Challenges in the DT Cycle Physics and Technology: T Self Sufficiency and start-up tritium inventories and major impact on defining the R&D pathways to DEMO and beyond

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

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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 the critical go/no-go multidisciplinary issues for the DT Fuel Cycle 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.

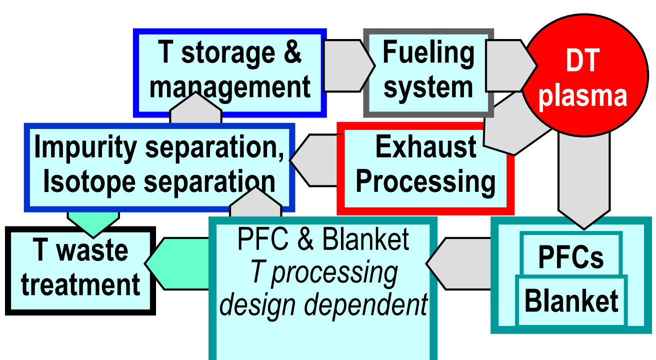
In-vessel Components ("Core")

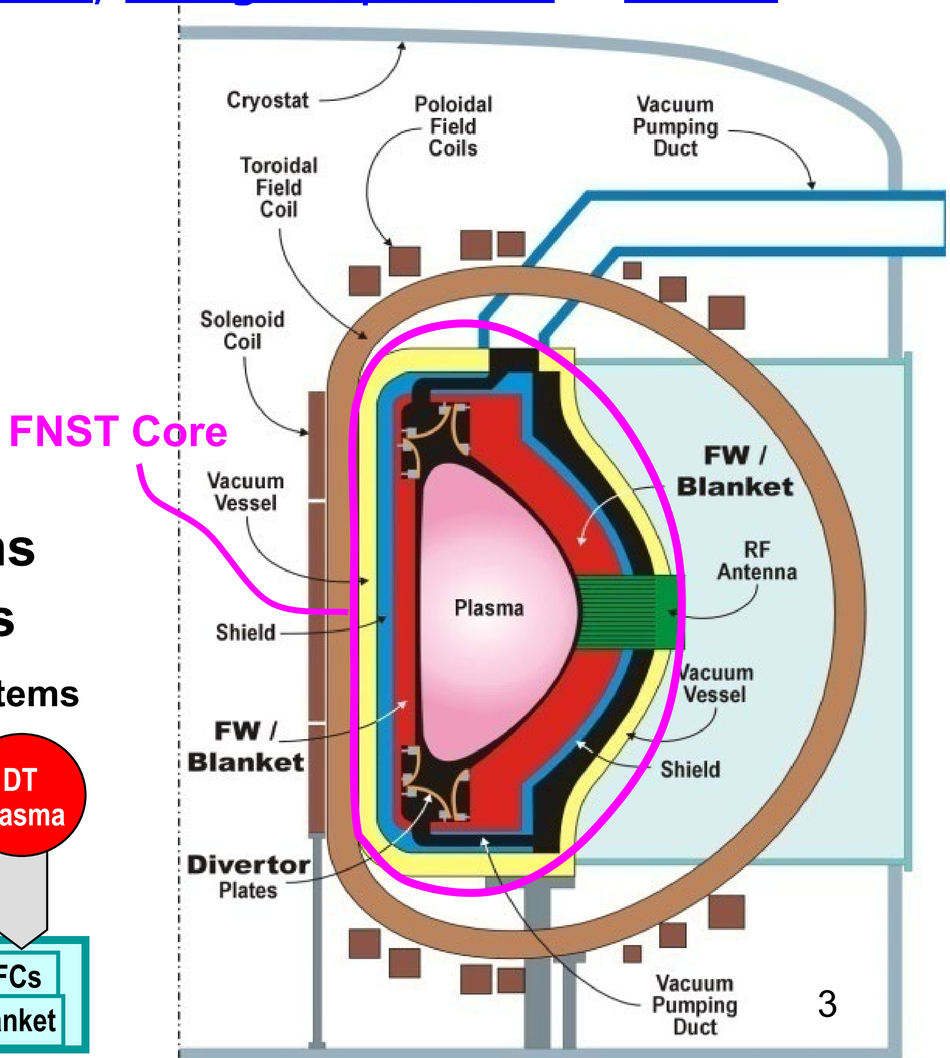
- **Blanket** and **Integral First Wall**
- **Divertor/PFC**
- **Shield** and **Vacuum Vessel**

Other Nuclear Systems

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

Tritium Fuel Cycle pervades entire fusion system





In D-T Fusion Systems, Tritium plays a Dominant Role

Major Areas of highest importance:

1. **Tritium Flow Rates and Inventories**
   - **Accurate calculations of time-dependent tritium flow rates and inventories in a fusion facility are essential for determining the characteristics of the fuel cycle**
2. **Tritium Startup Inventory**
   - **Initial startup inventory is necessary for any DT fusion facility**
3. **Tritium Self-Sufficiency**
   - **Absolutely required for D-T Fusion Energy Systems to be feasible**
4. **Safety**
   - **Tritium Inventories, permeation and release are key aspects of safety analysis**

All these areas have complex dependence on many plasma physics and fusion technology parameters/ conditions. Calculations/Analysis require detailed Dynamic Modelling of the T fuel Cycle

At present, there are very critical issues and uncertainties in providing the "startup" tritium inventory and attaining T self-sufficiency that require success in challenging R&D

- **Success can not be assured, but it definitely requires 1- "effective partnership" between plasma physicists and fusion technologists (e.g. in areas of plasma fueling, plasma dynamics and edge physics, tritium processing, and blanket/FW/PFC), and 2- Changing the current pathway and sequence of DT devices toward DEMO and power plants**

Tritium Consumption and Production

Tritium Physical constants

- Half life: 12.32 yr; Mean Life: 17.77 yr; 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 or any facility constructed and operated > 20 years from now**

Tritium Consumption in Fusion Systems is Huge

55.8 kg per 1000 MW fusion power per year

For 3000 MW Fusion Power Plant (~1000 MWe)

167.4 kg/year; 0.459 kg/day; 0.019 kg/hour

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

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

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

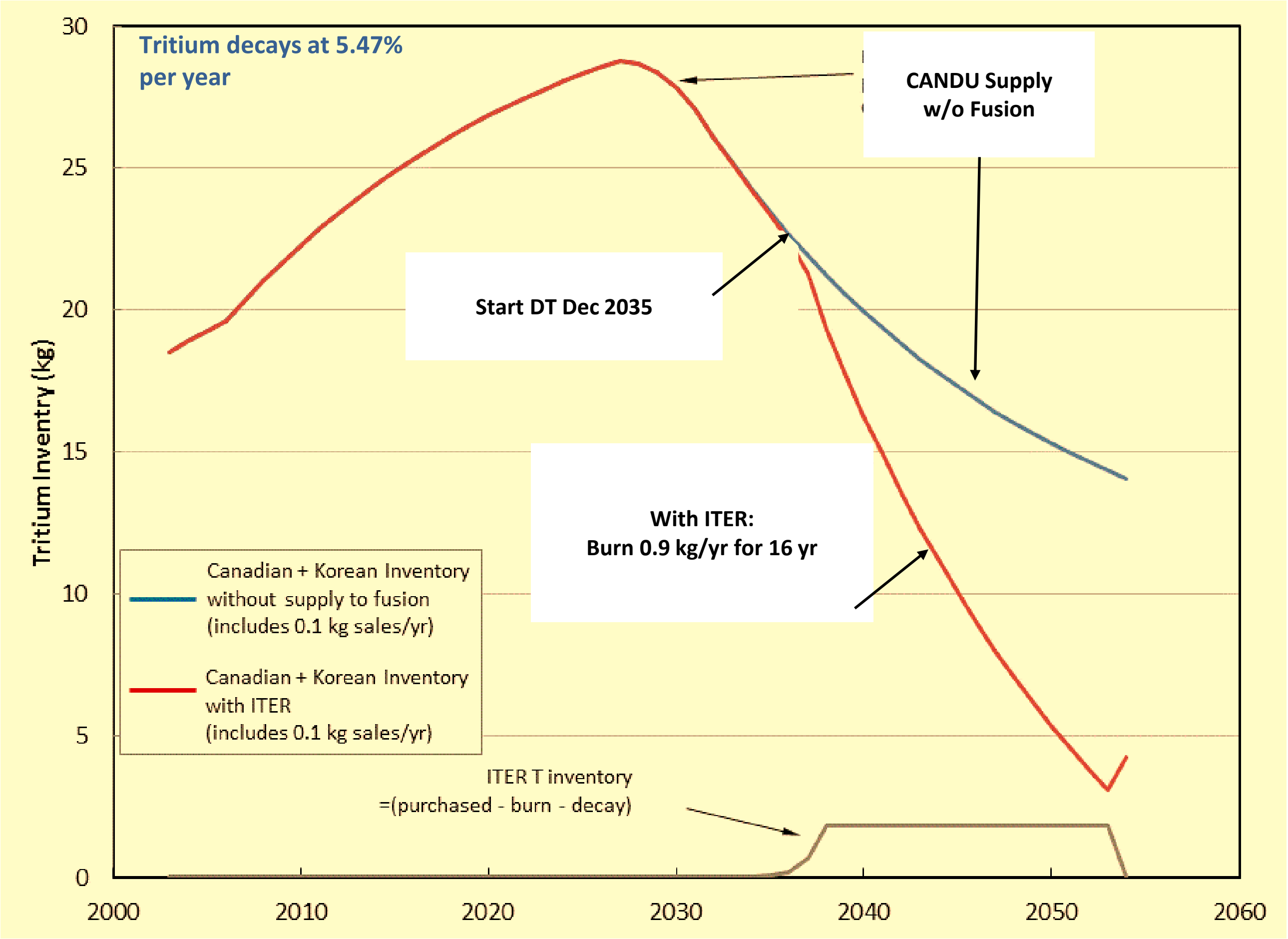
Typical CANDU produces ~ 130 g per year ***(0.2 Kg per GWe per full power year) (T is unintended by product)***

CANDU Reactors/Ontario Hydro: 27 kg from over 40 years, $30M/kg (current)

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 external non-fusion supply of 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!



Tritium self-sufficiency condition:

$TBR_a \geq TBR_r$

TBR_a= Achievable tritium breeding ratio (what is actually produced in the blanket)

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

TBR_r = Required tritium breeding ratio (what is required to keep the plant running)

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

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

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

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Dynamic Modelling of the D-T Fuel Cycle

- Dynamic Modelling and Analysis of the DT Fuel Cycle was started (at UCLA) 35 years ago and **is still ongoing** because it is essential to quantify the "startup" T inventory and T self-sufficiency requirements. Results have had a huge impact on the R&D pursued for physics, fueling, tritium processing, safety, as well as blanket/FW/PFC design and breeding requirements
- As progress was made in the physics and technology of the DT Cycle, the Dynamic Modelling/analysis went through major improvements every several years.
- An important aspect of this work has been direct interactions with plasma physicists, tritium processing experts, fueling technology developers, and others to provide input on critical R&D advances required beyond the state of the art
  - Important successes have been achieved in some areas, and promising solutions have been proposed in other areas.
  - But much more challenging advances are still required. These can be realized only by **intense R&D coordinated worldwide among plasma physicists, plasma support technologists, and FNST scientists/engineers.**

A Comprehensive Review Article Recently Published in J. of Nuclear Fusion

Mohamed Abdou, Marco Riva, Alice Ying, Christian Day, Alberto Loarte, L.R. Baylor, Paul Humrickhouse, Thomas F. Fuerst and Seungyon Cho

“**Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency**”

2021 *Nuclear Fusion* **61** 013001

Web link: https://iopscience.iop.org/article/10.1088/1741-4326/abbf35

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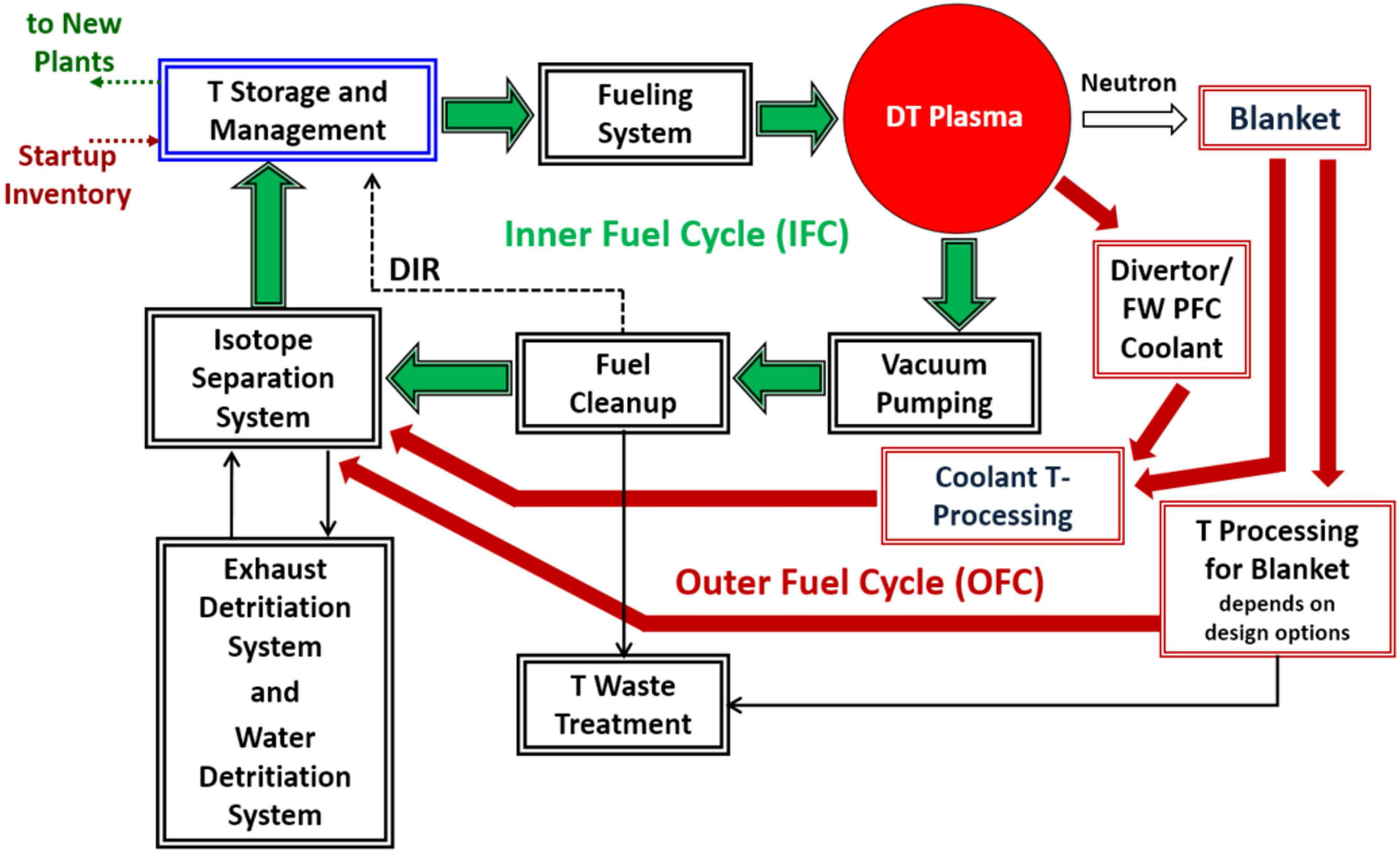
The Nuclear Fusion Article is a comprehensive review and analysis of the state-of-the art and required R&D for the physics and technology of the DT Cycle

- Co-authored by 7 experts and world leaders in plasma physics, fueling technology, tritium processing, blanket, and safety
- Comprehensive, 50 journal pages, 194 references, and Detailed Table of Contents to help readers navigate through the many complex topics.

Topics and Sections of the Paper:

1. Description of the Fuel Cycle
2. Dynamic Fuel Cycle Models to determine time-dependent Tritium Flow Rates and Inventories, and perform Self-Sufficiency Analysis and Start-up Assessment
3. Tritium Inventories and Self-Sufficiency Analysis
4. Calculation of the Required Tritium Start-up Inventory and Assessment of the Availability of External Tritium Supply for Start-up of near- and long-term Fusion Facilities
5. Plasma Physics Aspects of the Tritium Burn Fraction and Predictions for ITER and Beyond
6. Plasma Fueling Technology and Predictions of Fueling Efficiency for ITER and DEMO Based on Experiments and Modelling
7. Tritium Safety
8. Options for Tritium Fuel Cycle Technology for DEMO and Required R&D



Simplified Schematic of the D-T Fuel Cycle

Dynamic Modelling Results show that the Key Parameters Affecting Tritium Inventories, T Startup Inventory, and Required TBR are:

1) Tritium burn fraction in the plasma (f_b)
2) Fueling efficiency (η_f)
3) Time(s) required for tritium processing of various tritium-containing streams (e.g. plasma exhaust, tritium-extraction fluids from the blanket), t_p
4) Device Availability Factor, AF (major impact when Availability is <30%)
5) "Reserve Time", i.e. period of tritium supply kept in "reserve" storage to keep plasma and plant operational in case of any malfunction in a part (q) of any tritium processing system
6) Parameters and conditions that lead to significant "trapped" inventories in reactor components (e.g. in divertor, FW); and Blanket inventory caused by bred tritium released at a rate much slower than the T processing time
7) Inefficiencies (fraction of T not usefully recoverable) in various tritium processing schemes, ε
8) Doubling time for DT fusion facilities (time to accumulate surplus tritium inventory sufficient to start another fusion facility)

Before discussing the results of the dynamic modeling, let us ask:

What is the State-of-the-Art for these Key Parameters that greatly affect Tritium Inventories, T Startup Inventory, and Required TBR ?

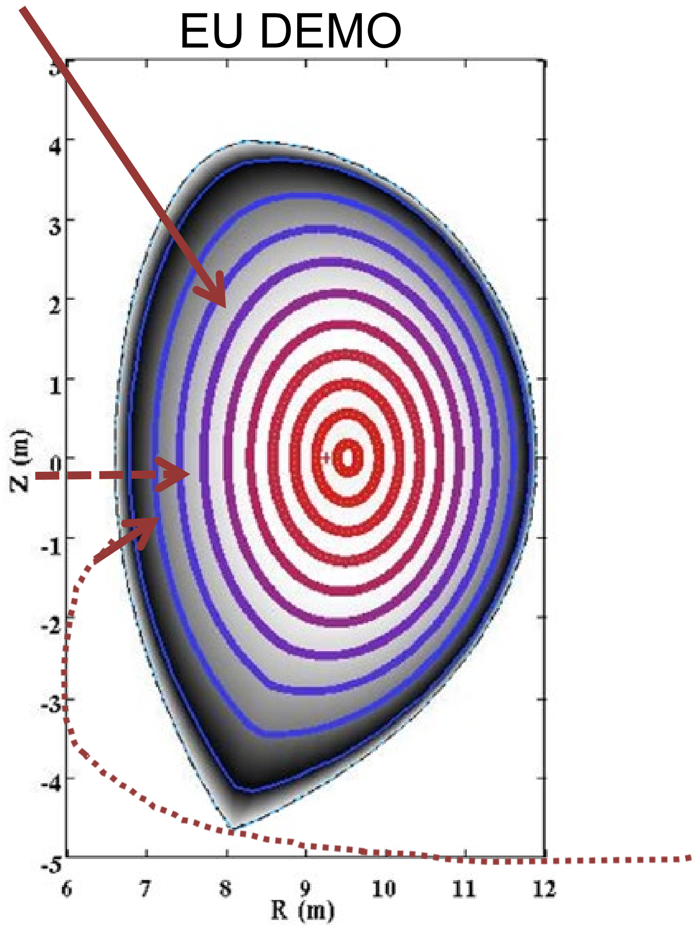
This is what I will summarize in the next several slides based on extensive evaluation that we presented in the Nuclear Fusion Paper

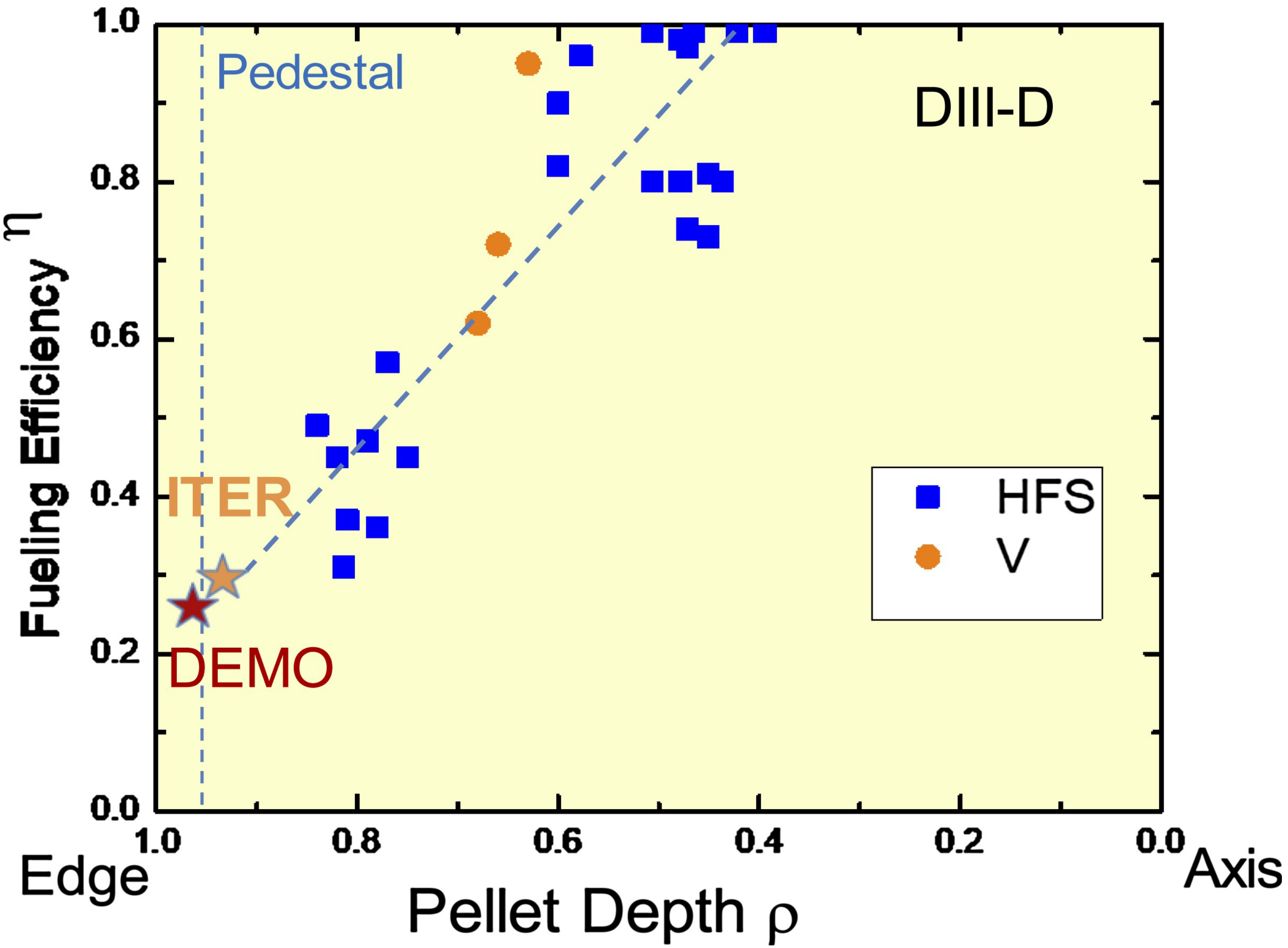
(2021 Nuclear Fusion 61 013001)

Fusion Fueling Efficiency (Summary from Larry Baylor)

Gas fueling/recycling in a reactor relevant regime is expected to be extremely poor and not very useful for getting DT fuel into the core plasma: recycling coefficient from the edge: R~0

- Higher fueling efficiency can be achieved with a suitable high speed High-Field Side (HFS) pellet injection in a tokamak DEMO
- ELM impact on HFS pellet fueling efficiency remains an open question
- The pellet fueling efficiency studies that have been performed on existing experiments point to reduced efficiency with shallow penetration as expected in a burning plasma





Fueling Efficiency Extrapolation from Deep to Shallow Penetrating Pellets Expected in ITER and DEMO is Highly Uncertain. Extrapolation shows <u>fueling efficiency η < 25% in ITER and even lower in DEMO</u>

Serious Consequences for required T start up and self-sufficiency

Tritium Burn Fraction (f_b)

f_b = fusion reaction rate / tritium fueling rate

tritium injection rate = $\dfrac{\text{fueling rate}}{\text{fueling efficiency } (\eta_f)} = \dfrac{\text{fusion reaction rate}}{f_b \eta_f}$

η_f = fueling efficiency = fraction of injected fuel that enters and penetrates the plasma

Need to minimize tritium injection rate: Need high η_f and high f_b

- An expression for f_b can be derived as $\mathbf{f_b = 1/(1 + \dfrac{2}{n\tau^* < \sigma v >})}$

$\tau^* = \tau / (1 - R)$ where R = recycling coefficient from the edge (that penetrates the plasma)

τ = particle confinement time

Status

- Reactor Studies since the 1980's assumed R=0.95 in order to get very high f_b of ~30 - 40%
  - This was an assumption with no theoretical or experimental evidence to support it
- But recent Experimental Results show that **gas fueling is highly inefficient, very ineffective: R~0**
- Reactor studies must change the unfounded assumption of R~0.95 to R~0 and confront the issue of extremely low R, low f_b
- **For ITER, f_b ~0.35%** Extremely low and we have raised loud alarms repeatedly –not acceptable
- Therefore, intense research and innovative ideas by plasma physicists to substantially increase burn fraction to at least 10% are required with highest priority for feasibility of DT fusion

Plasma Physics Aspects of Tritium Burn Fraction & Prediction for ITER (1/2) (Summary from Alberto Loarte et al)

- ITER systems (pellet and gas fueling) and total throughput (200 $Pam^{-3}s^{-1}$) provide appropriate flexibility to achieve Q = 10 mission by providing core plasma fueling, helium exhaust and edge density control for power exhaust (including ELM control)
  - $\Gamma_T^{burn} = 0.35\ Pam^{-3}s^{-1}$ $\qquad \Gamma_T^{fueling} = 100\ Pam^{-3}s^{-1}$

f_b □ $\Gamma_T^{burn} / \Gamma_T^{fueling}$ = **0.35 %**

This assumes all fueling (gas+pellet) done with 50-50 DT

- Fueling requirements for edge/power load control and ELM control dominate total throughput and can require up to 130 Pam^3s^{-1} → requirements for He exhaust are less demanding (~ 40 Pam^3s^{-1} out of a maximum of 200 Pam^3s^{-1})

- Recycling fluxes and gas puffing expected to be very ineffective in ITER to fuel the core plasma → edge and core D/T mixes should be decoupled
  - **T-burn can be optimized by using only T for core fueling with HFS pellets and D for edge density/power load/ELM control**
  - $\Gamma_T^{burn} = 0.35\ Pam^{-3}s^{-1}$, $\Gamma_T^{fueling} = 15\text{-}30\ Pam^{-3}s^{-1}$ →

$f_b = \Gamma_T^{burn} / \Gamma_T^{fueling}$ = **1.2 - 2.3 %**

Plasma Physics Aspects of Tritium Burn Fraction & Prediction for ITER (2/2)

- Achievable T-burn fraction optimization in ITER depends mostly on two uncertain physics issues:
  1. Required edge density (and associated gas fueling) to achieve power load control (i.e. power e-folding length λ_p)
  2. Fueling requirements to achieve ELM control (i.e. throughput associated with pellet pacing for ELM control and pellet+gas fueling associated with ELM control by 3-D fields)
- DEMO fueling and T-burn expected to be similar to ITER except:
  - ✓ Pellet deposition more peripheral than in ITER → pellet efficiency may be reduced due to more likely triggering of ELMs after injection of fueling pellets

Tritium Processing Time, t_p

- In 1986, **TSTA** at LANL demonstrated tritium processing time, t_p~24 hours
- Reactor Design Studies in the 1970's to 2000's assumed t_p similar to that from TSTA
- Dynamic Fuel Cycle Modelling results showed the extreme importance of achieving short t_p << 6 hours
- **ITER** has a tritium fuel cycle comparable to DEMO for plasma exhaust processing but with big differences in tritium inventories, plasma duty cycle, and plant duty factor
- From the early stages of ITER, the ITER Tritium Plant designers (Glugla, Willms, others) have been aware of the results of the Dynamic Fuel Cycle Modelling. They set an ambitious goal for t_p . Further advances are also being explored in EUROfusion for DEMO (Chris Day et al) and other world programs.
- **State-of-the-art prediction for DEMO and beyond:**
  - **t_p~2-6 hours likely achievable**

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 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 is needed 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**

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 very 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	16	5×10^{-6}	23	10^{4}	240	0.1	0.098	0.91
P C	[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 equi [illegible]							[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***

Detailed 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

Summary of the State of the art predictions for ITER, DEMO, and beyond with extrapolations from what we know now

Fueling Efficiency, η

- **Highest is with pellet fueling (from HFS). Extrapolation shows maximum is**

  η < 25%   (in ITER and even lower in DEMO)

Tritium Burn Fraction (TBF) , f_b

- With all fueling (gas+pellet) done with 50-50 DT : **f_b ~ 0.35%**
- With Loarte's idea: **using only T for core fueling with HFS pellets and D for edge density/power load/ELM control f_b ~ 1.2 - 2.3%**

Tritium Processing Time, t_p

With all recent advances in tritium processing technologies: t_p~2-6 hrs

Device Availability Factor, AF

Predicted availability, AF, is very low < 5%. Anticipated MTBF is hours/days (required is years), and MTTR is 3-4 months (required is days), and availability is very low < 5%. Reliability Growth will take very long time, a sequence of DT devices

Achievable TBR

Maximum achievable TBR with the current concepts is 1.05-1.15

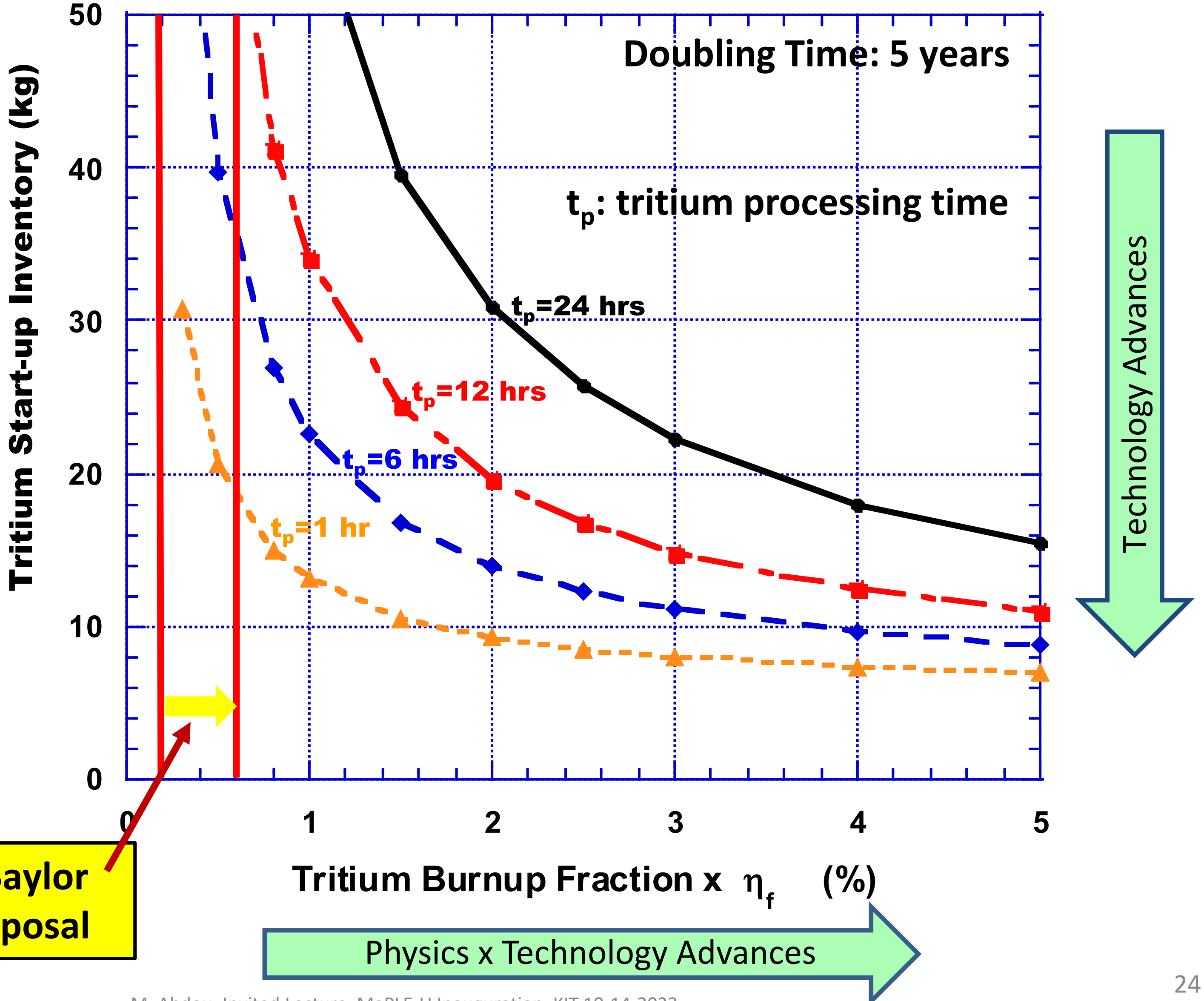
- uncertainties in the achievable TBR cannot be resolved without testing a full blanket sector in a plasma-based device

Results: **The required startup tritium inventory for DEMO and power plants is very large even if we assume success of recent ideas to increase fueling efficiency and T burn fraction, and promising advances in tritium processing time from the plasma exhaust.**
Major Improvements beyond known ideas are still needed/mandatory – Not clear how

With state-of-the-art
Startup inventory is > 50 Kg

With recent proposal for advances:
- Burn fraction ~ 2.3 %
- HFS fueling efficiency ~ 25 %
- t_p ~ 2 – 6 hrs

Startup inventory is ~ 15- 30 Kg
Still huge and very Problematic for self-sufficiency and safety



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

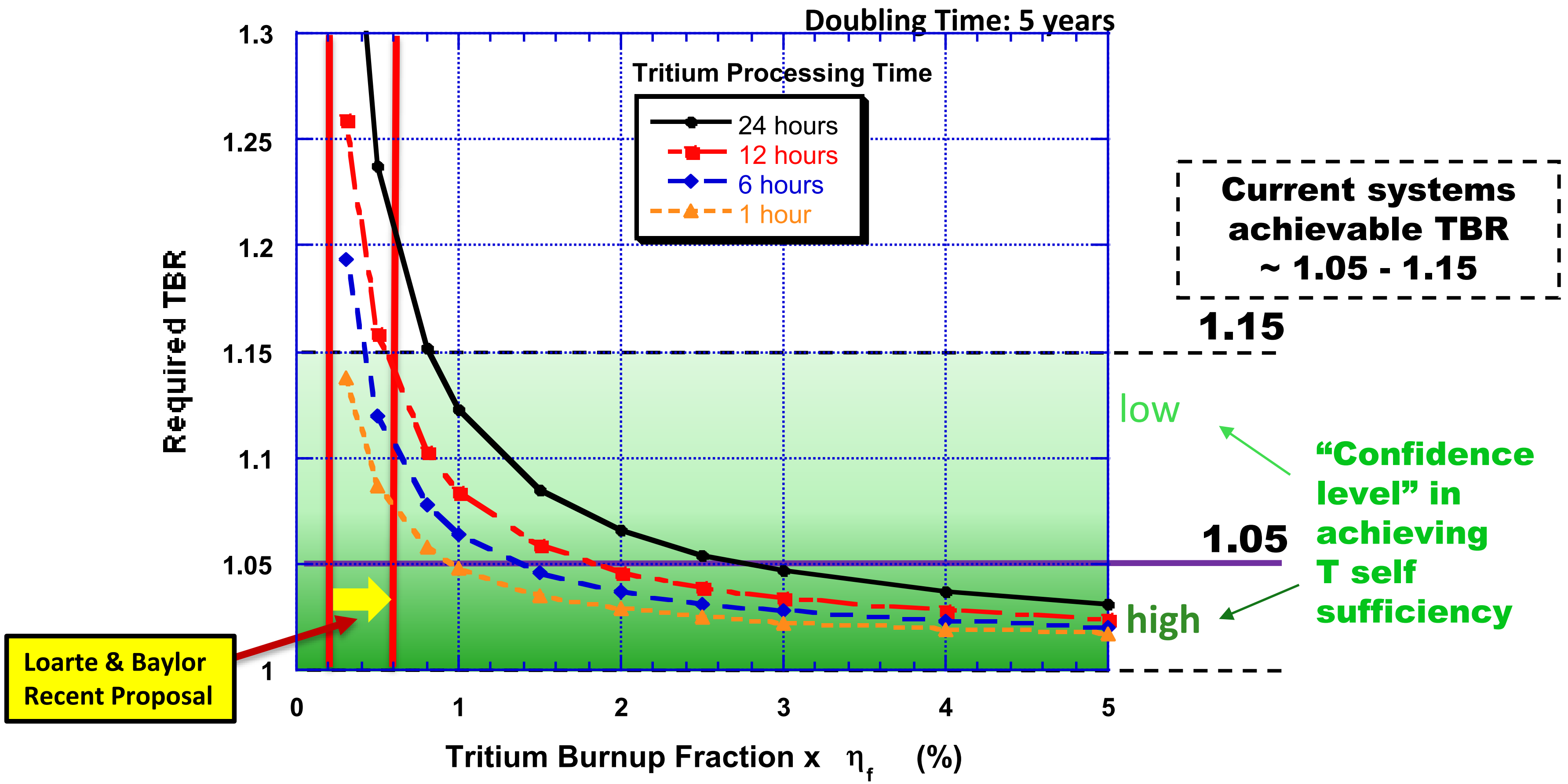
Achievable TBR

- **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) – these may seriously lower Achievable TBR
- **No blanket has ever been built or tested yet!** Accurate prediction of achievable TBR requires testing of a full blanket (or at least a full sector) in a 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, and reactor system availability
- With state of the art (ITER: f_b ~0.35%, η_f < 25%), the required TBR is > 1.2
- Recent proposals for improvements in $f_b \, \eta_f$ are promising but not assured, nor sufficient

Dynamic Modelling Results: **There are large uncertainties in achieving T Self-Sufficiency**. Analysis shows: **The required R&D is challenging**



State of the art: achieving T self-sufficiency ranges from Unlikely to possible

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.
- Reduce uncertainties in Achievable TBR; Requires testing blanket sector in DT device

Summary of other important results from Dynamic modelling

Doubling time

Required TBR and Tritium Self-Sufficiency also strongly depend on doubling time. Physics and technology state-of-the art will not enable sufficiently short doubling time needed for sensible pace of fusion development

- For Mature Power Industry, typical doubling time is 7 years
- But for Fusion from demonstration to initial commercialization stage, relatively short doubling time (e.g. 1-3 year) is needed. This will not be possible even with foreseen advances in physics and technology

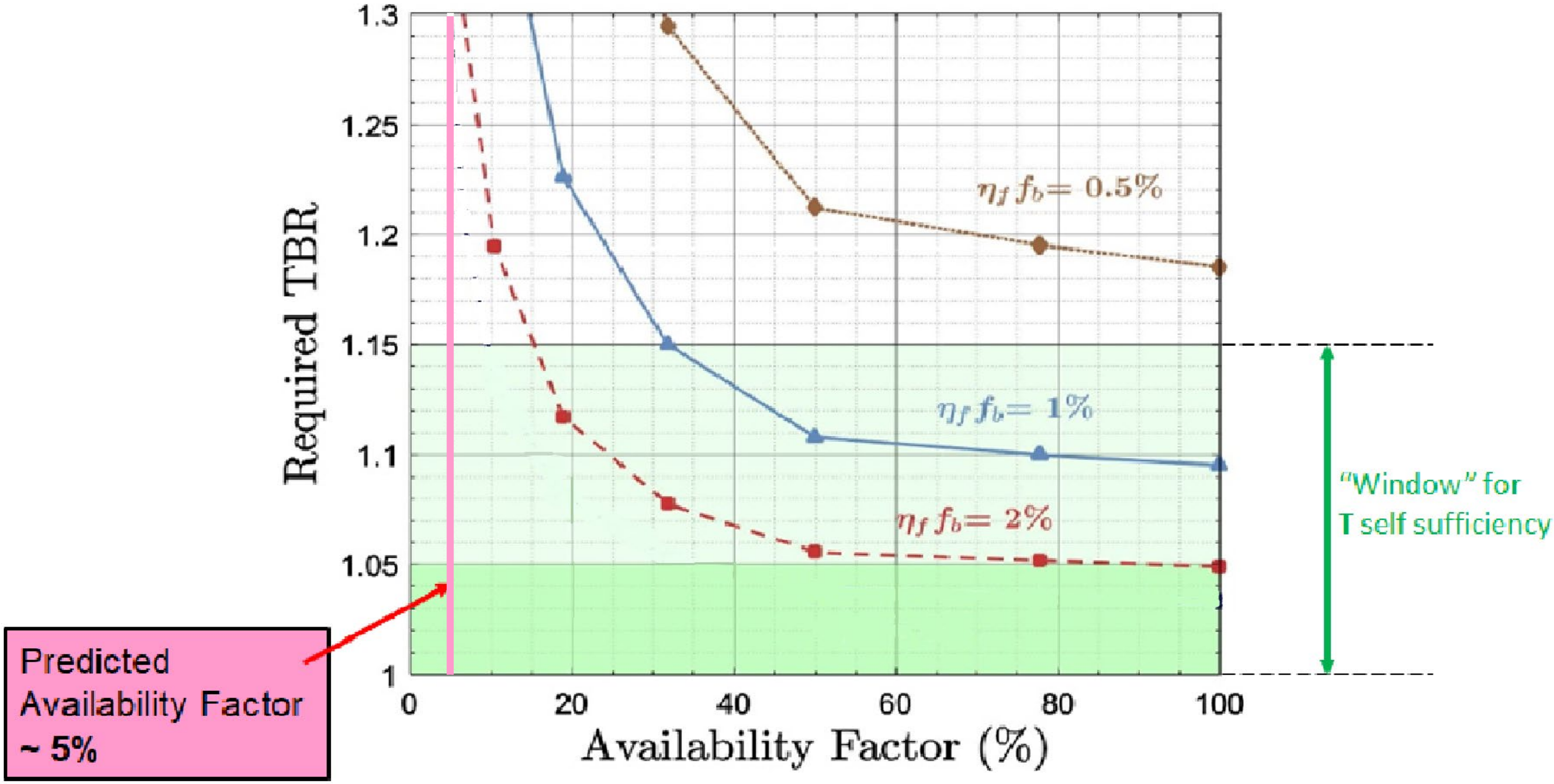
"Reserve" time inventory

A "reserve" tritium inventory is necessary for continued reactor operation under certain conditions, e.g. failure of a tritium processing line. Fusion plants will be "base load" and must avoid frequent or long shutdowns

- With state of the art, the max possible reserve time is found to be very short ~ 0.25 days !!
- **T processing systems must be designed with high reliability and redundancy**

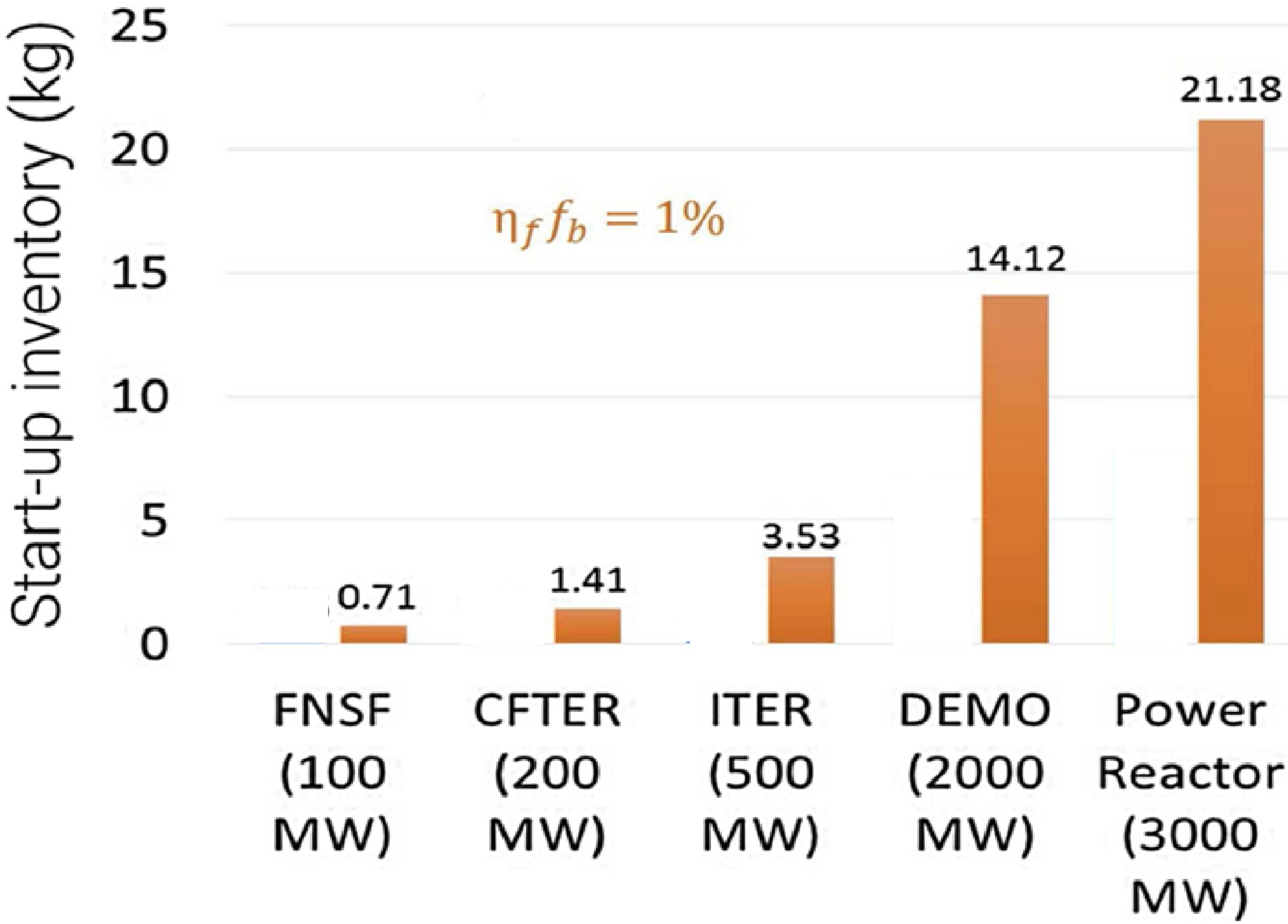
Currently predicted low MTBF, long MTTR, and low Availability Factor will make it impossible to achieve T Self-Sufficiency. (During device downtime, T production in the blanket is interrupted while T loss by radioactive decay continues, inexorably)

Therefore, First generation of DT fusion devices must have low fusion power and focus on RAMI and Reliability Growth



When AF is improved to 30% (which will take a long time), achieving T Self-Sufficiency may be possible if other advances are made, but only with long doubling time

The Required Tritium Start-up Inventory increases with Fusion Power. Plasma-based test facilities with low fusion power need relatively small and obtainable start-up inventory.



Concluding Remarks (1 of 2)

Alarming findings from DT Fuel Cycle Studies

1. **The underlying fundamental problem that we have now in fusion development is the absence of any DT fusion device in which we can learn about plasma and FNST components performance in the fusion environment.**
   Therefore, we have to rely on "modeling" to assess the state-of-the art and define R&D requirements. Dynamic modeling of the fuel cycle has been advanced over the past 30 years.

2. **A primary conclusion is that physics and technology state-of-the-art will not enable DEMO and future power plants of providing the required startup inventory, achieving T self-sufficiency, and reasonable pace of entry to market.**
   We quantified goals and defined specific areas and ideas for physics and technology R&D advances. But success cannot be assured.

Concluding Remarks (2 of 2)

"Missing step(s)" without which it seems nearly impossible to have credible pathway to DT fusion energy

The big picture for fusion pathway development that emerges from the detailed analysis of the physics and technology of the DT cycle including assessment of the state of the art and careful evaluation of the requirements for startup inventory and self sufficiency is that:

1. **A credible pathway must start with a DT plasma-based device that has low fusion power (<150 MW to minimize requirements for external T supply) , in which we can 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 understand failure modes, rates, effects (RAMI).**

   This first DT fusion device can be called FNSF (or VNS or any name you wish). It should have small size, ~ 1 MW/m2 NWL on 10-20 m2 test area. Only inside the vacuum vessel (FW/Blanket/divertor) need to be prototypical. Plasma can be highly driven, Q ~ 1-3.
2. **Results and experience from this first DT device will tell us much about the viability of current concepts, and whether we need another one or more devices for reliability growth and other physics and technology improvements; , and possibly produce excess tritium to supply the required Start up inventory for DEMO**
3. **When device availability approaches ~ 30 % , a Demonstration power plant can be built with moderate fusion power (1000-2000MW). Emphasis of DEMO need to be on RAMI / improvement of availability factor to > 50%.**
4. **Results from the DEMO is what will determine if the private sector will invest to introduce fusion power into the market place.**

Thank You!

Extra Slides follow

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

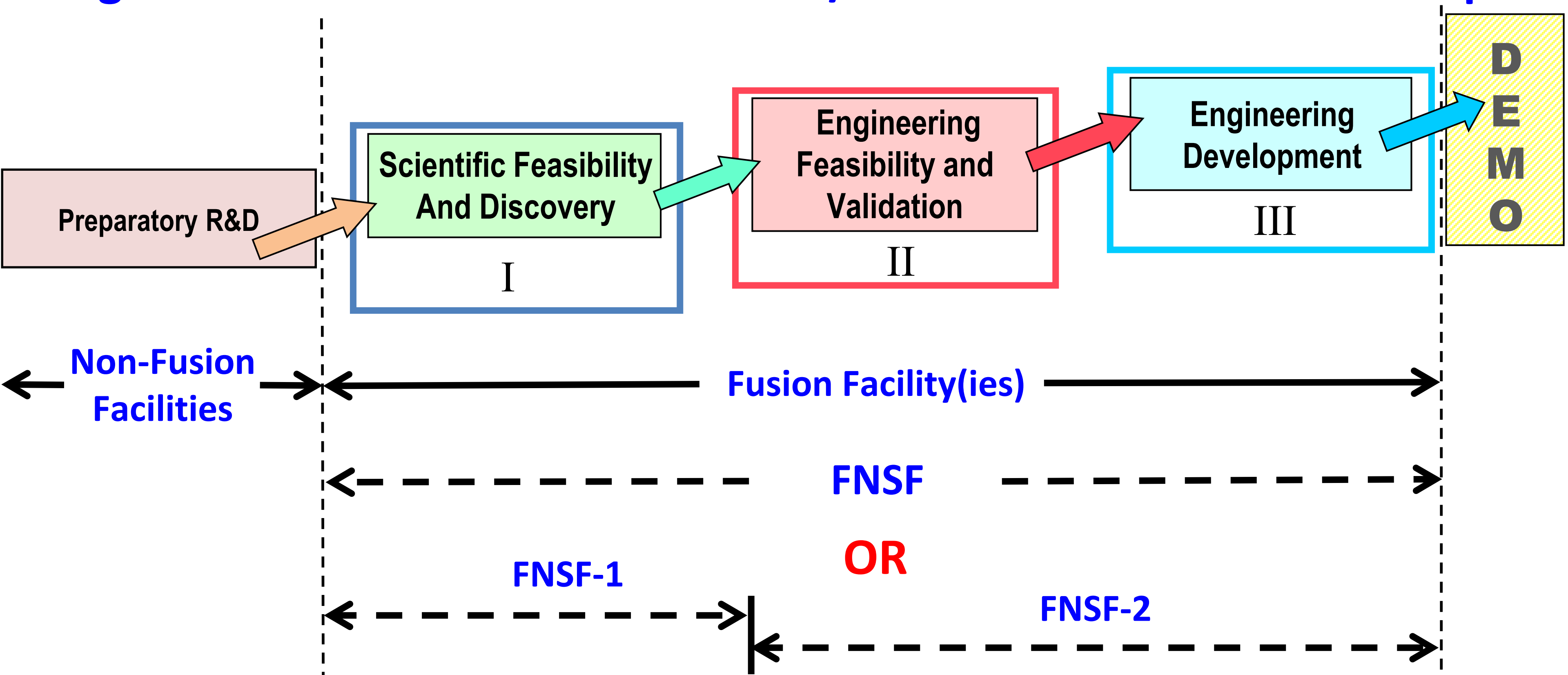
None of the top level technical issues can be resolved before testing in the fusion environment

FNST Testing in Fusion Facilities

	Scientific Feasibility	Engineering Feasibility	Engineering Development
	Stage I	**Stage II**	**Stage III**
Fluence	**Fluence ~0.3 MW-y/m²**	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**
Operation	**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**
Test articles	**Sub-Modules/Modules**	**Modules (10-20m^2)**	**Modules/Sectors (20-30m^2)**
Goals	• 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	• 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	• 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

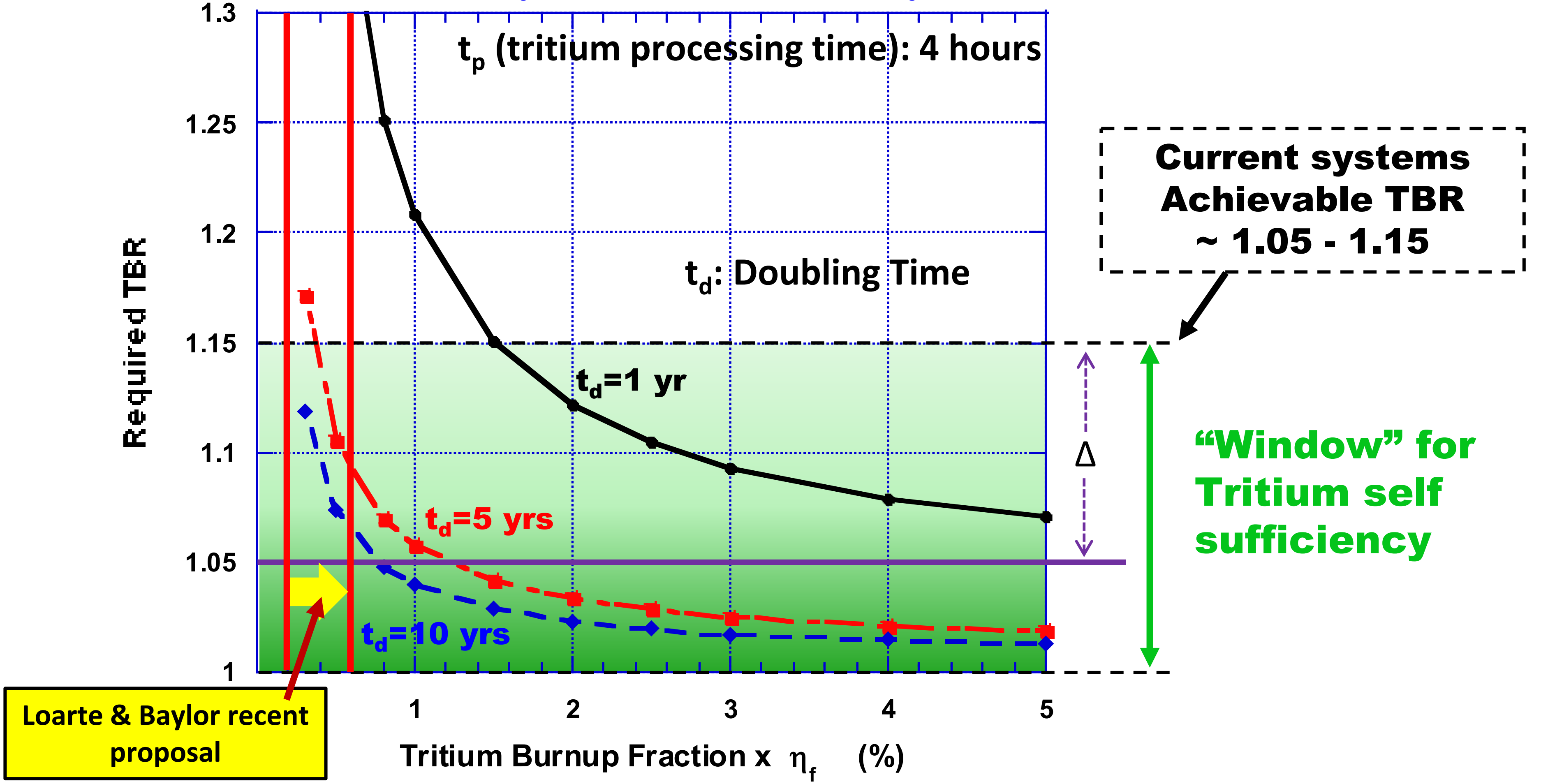
Day 1 Design

- 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

Required TBR and Tritium Self-Sufficiency also strongly depend on doubling time. Physics and technology state-of-the art will not enable sufficiently short doubling time needed for sensible pace of fusion development



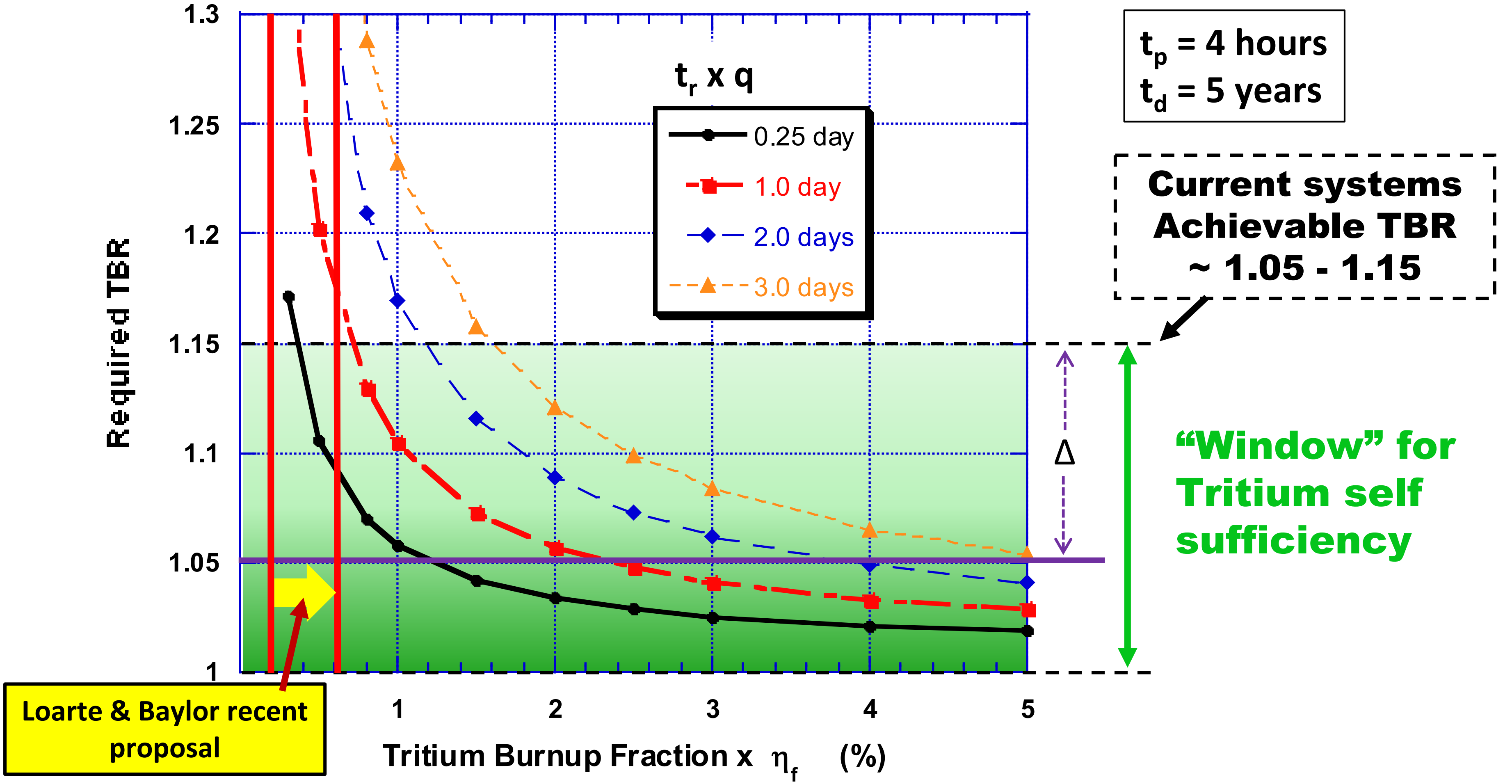
- For Mature Power Industry, typical doubling time is ~7 years
- For Fusion from demonstration to initial commercialization stage, relatively short doubling time (e.g. 1 year) is needed. This will not be possible even with foreseen advances in physics and technology

A "reserve" storage tritium inventory is necessary for continued reactor operation under certain conditions, e.g. failure of a tritium processing line. Fusion plants will be "base load" and must avoid frequent or long shutdowns

Variation of Required TBR with $f_b \times \eta_f$ for different $t_r \times q$ values

t_r = time (days) of T in "reserve storage" to continue operation in case of failure in the T system

q = fraction of the T processing system that has failure



- With state of the art, max allowable reserve time is very short 0.25 days.
- **T processing systems must be designed with high reliability and redundancy**

When AF is improved to 30% (which will take a long time), achieving T Self-Sufficiency may be possible, but only with long doubling time

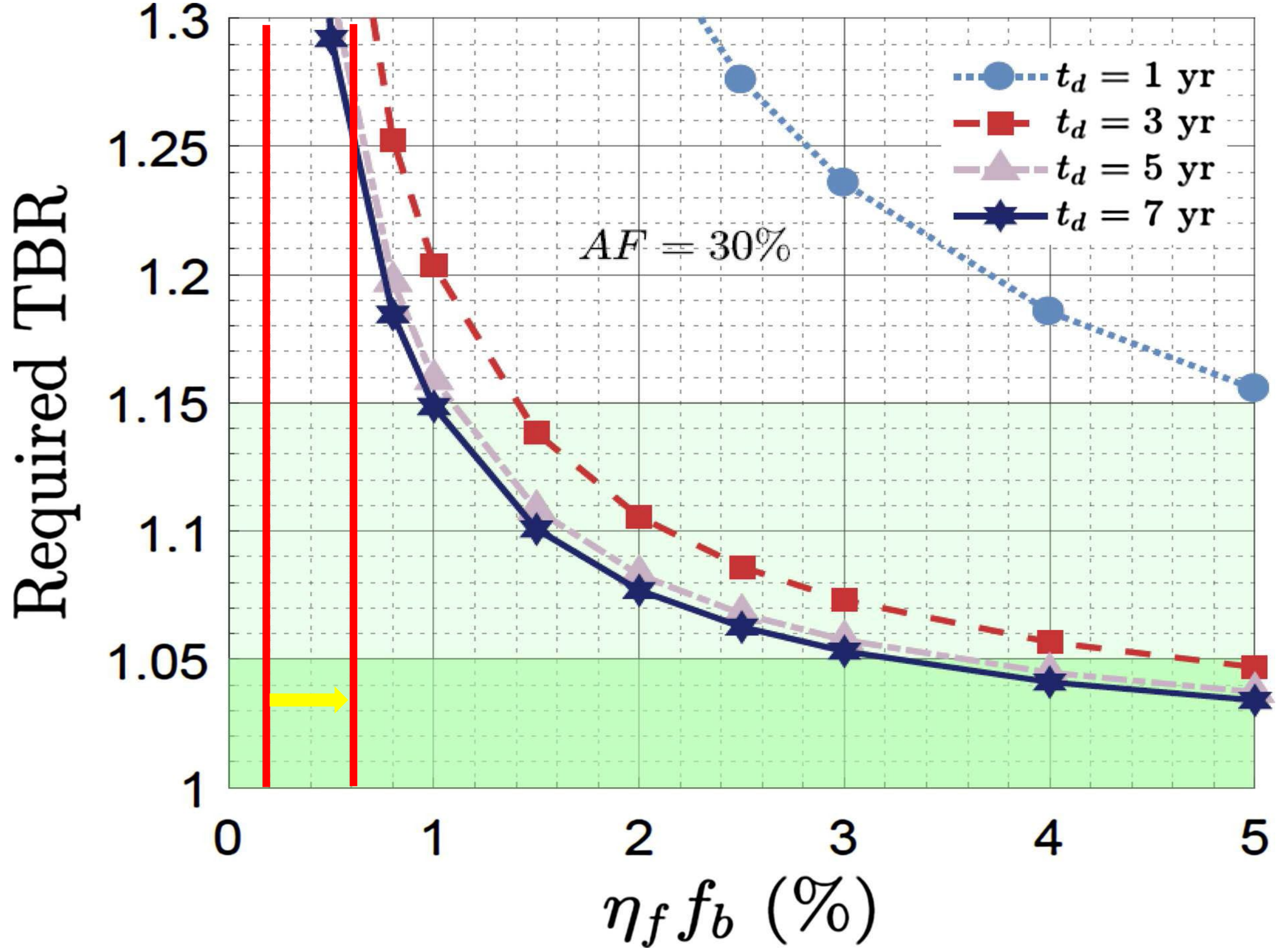


Figure 7. Required TBR as a function of the product of TBF and fueling efficiency for various doubling time (1, 3, 5, and 7 years) for availability factor of 30%. Parameters used in the analysis: processing time in the plasma exhaust (IFC) = 4 h, BZ residence time = 1 day, TES processing time = 1 day, fusion power = 3 GW, reserve time = 24 h, fraction failing = 25%, availability factor = 30%.

Required tritium Start-up Inventory

1- depends on many plasma physics and technology parameters.

2- increases with Fusion Power. Plasma-based test facilities with low fusion power need relatively small and obtainable start-up inventory.