Challenges for Nuclear Fusion Science and Technology

Mohamed Abdou

Distinguished Professor of Engineering and Applied Science

Director, UCLA Fusion Science and Technology Center

https://www.fusion.ucla.edu/

With much appreciation to the many scientists and engineers I have worked with over decades!

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Materials Challenges for Sustainable Fission and Fusion Technologies

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City Center
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Introductory Remarks

- Fusion, if it works, will be the ultimate energy source for mankind
- But the Pace of fusion development has been painfully slow
- The reasons for the painful reality that "the time to fusion is 40 years away, and expanding" include:
  - scientific/technological challenges
  - Many programmatic, management, leadership, institutional, and other issues involved in the complex fusion energy development – inflexibility in making timely changes in strategy and pathways

- This presentation will address only scientific/technological challenges. **My focus is on some of 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**

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.

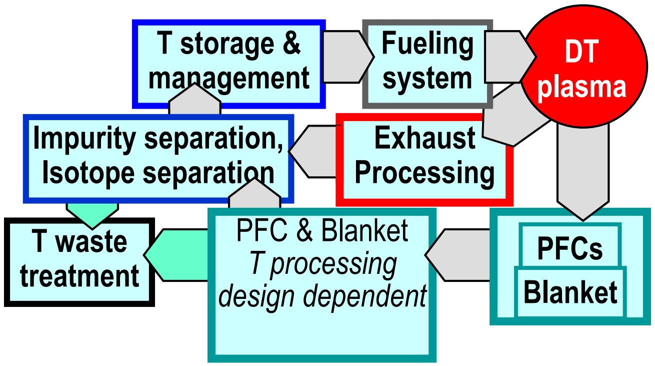
In-vessel Components ("Core")

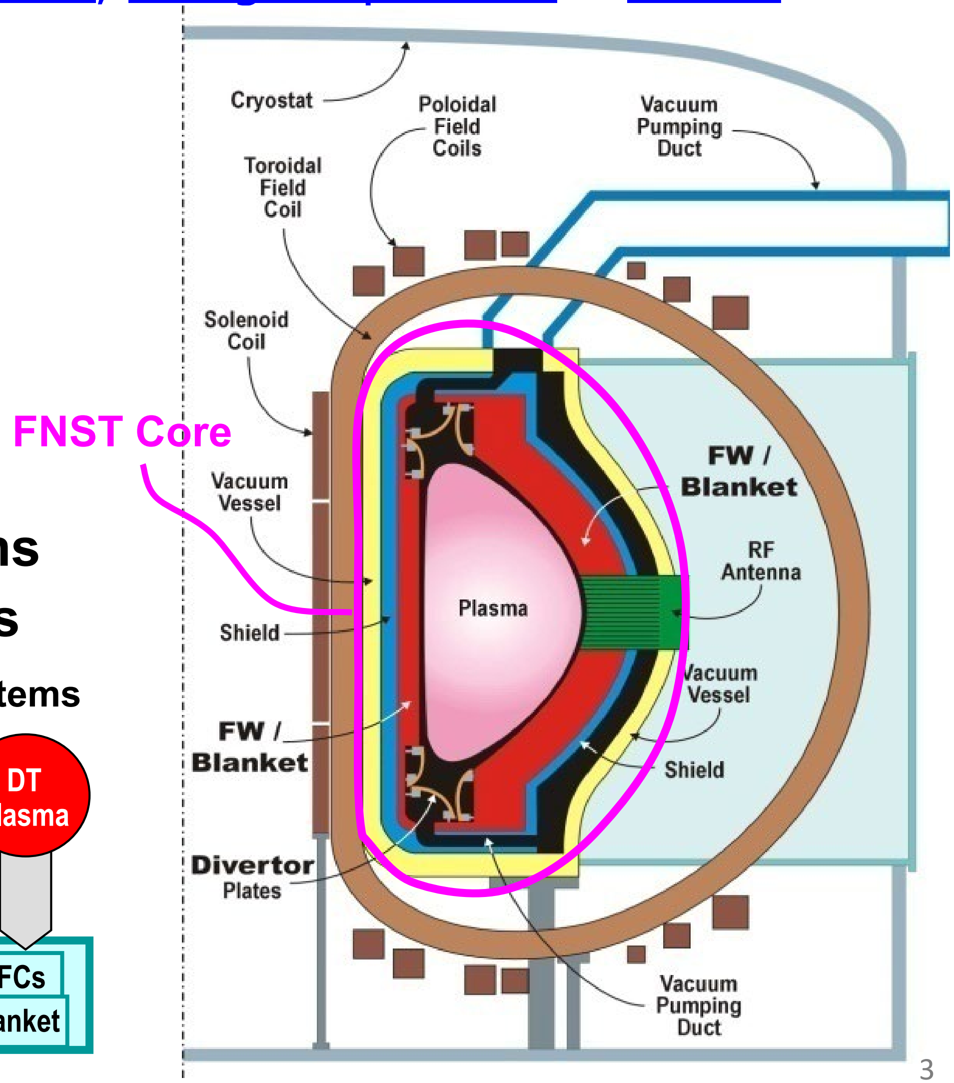
- **Blanket** and **Integral First Wall**
- **Divertor/PFC**
- **Shield** and **Vacuum Vessel**

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)*

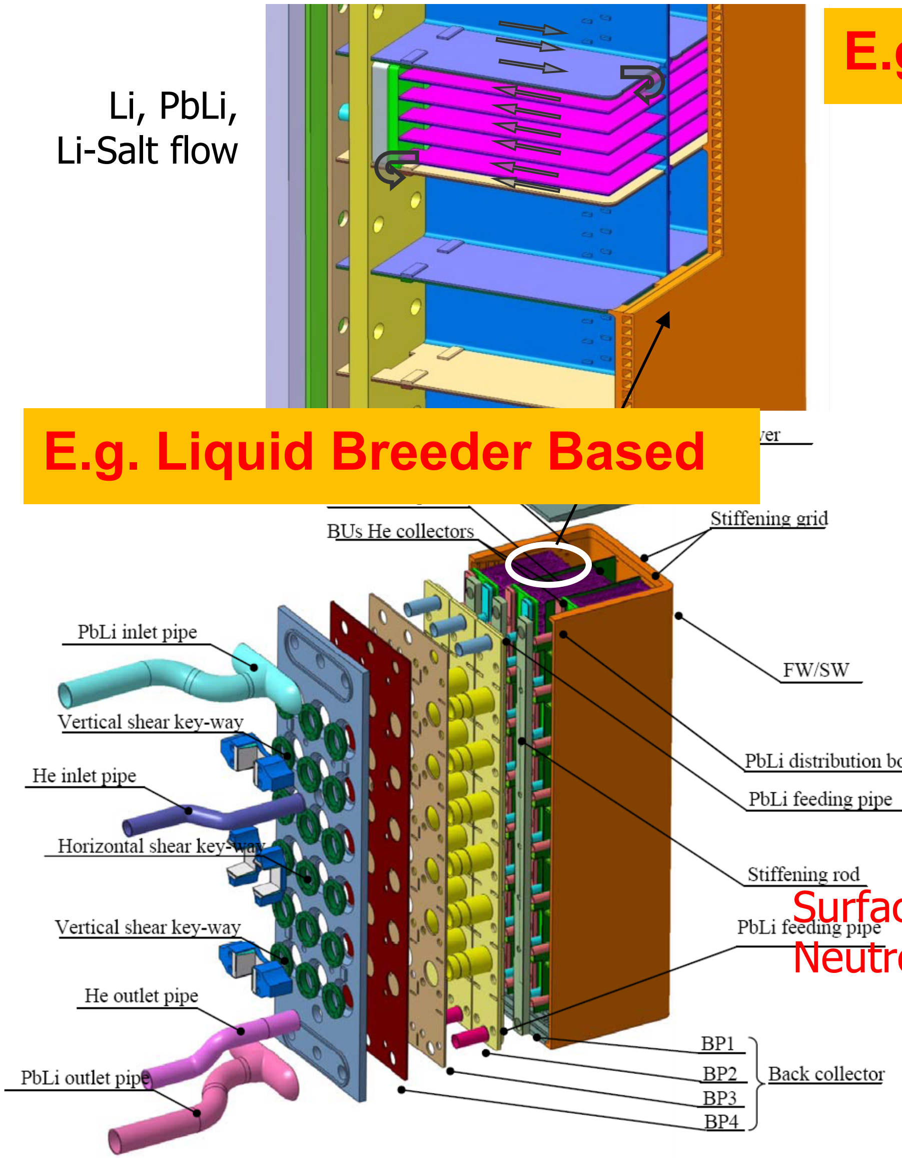
Multiple functions, materials, and many interfaces in highly constrained system

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

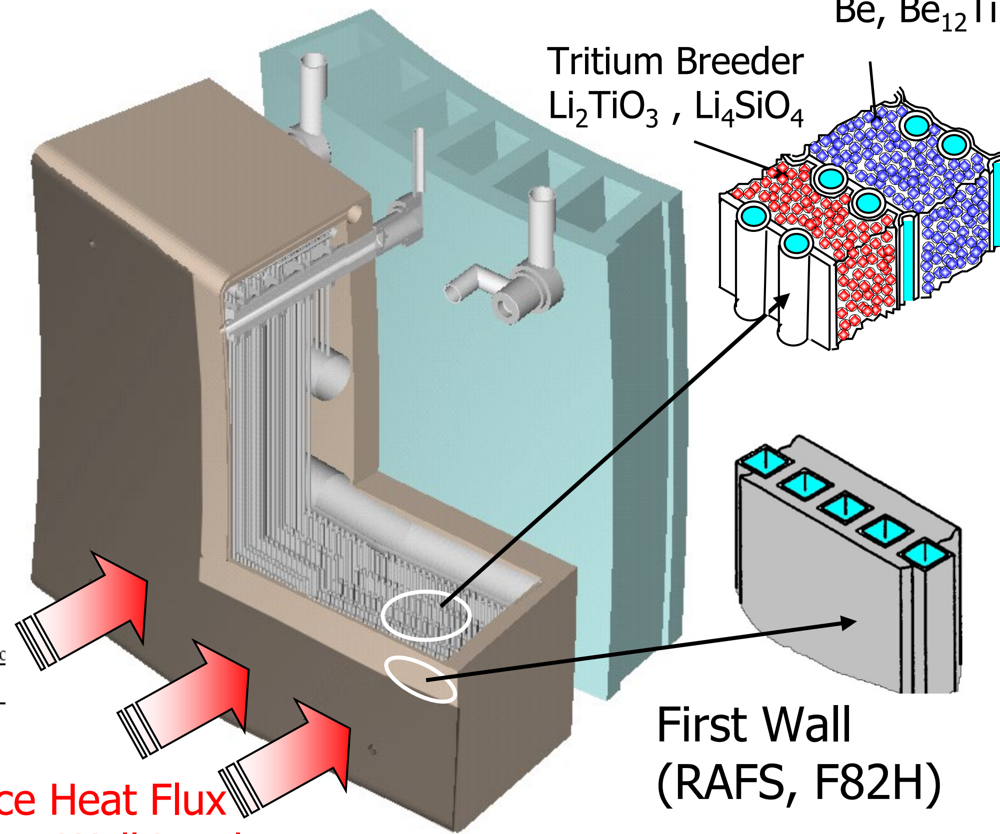
Blanket/FW systems are complex and have many functional materials, joints, fluids, and interfaces

E.g. Liquid Breeder Based

Li, PbLi,
Li-Salt flow



E.g. Ceramic Breeder Based



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

- **<u>The Fusion Nuclear Environment</u>**: 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)*
- **<u>Nuclear heating</u>** 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)*
- **<u>Complex configuration</u>** with FW/Blanket/Divertor <u>inside</u> the vacuum vessel. Makes the fusion system not fault tolerant and challenging to maintain. RAMI is a central issue

Key Challenges/Issues and Required R&D for which progress over the past decades has been frustratingly slow But must be confronted in any serious plan to develop fusion

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3. Tritium Fuel Cycle and Tritium Self-Sufficiency
4. External T Supply and Required T Startup Inventory
5. High Power Density and High Temp. Operation/Economics
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7. Confinement Concepts

Moving forward with

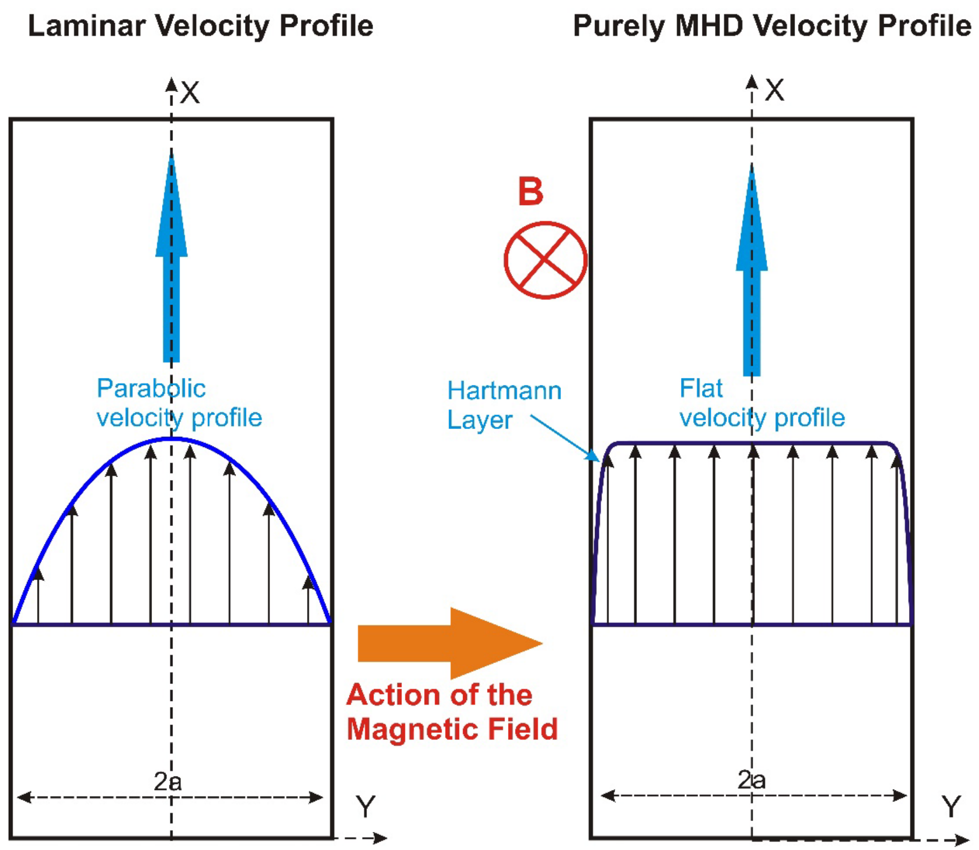
Multiple Effects/Multiple Interactions

Experiments and Modelling is NECESSARY to understand and learn the behavior of blankets in the fusion environment

Example: MHD Thermofluids

For 30 years fusion researchers 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**



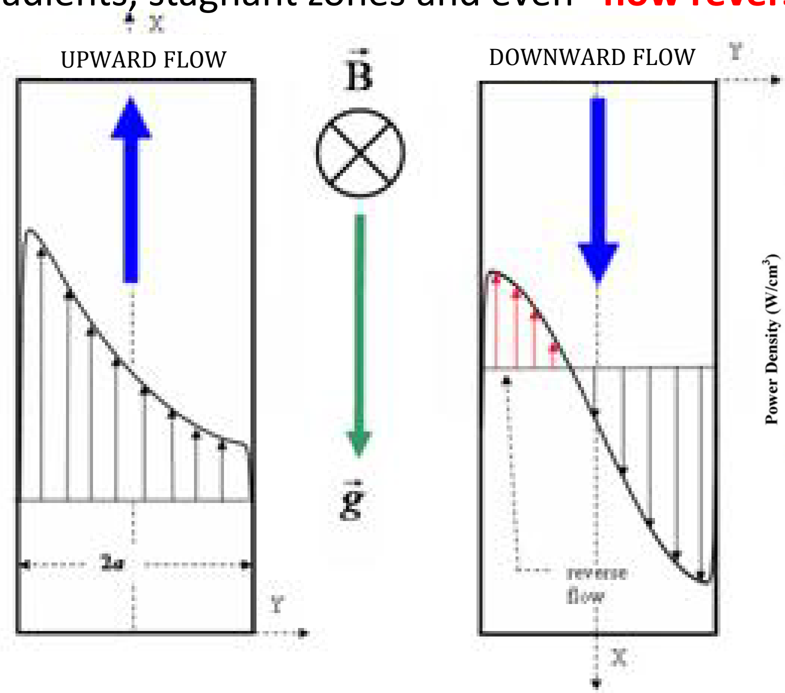
But we just discovered that what we assumed for 30 years is wrong

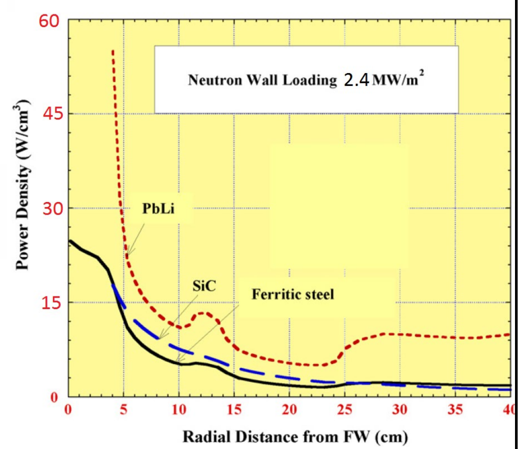
Discovery: Spatial gradients in nuclear heating & temperature in LM blanket combined with $\vec{g}$ and $\vec{B}$ lead to New Phenomena that fundamentally alter our understanding of the MHD Thermofluid behavior, Tritium Transport/Permeation and Materials Interactions in the blanket in the fusion nuclear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

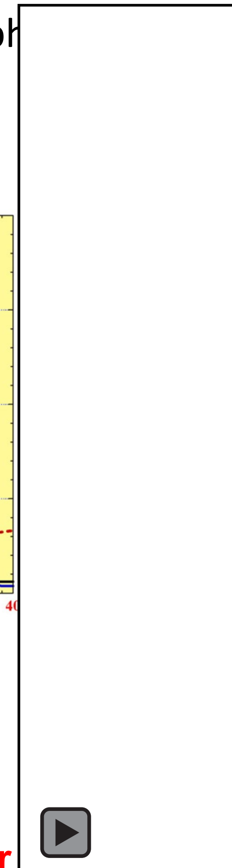
Lead to **Buoyant MHD interactions resulting in an unstable "Mixed Convection" flow regime**

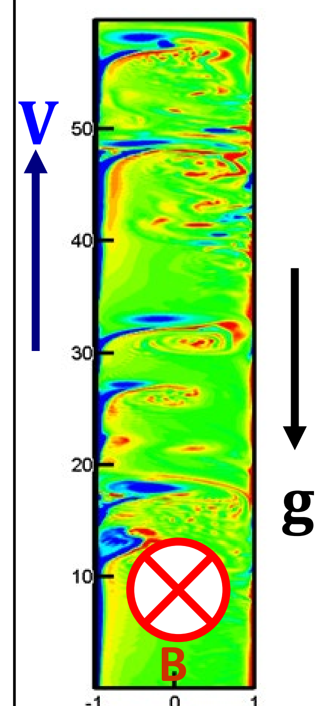
Base flow strongly altered leading to velocity gradients, stagnant zones and even "**flow reversal**"

Vorticity Field shows new **instabilities** that affect transport 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 are at best misleading, and quite often simply wrong**
- **Blankets designed with current knowledge of phenomena and data will not work**

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

DEMO BLANKET: $Ha \sim 10^4$, $Gr \sim 10^{12}$, $Re \sim 10^5$

EXPERIMENT: $Ha \sim 10^3$, $Gr \sim 10^9$, $Re \sim 10^5$

Grand Challenge

Since blankets in DEMO/Power Reactors have very high parameters (e.g. Ha, Gr) that cannot be reached in laboratory, **how do we scale results from experiments to predict Blanket behavior in DEMO?**

- Non-linear phenomena (difficult to scale)
- Higher Ha will suppress 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?**

Encouraging recent progress in Multiple Effects/Multiple Interactions R&D

- Very few multiple effects/multiple interactions 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.

Recent Lesson Learned

- Multiple Effects/Multiple Interaction facilities and experiments are much more complex than those for separate effects
- They require long time, expensive equipment, substantial experiment planning, complex instrumentation all accompanied by intensive 3D modeling effort. This means substantially more resources will be required going forward and funding agencies need to understand this need

Key Challenges/Issues and Required R&D for which progress over the past decades has been frustratingly slow But must be confronted in any serious plan to develop fusion

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Reliability/Availability/Maintainability/Inspectability (RAMI)

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

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 <u>an assumed number</u> 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))**
  - **<u>The results of this IEA HVPNS Study were very alarming. They show that RAMI is the Achilles' Heel issue for fusion</u>**

Reliability/Availability/Maintainability/Inspectability (RAMI) is a serious challenge that has major impact on engineering feasibility and economics

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
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.884
Fueling	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.998
Tritium System	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.995
Vacuum	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.998
Conventional equipment - instrumentation, cooling, turbines, electrical plant							[illegible]	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 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!!

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.*

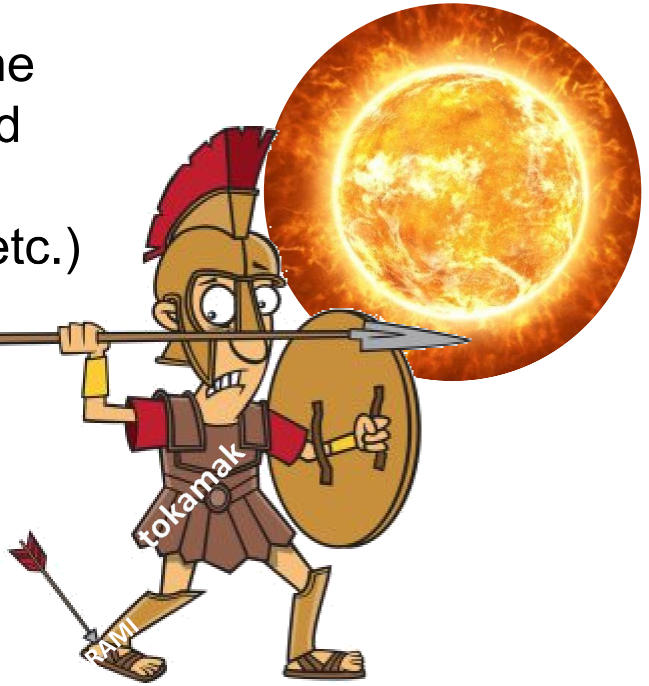
- Large surface area of the first wall results in high failure rate for a given unit failure rate per unit length of piping, welds, and joints → ***short MTBF***

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:

- 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

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

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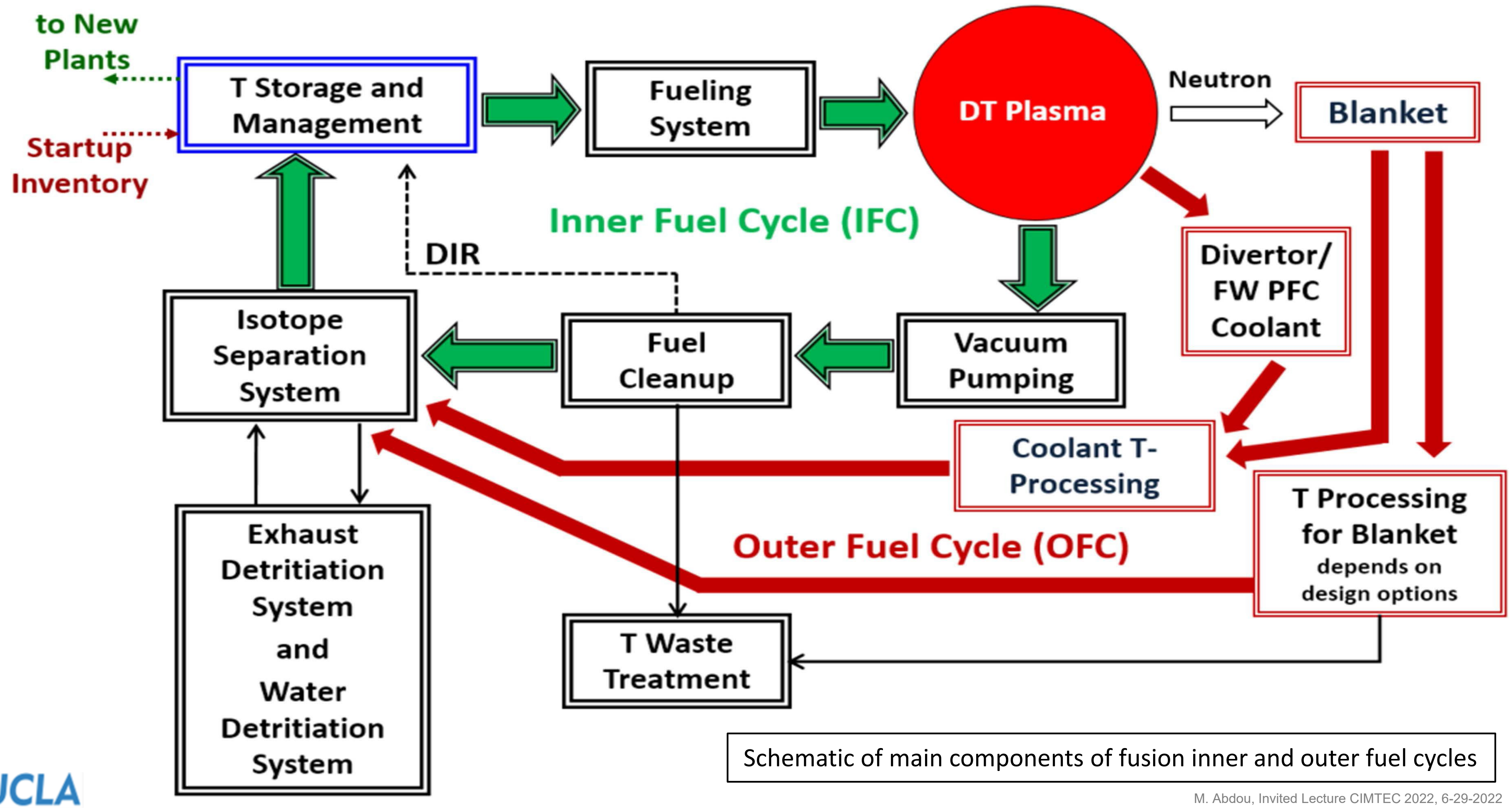
Tritium Fuel Cycle: Dynamic models developed & advanced since 1986 to calculate time-dependent tritium flow rates and inventories and required TBR

- 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 2022: more challenging issues and R&D remain (See Paper in Nuclear Fusion 2021:
    - Mohamed Abdou *et al* 2021 *Nucl. Fusion* **61** 013001



Schematic of main components of fusion inner and outer fuel cycles

Issues in Achieving Tritium Self-Sufficiency Condition : Achievable TBR ≥ Required TBR

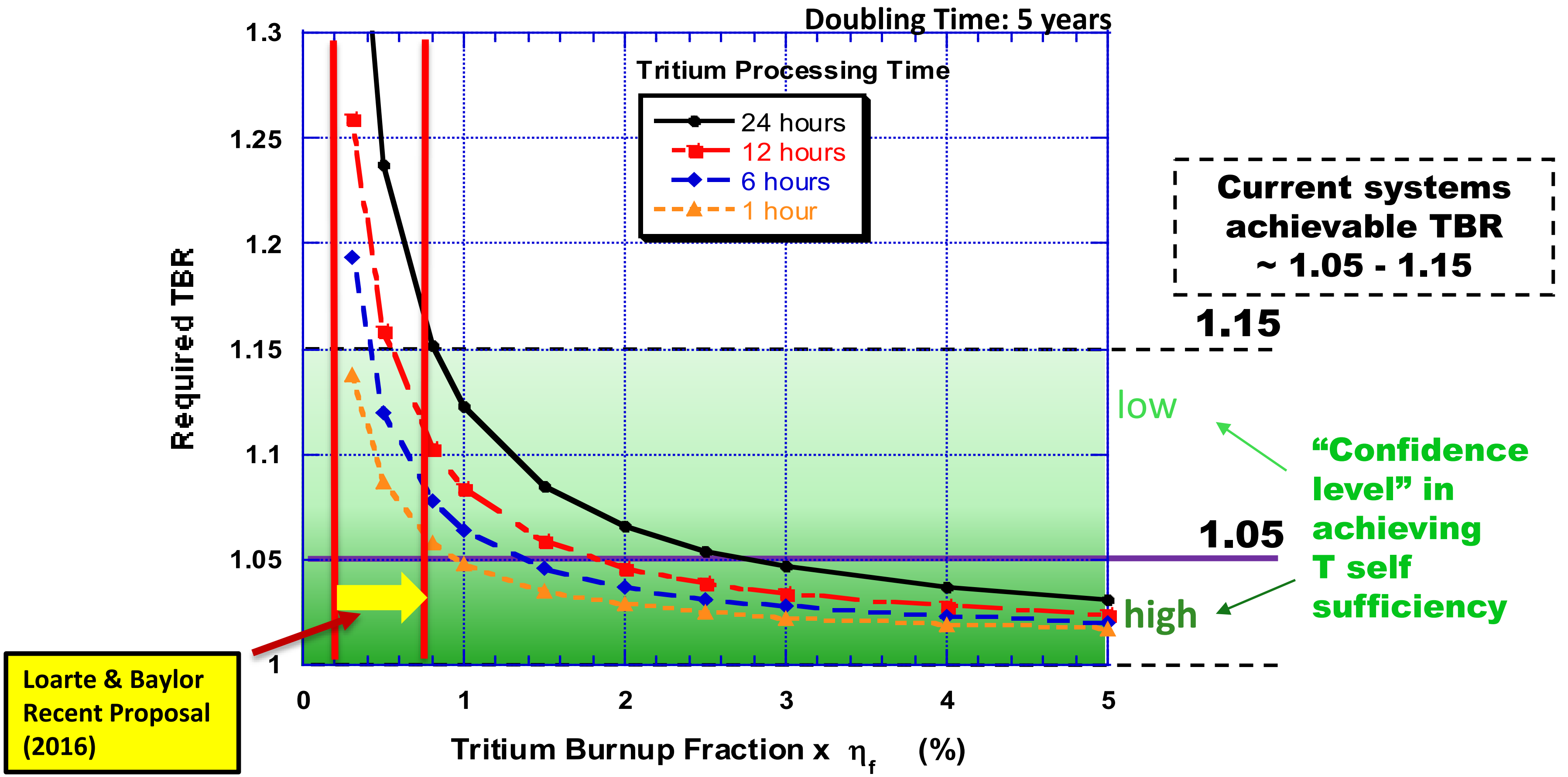
Achievable TBR

- 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 ~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

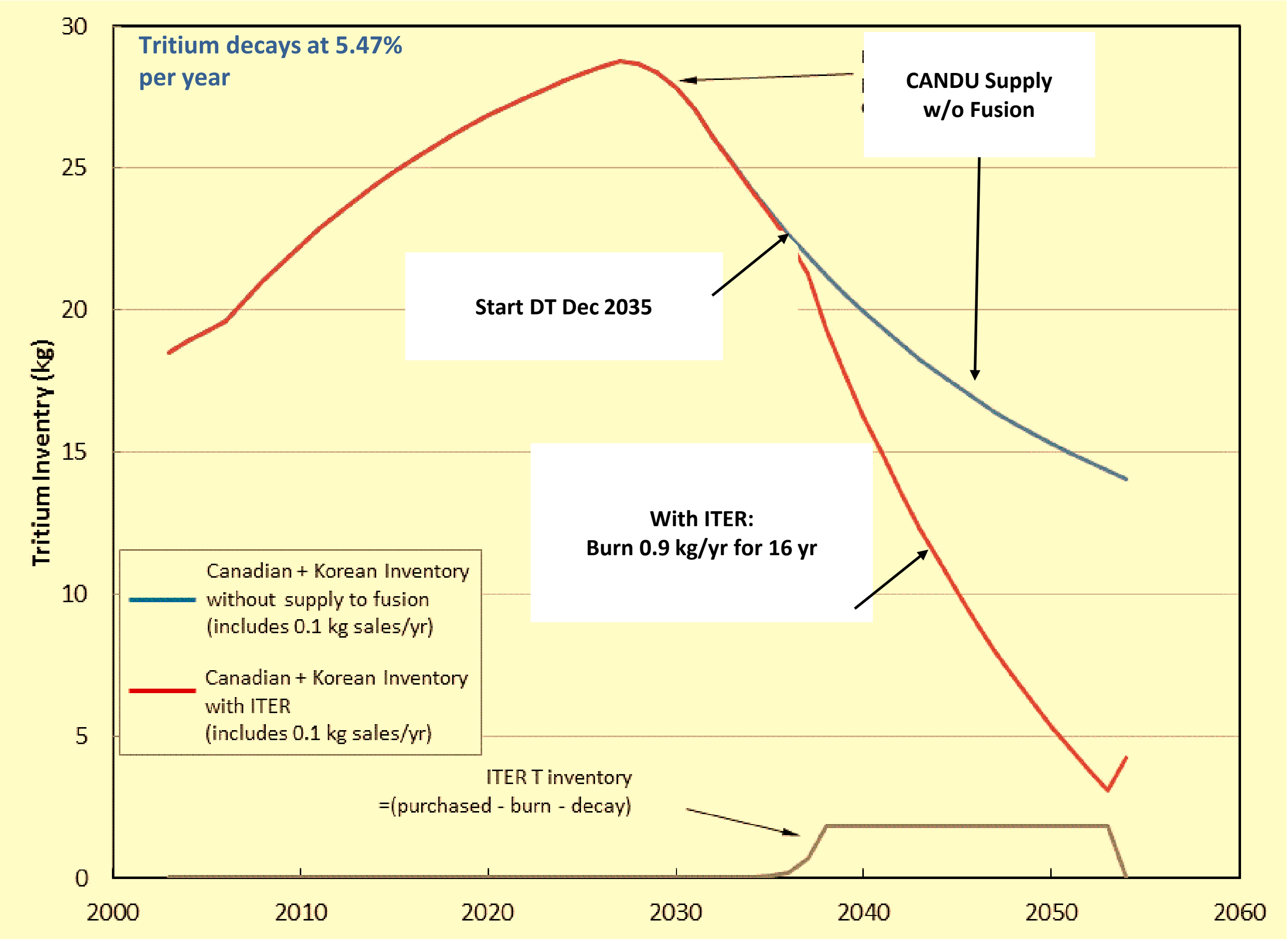


State of the art (ITER: f_b ~0.35%, η_f < 50%) achieving T self-sufficiency is <u>Unlikely</u>.

To change this to <u>Likely</u>, we must:

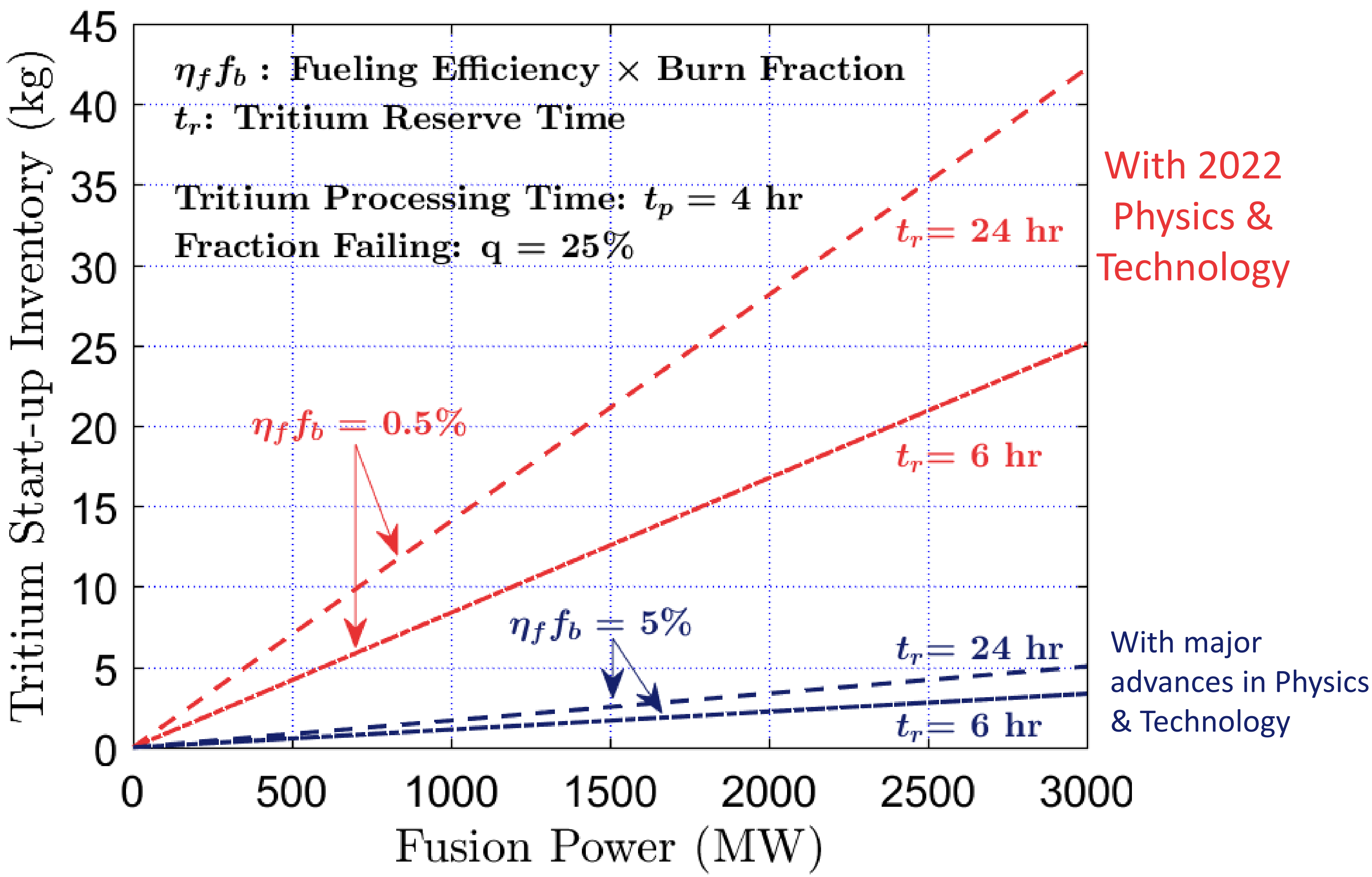
- **Lower Required TBR:** R&D to achieve $f_b \times \eta_f$ > 5% and t_p< 6 hours **(how to get there?)**
- **Increase Achievable TBR:** Reduce structure and non breeding materials, etc.&

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

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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)

	PWR	BWR	LMFR	ITER-Type
Average core power density (MW/m3)	96	56	240	**0.4**

- 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/m^2, and Surface Heat flux < 1 MW/m2 **Still too low for economic competitiveness?**
- **ITER estimates β of only 2%. EUROfusion DEMO using realistic assumptions has β of ~ 2%, which leads to Neutron Wall Load of only ~1 MW/m^2 !!**

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

2022: Unpleasant surprise: Recent estimate of the cost of EUROFER for FW/Blanket in one DEMO 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!!

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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/m^2 on 10-20 m^2 test area. Only inside the vacuum vessel (FW/Blanket/divertor modules) need to be prototypical. Plasma can be highly driven, Q ~ 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: <u>Two facilities are faster, less expensive, and more practical than one facility!!!</u>

Launching an initiative to build FNSF soon is good for ITER, good for DEMO, good for fusion

- **In 2022:** 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.

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

Key Challenges/Issues and Required R&D for which progress over the past decades has been frustratingly slow But must be confronted in any serious plan to develop fusion

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
5. High Power Density and High Temp. Operation/Economics
6. Construction and operation of a facility in which the fusion nuclear components inside the vacuum vessel can be tested and developed in the true fusion nuclear environment (FNSF, VNS, CTF, or whatever you call it)
7. **Confinement Concepts**

Confinement Concepts

- **In the 1970's:** three confinement concepts (theta-pinch, mirrors, and tokamaks) were competing. By late 1970's, only tokamaks and mirrors.
- Some other "innovative confinement concepts" (e.g. FRC, Spheromak) have been pursued since the 1970's with a small budget up and down until now.
- Stellarator was considered from the 1950's and nearly abandoned, but gained momentum the past decade because of some physics success, and construction of W-7.
- **In 2022: Only the "Tokamak"** is considered in plans of all countries **for DEMO**.
  - But many scientists/engineers have concerns about its ultimate suitability for a competitive, maintainable fusion energy system. Stellarator is a back-up but shares many of the "go-no go" issues of tokamaks.

Not a good situation. What do we do now?

- Continue to work with the confinement concept we have and finish ITER
- But aggressively encourage innovative research to discover/invent an attractive fusion confinement concept with much higher potential for commercialization (e.g. simplicity of configuration, better maintainability, more manageable RAMI problems, and higher power density)

Summary (1 of 2)

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 2)

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 an 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.

Concluding Remarks

- Pace of fusion development has been too slow.
- Regardless of the reasons for this, the negative effects on the perception of fusion outside the community and the confidence and enthusiasm inside the community are obvious.
- We can not continue to talk about issues we know how to solve and ignore critical go/no-go problems that we don’t know yet how to solve.
- It is time for all of us to bring in **ingenuity, experience, determination**, and **honest critical thinking**, and to **ask for a more effective, more agile management and leadership,** to develop a credible strategy for solving them and begin serious implementation at a much faster pace– *than over these past 40 years.*

Thank you!