the multi-component fields of the fusion environment









These gradients play a major role in the behavior of fusion nuclear components. Simulating these gradients in experiments is challenging but Essential.