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

Mohamed Abdou
Distinguished Professor of Engineering and Applied Science, UCLA
Director, Fusion Nuclear Science and Technology, UCLA

with input from N. B. Morley, A. Ying
and many US and worldwide collaborators over many years

Presentation To Prof Bo Sun Kang
Program Manager, National Research Foundation of Korea

UCLA    January 27, 2020
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
UCLA for the past 35 years has led the World on FNST and has served a Central Role of Core Competency for Blanket/FW, Power Extraction and Tritium Fuel Cycle

A broad scope of UCLA Activities

**R&D** – Focus on most important issues with strong scientific content and impact, and substantial potential for an improved vision of a fusion energy system

**Design/Analysis** – BCSS, IFE, APEX, TBM, Liquid Metal and ceramic breeder blankets/FW, He/Water-cooled PFCs, ITER FW/Shielding Blanket

**Technical Analysis & Planning** – FINESSE, VNS, IEA-HVPNS(FNSF), and participate in all important Panels (NAS, FESAC, and FES panels: 35-yr Panel, Priorities Panel, RENEW, FNS-PA, FESAC Materials and Technology Opportunities, etc.)


**Training of Students, Post-Docs, and Visiting Scholars**

- UCLA has the strongest and longest record of any institution in the world of training US and World FNST leaders
- UCLA played a key role in starting FNST programs not only in the US, but also in the EU, Japan, Korea, China, India
A number of major UCLA-led studies have provided the basis for the current FNST world research programs and for defining a credible science-based technical strategy for the future.

1980s
- Blanket Comparison and Selection Study (BCSS)
- FINESSE: major study identified and characterized the issues, requirements for experiments and non-fusion and fusion facilities for all FNST. The study involved experts from the Aerospace and fission industry, experts on technology development, and strong participation by Japan and EU (>200 man-yr). Seminal contribution-guided world FNST programs. Idea of VNS/FNSF was proposed
- Fuel Cycle Dynamic Modelling and Neutronics R&D: major contributions and impact

1990s
- Integral Neutronics Experiments: major achievements and made neutronics mature field
- ITER Test Blanket TBWG: initiated & led international ITER TBM Program
- Prometheus IFE Design Study: most comprehensive IFE study with Industry
- IEA High Volume Neutron Source Study: VNS/FNSF most comprehensive study

2000s
- Advanced Power Extraction Program (APEX): LED 12 US institutions to develop innovative FNST concepts (e.g. Liquid Surfaces and W solid wall EVOLVE)
- US Test Blanket Module Planning Study and R&D program (TBM)

2010s
- Collaborations with India, Korea, Japan, and EUROfusion
  - Discovery of “non-synthesis” of multiple effect phenomena, and discovery of mixed convection
    - MaPLE upgrade and UCLA-EUROfusion major activities

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.
Examples of major, long lasting UCLA contributions that had great impact on the US and World Fusion Programs

- **Identified FNST key issues**, uncovered phenomena, and developed R&D plans of facilities and modelling, which were implemented by major programs around the world. For example, FINESSE reports and papers are still key references for researchers and program planners.
- **First to identify need for FNSF** (VNS/CTF/HVPNS/CFETR) and define its mission and objectives. Led studies over 3 decades to define and compare options for FNSF facility.
- Identified need and studied options for high power density capability in FW, blanket and divertor- Pioneering studies in liquid walls before, during and after APEX.
- Developed **Dynamic Model for tritium fuel cycle and T self-sufficiency** that revealed the critical problems of plasma burn fraction, tritium fueling efficiency, speed of tritium processing, etc. – all have had major impact (and will continue for a long time) on R&D for plasma edge physics, fueling, and tritium processing systems in ITER, DEMO and beyond. (Invited Plenary Keynotes in IAEA Nov. 2016 and ISFNT Sept. 2017)
- Performed the largest neutronics R&D of codes, methods, and data, and integral neutronics experiments, and brought fusion neutronics to “mature” field by 1995.
- Development of consistent/conservative numerical formulation of MHD terms in Navier-Stokes/MHD equations that opened the door to huge advances in 3D MHD simulations.
- Development of innovative method to obtain fusion prototypical He/dpa ratio data in reduced activation ferritic steel from fission reactor irradiation by enriching iron in Fe-54 and Fe-55.
- Development of unique and powerful discrete element “pebble scale” numerical techniques that enabled thermomechanical time evolution studies of pebble beds.
- Unique studies of multiple effects/multiple interactions using UCLA research codes and facilities, discovered new MHD phenomena (e.g. MHD mixed convection) that are fundamentally changing what and how to do LM-MHD/Heat Transfer R&D for FNST.
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

Other Info, notes on IFMIF type, key references, 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 has multi-component fields with strong gradients, and 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)*

**Combined Loads, Multiple Environmental Effects**
- Thermal-chemical-mechanical-electrical-magnetic-gravitational-nuclear interactions and multiple/synergistic effects
- Interactions among physical elements of components

Experiments and modelling on multiple effects/multiple interactions are essential to predict performance and behavior of fusion nuclear components
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.
Blanket/FW systems are complex and have many functional materials, joints, fluids, and interfaces. Li, PbLi, Li-Salt flow. E.g. Ceramic Breeder Based: Neutron Multiplier Be, Be$_{12}$Ti, Tritium Breeder Li$_2$TiO$_3$, Li$_4$SiO$_4$. First Wall (RAFS, F82H). E.g. Liquid Breeder Based: Neutron Wall Load. Surface Heat Flux. Coolants: He, H$_2$O, 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 (fission reactors: very limited testing volume, wrong spectrum, wrong gradient)
  – 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.

But we just discovered that what we assumed for 30 years is wrong.
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 phenomena (Heat, T, Corrosion)

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

- Predictions from separate effect tests for the integrated fusion nuclear environment are at best misleading, and quite often simply wrong
- Blankets designed with current knowledge of phenomena and data will **not 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 scaled down conditions from blankets in DEMO. How do we preserve phenomena?

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

<table>
<thead>
<tr>
<th>Non-Dimensional Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Reynolds Number, ( Re = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{\rho u L}{\mu} )</td>
</tr>
<tr>
<td>➢ Hartmann Number, ( Ha = \left( \frac{\text{Electromagnetic forces}}{\text{Viscous forces}} \right)^{0.5} = BL \sqrt{\frac{\sigma}{\mu}} )</td>
</tr>
<tr>
<td>➢ Grashof Number, ( Gr = \frac{\text{Buoyancy forces}}{\text{Viscous forces}} = \frac{g \beta \Delta T L^3}{\nu^2} = \frac{g \beta q L^4}{\nu^2 \kappa} )</td>
</tr>
</tbody>
</table>

- 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!)

**DEM0 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, called MaPLE-U, has been completed at UCLA, in partnership with EUROfusion, to study MHD thermofluids multiple-effects, material interactions, and tritium transport & permeation.

• First experiments on mixed convection in MaPLE-U successfully started August 2018. Results show unstable mixed convection with flow reversal -- direct proof of the underlying scientific motivation for this MaPLE-U.

• 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
Availability = \frac{MTBF}{MTBF + MTTR}

MTBF – Mean time between failures
MTTR – Mean time to repair

- RAMI/Availability is a key factor in COE - economics
- For fusion, RAMI is also a most serious Engineering Feasibility Issue.
- Yet, the world fusion program still has no dedicated RAMI experts, and no serious R&D and no database to realistically estimate what availability can be realized.
  - Availability has been an assumed number in ALL fusion studies (reactors, DEMO, test facilities, ITER) because we know what we need (75% - 85% for reactors), but no one estimated what can be achieved (except for small individual efforts).
  - The IEA International Study on High Volume Plasma-Based Neutron Source (HVPNS) (1994-96) made good effort to predict availability based on extrapolation from fission and aerospace industry and how much testing in the fusion nuclear environment (See Fusion Technology, 29: 1-57 (1996))
  - The results of this IEA HVPNS Study were very alarming. They show that RAMI is the Achilles’ Heel issue for fusion
Availability required for each component needs to be high

<table>
<thead>
<tr>
<th>Component</th>
<th>#</th>
<th>failure rate (1/hr)</th>
<th>MTBF (yrs)</th>
<th>MTTR/type</th>
<th>Fraction Failures Major</th>
<th>Outage Risk</th>
<th>Component Availability</th>
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<tbody>
<tr>
<td>Toroidal Coils</td>
<td>16</td>
<td>5 x 10^-6</td>
<td>23</td>
<td>10^4</td>
<td>240</td>
<td>0.1</td>
<td>0.098</td>
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<td>Magnet supplies</td>
<td>4</td>
<td>1 x 10^-4</td>
<td>1.14</td>
<td>72</td>
<td>10</td>
<td>0.1</td>
<td>0.007</td>
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<tr>
<td>Cryogenics</td>
<td>2</td>
<td>2 x 10^-4</td>
<td>0.57</td>
<td>300</td>
<td>24</td>
<td>0.1</td>
<td>0.022</td>
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<tr>
<td>Blanket</td>
<td>100</td>
<td>1 x 10^-5</td>
<td>11.4</td>
<td>800</td>
<td>100</td>
<td>0.05</td>
<td>0.135</td>
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<td>Divertor</td>
<td>32</td>
<td>2 x 10^-5</td>
<td>5.7</td>
<td>500</td>
<td>200</td>
<td>0.1</td>
<td>0.147</td>
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<td>Htg/CD</td>
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<td>Tritium System</td>
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<td>Vacuum</td>
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<tr>
<td>Conventional equipment</td>
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<td>0.952</td>
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<tr>
<td>TOTAL SYSTEM</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.624</td>
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</tbody>
</table>

DEM0 availability of 50% requires:
- Blanket/Divertor Availability ~ 87%
- Blanket MTBF >11 years
- MTTR < 2 weeks

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

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

Reliability/Availability/Maintainability/Inspectability (RAMI) is a serious challenge that has major impact on engineering feasibility and economics.
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 require 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:
  o Can continue operation with ~2% of fuel rods with failures (MTBF ~ years)
  o An entire fuel bundle can be replaced in ~ 2 days (MTTR ~ 2 days).
  o Fission reactors have been able to achieve 90% availability
Lessons learned and suggestions for improving the situation with RAMI, the Achilles’ Heel issue 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
   - Strive for design simplicity and bring Industry into the design process
   - 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 developed & advanced since 1986 to calculate time-dependent tritium flow rates and inventories and required TBR

- These models revealed serious issues with the likelihood of attaining tritium self sufficiency in current fusion systems: Very challenging advances in plasma physics and fusion technology are required.
- Since 1986, we have worked with physicists and technologists to perform needed R&D. Progress made.
- But in 2019: more challenging issues and R&D remain

M. Abdou, Keynote ISFNT-14, 9-23-2019
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
Issues in Achieving Tritium Self-Sufficiency Condition:
Achievable TBR ≥ Required TBR

Achievable TBR
- Maximum achievable TBR with current concepts is 1.05-1.15 (the range is due to uncertainties in calculations and data)
- Strong dependence on “System Definitions” (e.g. amount of structure in FW/Blanket/Divertor, presence of passive coils for plasma stabilization, penetrations)
- Accurate prediction of achievable TBR requires testing of full blanket (or at least a full sector) in plasma-based device (cannot be done with ITER TBM modules)

Required TBR
- Very strong dependence on plasma and technology parameters: e.g. plasma burn fraction, fueling efficiency, tritium processing time, reliability of tritium system, reactor system availability
- With state of the art (ITER: \(f_b \sim 0.35\%\), \(\eta_f < 50\%\)), the required TBR is \(> 1.2\)
- Recent proposals for improvements in \(f_b \eta_f\) are promising but not assured, nor sufficient
There are large uncertainties in achieving T Self-Sufficiency.
The required R&D is challenging.

State of the art (ITER: $f_b \sim 0.35\%$, $\eta_f < 50\%$) 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 to get there?)
- **Increase Achievable TBR**: Reduce structure and non breeding materials, etc.

Loarte & Baylor Recent Proposal (2016)
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. The tritium we had at the beginning of ITER design has already decayed!
Required tritium Start-up Inventory depends on many plasma physics and technology parameters.

Also note that it increases with Fusion Power. Plasma-based test facilities with low fusion power need relatively small and obtainable start-up inventory.
Lessons learned regarding tritium supply for start up inventory

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, and 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
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.

- **Theory/Modeling**
  - Basic
  - Separate Effects
  - Multiple Effect/Interactions
  - Partially Integrated
  - Integrated
  - Component

- **V&V’d Predictive Capability, Design Codes/Data**

- **Testing in Fusion Facilities**

- **Non-Fusion Facilities**
  - (laboratory facilities/experiments, fission reactors and accelerator-based neutron sources)

- **Property Measurement**
  - Phenomena Exploration

- **Engineering Development & Reliability Growth**
  - Scientific Feasibility
  - Concept Screening
  - Performance Verification
We are now in mostly “Separate Effects” stage. We Need to move to “multiple effects/ multiple interactions” experiments and modelling.

- Basic
  - Separate Effects
  - Multiple Effect/Interactions
  - Partially Integrated
  - Integrated
  - Component

**Science & Modeling**
- Theory/Modeling
- V&V’d Predictive Capability, Design Codes/Data

**Next 10 Years**
- 2 or more facilities will be needed, plus TBM in ITER/FNSF DD Phase

**Non-Fusion Facilities**
- (laboratory facilities/experiments, fission reactors and accelerator-based neutron sources)
- Property Measurement
- Phenomena Exploration

**Testing in Fusion Facilities**
- Scientific Feasibility
- Concept Screening
- Performance Verification

**Engineering Development & Reliability Growth**
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

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

M. Abdou NAS Committee in La Jolla, CA 02-26-2018
Planning the Pathway to DEMO Must Account for Unexpected Negative Results for Current Blanket/PFC and Confinement Concepts

Preparatory R&D

Scientific Feasibility And Discovery

Engineering Feasibility and Validation

Engineering Development

I

II

III

Fusion Facility(ies)

Non-Fusion Facilities

FNSF

FNSF-1

OR

FNSF-2

• 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

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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/m² on 10-20 m² 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
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 ($A \sim 3.5$) with demountable TF coils, 
  $R \sim 2.5$ m, $P_{\text{fusion}}=125$ MW at $P_{\text{NW}}=1$ MW/m²

- **Small Aspect Ratio (ST)**
  
  Example of design by M. Peng et al., ORNL; $R=1.2$ m, $A=1.5$, $\kappa=3$, $P_{\text{fusion}}=75$MW, $P_{\text{NW}}=1$ MW/m²

- **GDT**
  
  Several studies, several variants. One studied in IEA HVPNS study had only 0.5 m² 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, $R=2.5\text{m}$, $P_{\text{fusion}} =125\text{ MW}$, $P_{\text{NW}} = 1\text{ MW/m}^2$

- 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, $\kappa=3$, $P_{\text{fusion}} = 75\text{MW}$, $P_{\text{NW}} = 1 \text{ MW/m}^2$

<table>
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<th>0.1</th>
<th>1.0</th>
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<tr>
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<tr>
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<td>$Q_{\text{cyl}}$</td>
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<td>$B_t$ [T]</td>
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<td></td>
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<td>10.3</td>
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</tr>
<tr>
<td>$T_{\text{avge}}$ [keV]</td>
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</tr>
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<td>HH98</td>
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<td></td>
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<tr>
<td>$Q$</td>
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<td>2.5</td>
<td>3.5</td>
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<tr>
<td>$P_{\text{aux-CD}}$ [MW]</td>
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<tr>
<td>$E_{\text{NB}}$ [keV]</td>
<td>100</td>
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<td>294</td>
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<tr>
<td>$P_{\text{Fusion}}$ [MW]</td>
<td>7.5</td>
<td>75</td>
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<tr>
<td>T M height [m]</td>
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</tr>
<tr>
<td>T M area [m²]</td>
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<td>14</td>
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</tr>
<tr>
<td>Blanket A [m²]</td>
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<td>66</td>
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<tr>
<td>$F_{n\text{-capture}}$</td>
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</tr>
</tbody>
</table>

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GDT-based neutron source for subcomponent and material testing*

- 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
Why FNSF (i.e. VNS, CTF, etc.) was proposed in 1984 with many subsequent studies confirming the need for such a facility

• Laboratory facilities cannot simulate adequately the multiple field fusion nuclear environment. In particular, nuclear heating in a large volume with steep gradients cannot be simulated in laboratory facilities or fission reactors. These can be simulated only in a DT Plasma-based facility (now called FNSF).

• FNSF is a plasma-based facility 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).

• The requirements for FNSF were defined in FINESSE (1983-85) and refined in IEA HVPNS (1994-96): 1-2 MW/m² on 10-20 m² test area. Only inside the vacuum vessel (FW/Blanket/divertor modules) need to be prototypical. Plasma can be highly driven, $Q \sim 1-3$. Recommend normal conducting TF coils (to reduce inboard B/S thickness, also increase maintainability e.g. by using demountable coils).

• In the 1980’s, we studied if plasma physics and FNST development should be combined into one facility or performed in two separate facilities (one ITER-type facility for burning plasma physics and plasma support technology, and another smaller size FNSF for FNST). The conclusion was DEFINITIVE: Two facilities are faster, less expensive, and more practical than one facility!!!
IFMIF

- IFMIF is an accelerator-based “point” neutron source to irradiate thousands of “miniaturized specimens, mm-scale” in a very small volume (0.5 litre at flux ~2MW/m²)

- The reason IFMIF was conceived back in the 70’s was the mistaken belief then that:
  - Fusion Development would be very fast: DEMO by 1980-90
  - The only challenge was attaining long life, 200dpa in structural materials

- BUT “Today”, we understand:
  - Experiments on FNST (blankets/divertors) require a plasma-based DT fusion facility to simulate complex fusion nuclear environment (particularly nuclear bulk heating in large volume, surface heat flux, plasma transients, etc) and neutron reactions and materials interactions.
  - We do not know the failure modes, and there is no data on MTBF but is likely to be short minutes/hours on our current never built, untested, in-vessel components. So "reliability growth" is needed in imperfect non-nuclear testing facilities and then in fusion nuclear facilities. It may take 10-20 years of fusion nuclear testing to get to 10-20 dpa.
Role of IFMIF?

* Can we skip FNSF, use IFMIF and ITER TBM and go directly to DEMO (like in the old world-strategy or some recent proposals) ?

No, this is not credible

It would violate the results of extensive scientific and engineering FNST studies of the past 25 years.

“blanket tests in ITER alone can not demonstrate a blanket system availability in DEMO higher than 4%....... The presence of IFMIF does not significantly change this conclusion.” *

* Does FNSF need IFMIF?

Absolutely Not!!

– FNSF will do the first experiments on the nuclear components. RAMI issues, testing and reliability growth will be dominant (most likely it will take > 10 years to get 10 dpa). There is enough data from fission and other sources to design for this first stage.
– Once we pass the first stage of 10 dpa in FNSF, we can extrapolate by a factor of 2 from “real results” as we outlined earlier.

* M. Abdou et. al., Fusion Technology, vol. 29 (January 1996)
Launching an initiative to build FNSF soon is good for ITER, good for DEMO, good for fusion

• In 2019: The changes in ITER design, ITER TBM and what we are learning about the importance of extensive FNST testing for multiple effects, RAMI, tritium self sufficiency, etc. show that the conclusions of the 1980’s and 1990’s studies about the need for both ITER and FNSF were far-sighted.
  – Blanket testing in ITER has been sharply reduced from the original program planned on ITER in the 1980’s. ITER has a good reason to do this: ITER is focused on burning plasma physics and large-scale plasma effects (e.g. disruptions). So now ITER TBM is useful but does not address the FNST development needs for DEMO

Recommendations

• Build FNSF soon, parallel to ITER, to focus on development of FW/Blankets/PFCs/Materials/RAMI for DEMO. This way we can build the DEMO sooner and let ITER focus on its primary mission.

• 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.
Who should lead the effort to build FNSF?

• Not fair to ask the EU. EU is contributing its fair share for fusion development by taking the lead on ITER and carrying out a very strong program on DEMO with associated extensive R&D program.

• Taking the lead on FNSF is an excellent opportunity for the US to restore a leadership role, enhance contributions to fusion development, and to provide a solution for the rapid erosion of experienced human resource base, and the severe decline in R&D facilities.

• China has made an excellent initiative by introducing CFETR and by rapidly expanding R&D facilities and man-power.
  – CFETR plan has two phases: phase-I is FNSF-type mission with low fusion power (~100 MW) while phase-II is an upgrade of the same facility with much larger power to serve as DEMO. The device is large, comparable to the size of ITER (R \sim 6 \text{ m}).
    FNSF Phase-I in CFETR is important to the world fusion program.

• JA and KO can also take the lead, or contribute to the R&D for FNSF.
Thank You!

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


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


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

Situation we are running into with breeding blankets: **What we want to test (the breeding blanket) is by itself An ENABLING Technology**
COE is a function of plasma performance and is substantially affected by FNST issues most of which have not yet been resolved and technologies not yet developed.

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

**Need Low Failure Rate**

\[
COE = C \cdot i + \text{replacement cost} + O \& M
\]

\[
P_{\text{fusion}} \cdot \text{Availability} \cdot M \cdot \eta_{th}
\]

\[P_f \sim \beta^2 B^4 \cdot \text{Volume}\]

**Need High Temp. Energy Extraction Blanket**

**Need High Availability / Simpler Technological and Material Constraints**

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

\[
\text{(1/failure rate)} = \frac{1}{\text{failure rate} + \text{replacement time}}
\]

M. Abdou, Keynote ISFNT-14, 9-22-2019
Need for High Power Density was realized early. But after 40 years we do not have a way to achieve it!!

- Need High Power Density to improve potential attractiveness of fusion power compared to other energy sources (e.g., fission)

<table>
<thead>
<tr>
<th></th>
<th>PWR</th>
<th>BWR</th>
<th>LMFR</th>
<th>ITER-Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average core power density (MW/m3)</td>
<td>96</td>
<td>56</td>
<td>240</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- The challenges in realizing High Power Density in current fusion concepts are:
  1- Difficulty achieving high power density in the plasma (high $\beta^2 B^4$)
  2- Limitations on power handling capabilities of Current FW/Blanket/Divertor concepts (high wall load and surface heat flux)

- The APEX Study (1997-2003) made a lot of progress in developing concepts with higher wall load/surface heat flux capability: Liquid Surfaces, Solid Tungsten Wall with 2-phase Li (EVOLVE)
  But the highest practical Neutron Wall Load was < 5 MW/m², and Surface Heat flux < 1 MW/m² Still too low for economic competitiveness?

- ITER estimates $\beta$ of only 2%. EUROfusion DEMO using realistic assumptions has $\beta$ of ~ 2%, which leads to Neutron Wall Load of only ~1 MW/m²!!

Alarm: We don’t have a credible pathway to achieve high power density. Current pathway is trending toward even lower power density - unlikely to lead to an economically competitive system.
Need for High-Temperature Structural Material was realized early. *But after 40 years we do not have it!!*

The need for development of structural material with high temperature operational capability was recognized from the very early 1970’s. A range of structural materials were evaluated: Steels, PE-16, ferritic steels, V, Nb, TZM, SiC.

Refractory alloys were initially considered attractive because of high temperature operation (~750 C) and resistance to radiation damage. But detailed investigations ruled them out because:

- Refractory materials are expensive: primarily the cost of the heat transport system/piping. High thermal efficiency cannot offset the cost of piping. (Results of UWMAK-III, 1975; Abdou ICFRM 1979)
- Nb and TZM are high activation
- V is low activation but compatible only with Li (embrittlement by interstitial impurities). But development of MHD insulators for V-Li system failed

So, **only steels remained as the primary option for fusion.** Modified stainless steel (PCA) in the late 1970’s, early 1980’s. Then **ferritic-martensitic steel** (small alloy variation among countries). Limited to ~550 C

2019: Unpleasant surprise: Recent estimate of the cost of EUROFER for FW/Blanket may be $3 Billion!!!

So, after 40 years, the only viable structural material that fusion has now is limited to < 550 C and is very EXPENSIVE!!