Physics and technology considerations for the D-T fuel cycle and conditions for tritium fuel self-sufficiency

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

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

Major Areas of highest importance:

1. Tritium Inventories and Startup Inventory

Accurate calculations of time-dependent tritium flow rates and inventories in a fusion plant are critical for determining:

a) **Required initial inventory for startup of DEMO and future fusion devices beyond ITER**
b) **Conditions Required to attain Tritium Self-Sufficiency in DEMO and future Power Plants**
c) **Impact on Safety**

2. Tritium Self-Sufficiency

- **Absolutely required for D-T Fusion Energy Systems to be feasible**
- **Complex dependence on many plasma physics and fusion technology parameters/ conditions**
- **The required TBR and the achievable TBR have very different dependence on fusion system physics and technology**

3. Safety

- Tritium Inventories, permeation and release are key aspects of safety analysis

Calculations/Analysis for all these 3 areas 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 "effective partnership" between plasma physicists and fusion technologists (e.g. in areas of plasma fueling, plasma dynamics and edge physics, tritium processing, and blanket)**

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): ~ 0.5-1 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 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

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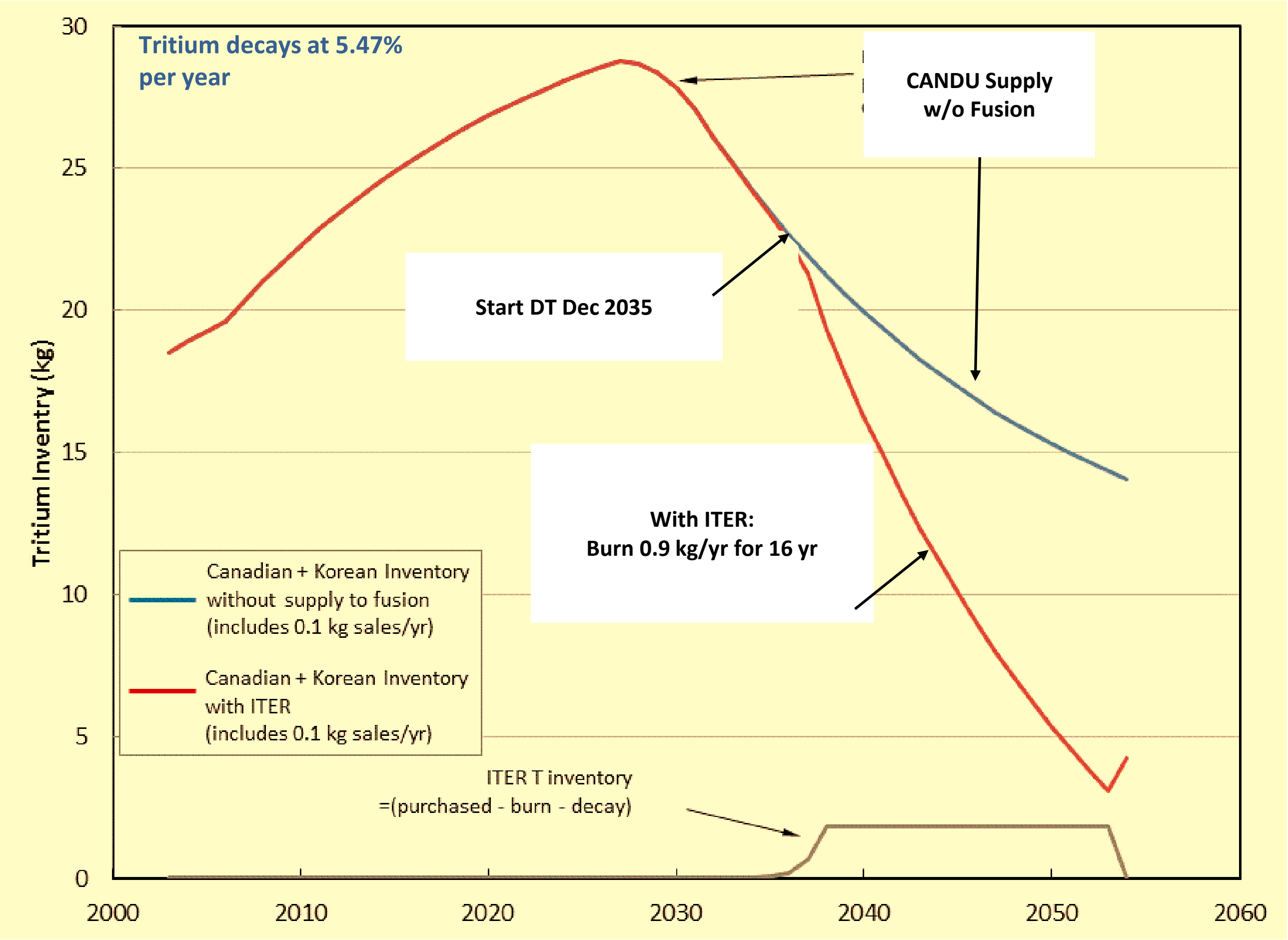
Issue: With ITER DT start in 2036, there will be no external non-fusion supply of tritium left to provide "Start up" T inventory for any major DT Fusion facility beyond ITER

The tritium we had at the beginning of ITER design has already decayed!



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Tritium self-sufficiency condition:
$TBR_a \geq TBR_r$

TBR_a= Achievable tritium breeding ratio

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

TBR_r = Required tritium breeding ratio

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

1) *Compensate for 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

Dynamic Modelling of the D-T Fuel Cycle

- Dynamic Modelling and Analysis of the Tritium 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. These have had a huge impact on the R&D for physics, fueling, tritium processing, safety, as well as blanket design and breeding requirements
- This Dynamic Modelling/analysis went through major improvements in 1986, 1999, 2011, 2015, 2016, 2017, 2019, and 2020
- 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 very 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 just 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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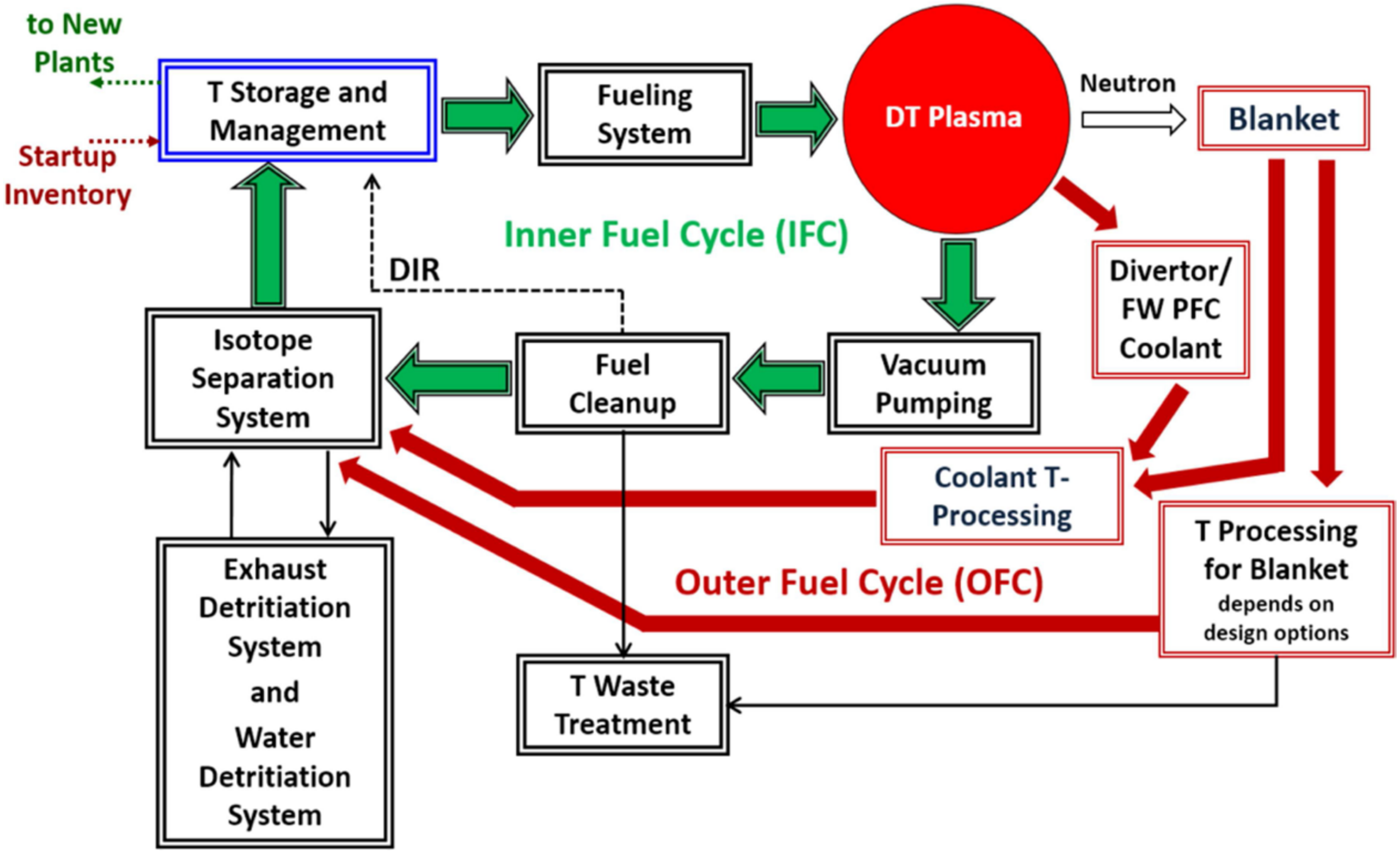
The Nuclear Fusion Article is a comprehensive review and analysis of the state-of-the art and required R&D for the physics and technology of the DT Cycle

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

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

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) "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

5) 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

6) Inefficiencies (fraction of T not usefully recoverable) in various tritium processing schemes, ε

7) Doubling time for fusion power plants (time to accumulate surplus tritium inventory sufficient to start another power plant)

Required Tritium "Startup Inventory" depends strongly on tritium burn fraction (f_b), tritium fueling efficiency (η_f), and tritium processing time (t_p)

Required Startup Inventory

I_0 < 7KG

if $f_b \times \eta_f > 5\%$

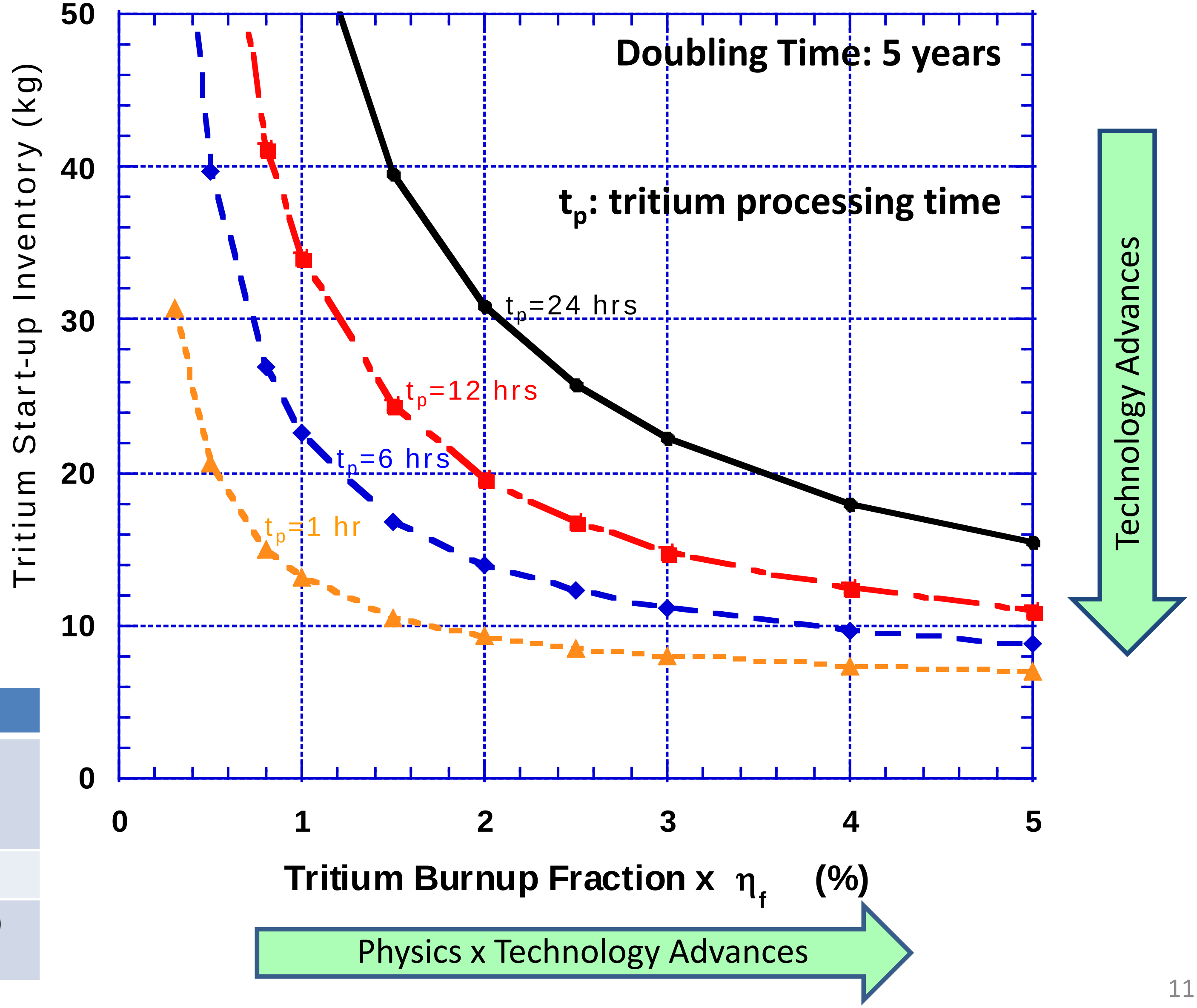
And t_p < 2hrs

I_0 > 20kg

if $f_b \times \eta_f < 1\%$

And t_p > 6 hrs

Fusion Power = 3000 MW
Reserve time for outage x fraction of tritium plant failing = 0.25 day
Inefficiency, ε = 0.01%
Blanket mean residence time = 10 days



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) – this may seriously lower Achievable TBR
- 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

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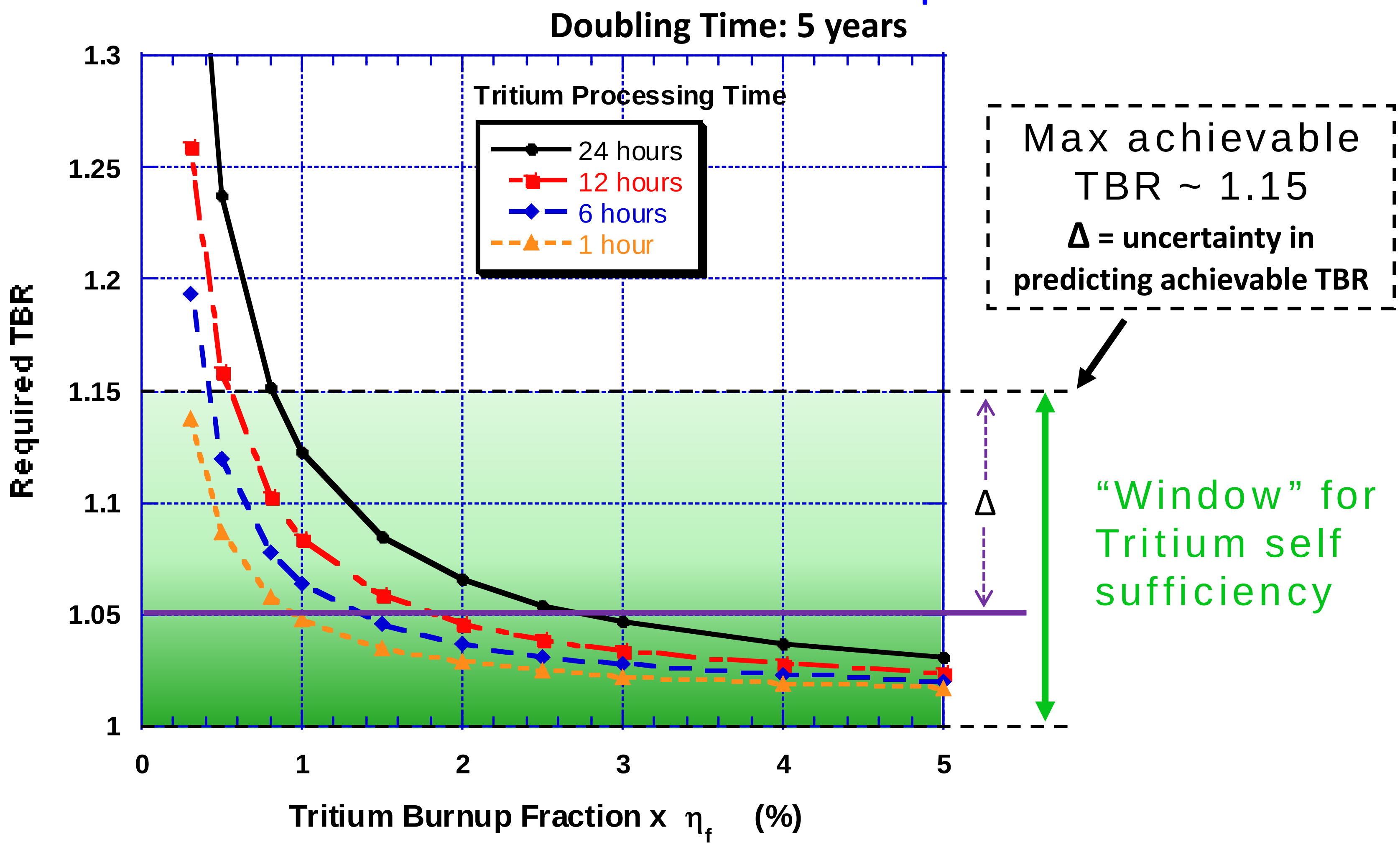
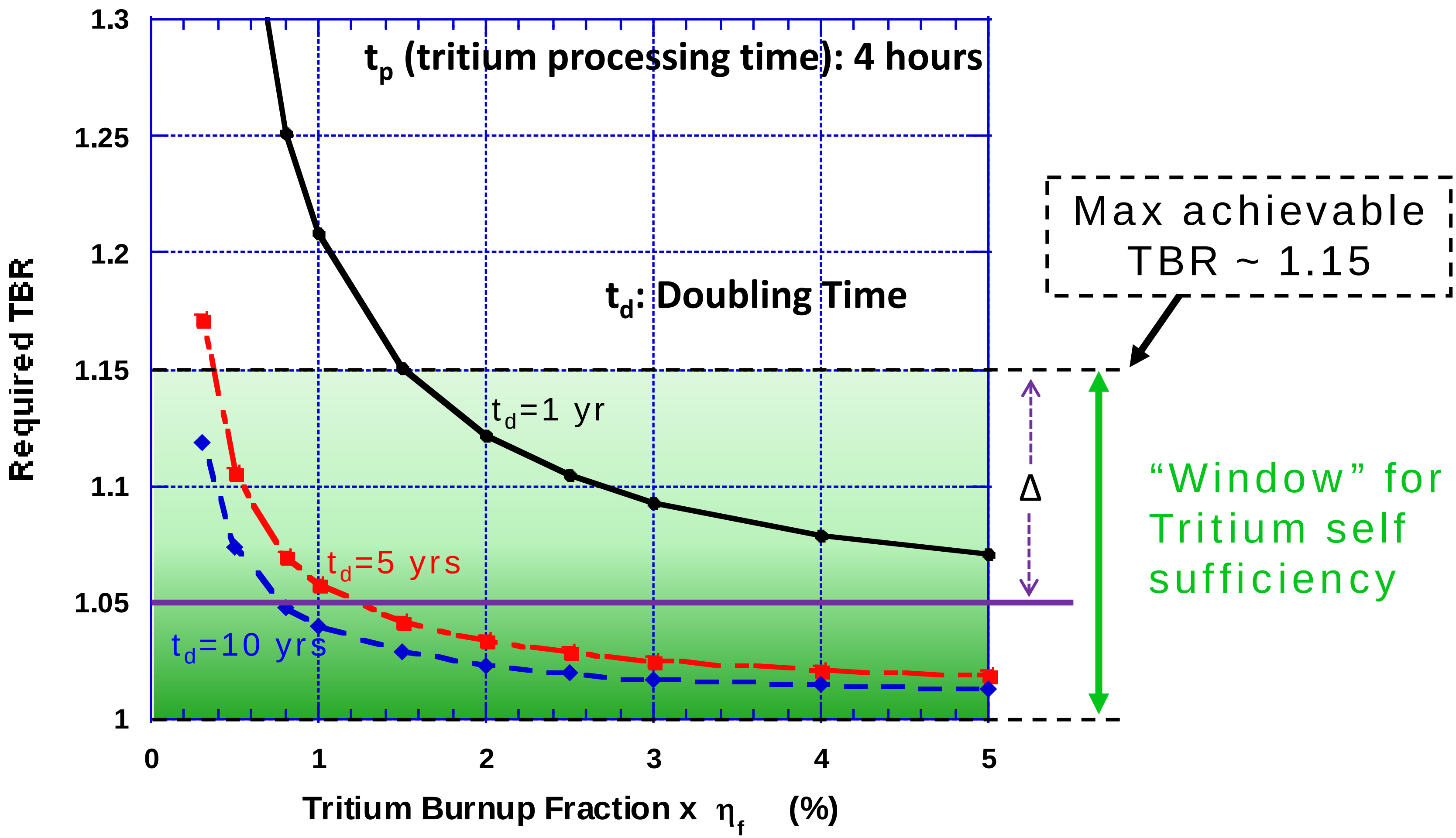
Required TBR and Achieving T Self-Sufficiency are strongly dependent on $f_b \times \eta_f$ and t_p



Likelihood of Attaining Tritium Self-Sufficiency:

- Unlikely if $f_b \times \eta_f < 0.5\%$ and $t_p > 12$ hrs
- Possible if $f_b \times \eta_f > 1\%$ and $t_p < 12$ hrs
- Attained with High Confidence if $f_b \times \eta_f > 5\%$ **or** $f_b \times \eta_f > 2\%$ and $t_p < 12$ hrs

Required TBR and Tritium Self-Sufficiency also strongly depend on doubling time



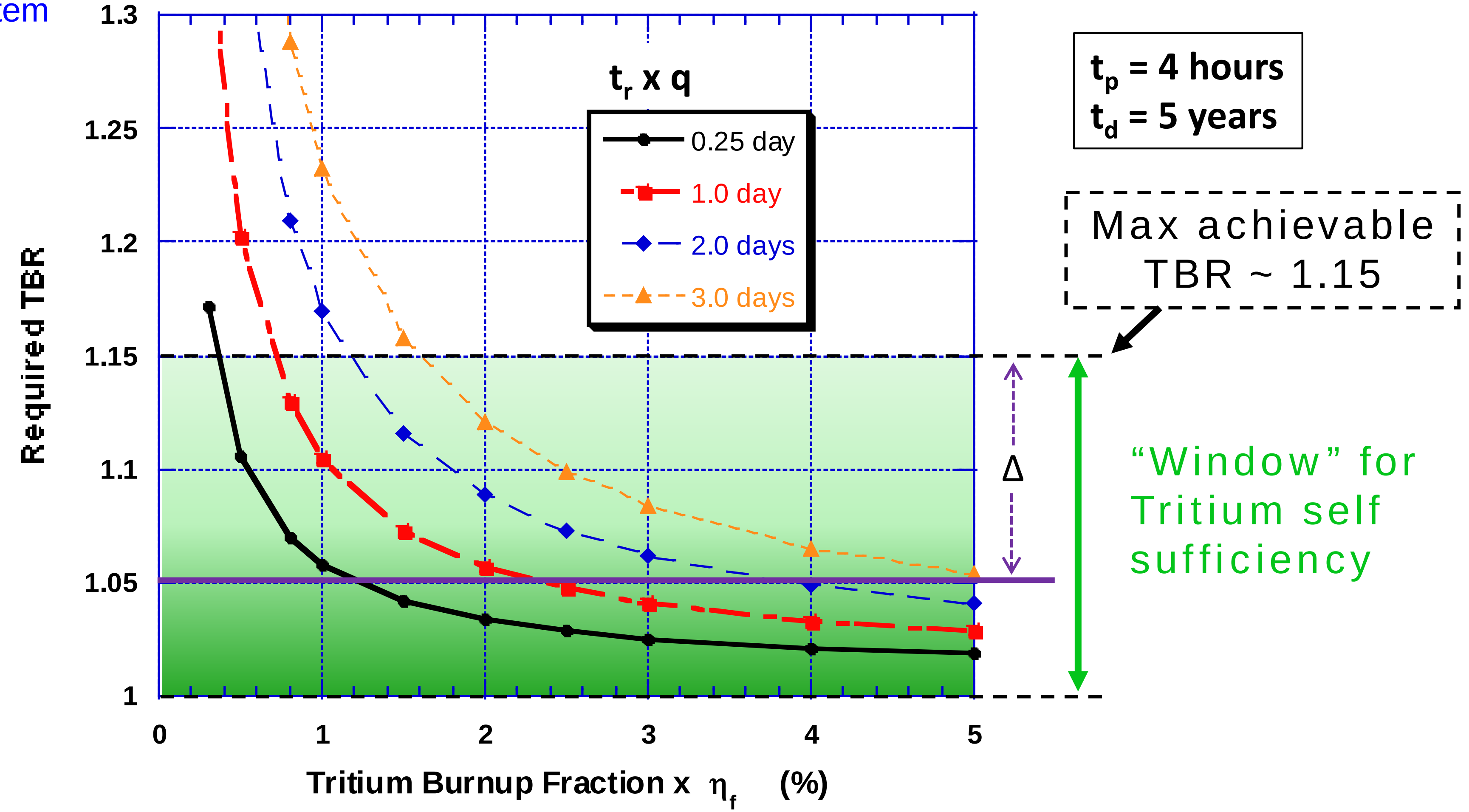
- For Mature Power Industry, typical doubling time is ~7 years
- For Fusion from demonstration to initial commercialization stage, relatively short doubling time (e.g. 1 year) is needed
- This will not be possible if f_b x η_f < 1% even if t_p~4 hrs. It is attainable with higher f_b x η_f > 5%

A "reserve" storage tritium inventory is necessary for continued reactor operation under certain conditions, e.g. failure of a tritium processing line

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



- Higher f_b and η_f mitigate the problems with T processing system outage
- T processing systems must be designed with high reliability and redundancy

What is the State-of-the-Art for η_f, f_b, and t_p?

And What Should be the Goals for R&D?

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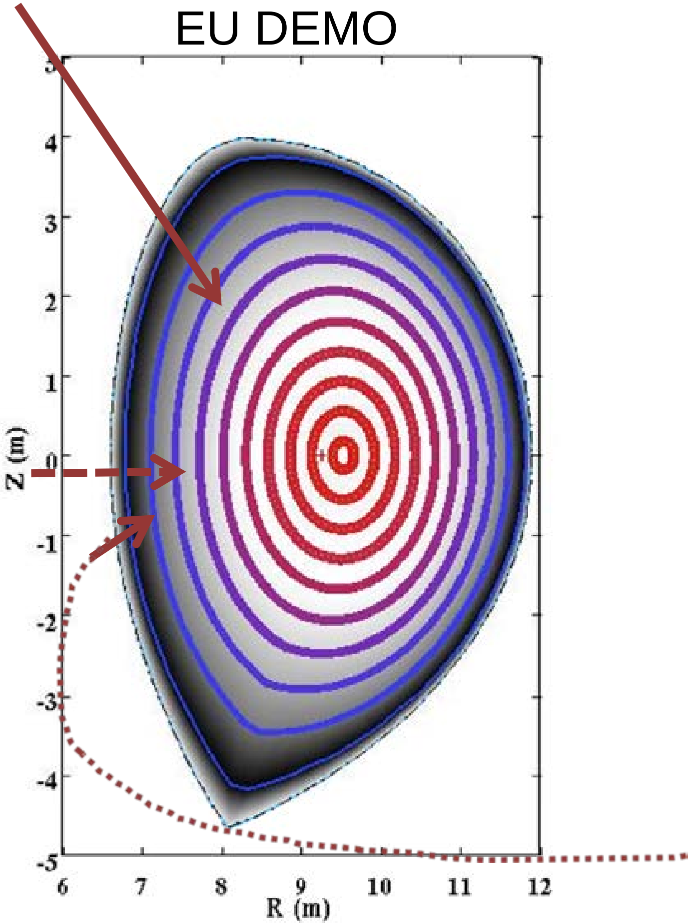
Fusion Fueling Efficiency (Summary from Larry Baylor)

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



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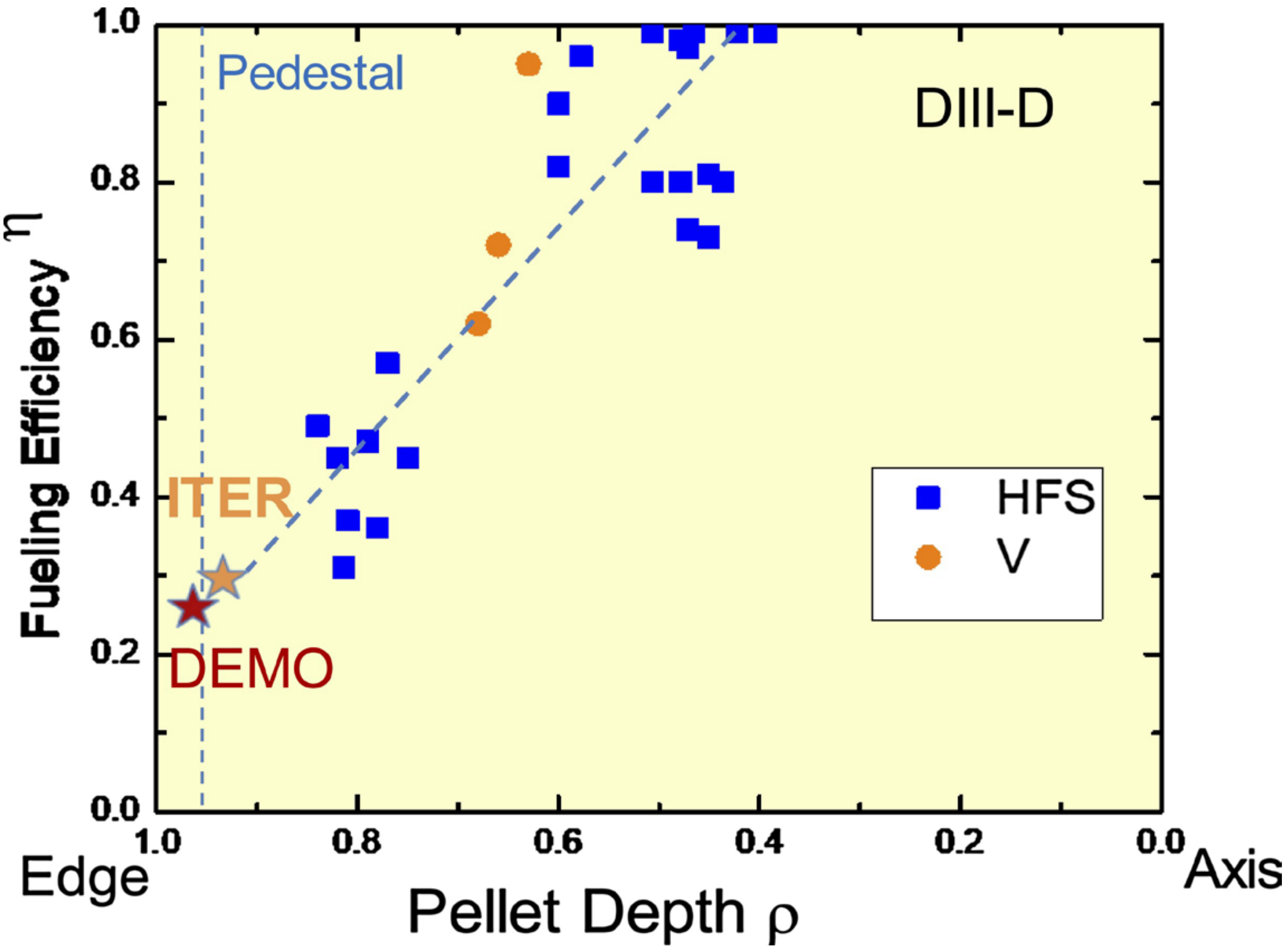

Fueling Efficiency Extrapolation from Deep to Shallow Penetrating Pellets Expected in ITER and DEMO is Highly Uncertain. Extrapolation shows fueling efficiency η < 25% in ITER and even lower in DEMO

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 $\boxed{\mathbf{f_b = 1/\left(1 + \dfrac{2}{n\tau^* < \sigma v >}\right)}}$

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

τ = particle confinement time

<u>Status</u>

- 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
  - Very important research by Alberto Loarte and others in ITER is underway to find methods to increase f_b as discussed in the next slides (See Nuclear Fusion paper for details)

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

- 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)
  - Γ_T^{burn} = 0.35 Pam^{-3}s^{-1} $\Gamma_T^{fueling}$ = 100 Pam^{-3}s^{-1}

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

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^{3}s^{-1} → requirements for He exhaust are less demanding (~ 40 Pam^{3}s^{-1} out of a maximum of 200 Pam^{3}s^{-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**
  - Γ_T^{burn} = 0.35 Pam^{-3}s^{-1}, $\Gamma_T^{fueling}$ = 15-30 Pam^{-3}s^{-1} →

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

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
- **ITER** has a tritium fuel cycle comparable to DEMO for plasma exhaust processing but with big differences in plasma duty cycle and plant duty factor
- The **ITER** Tritium Plant designers (Glugla, Willms, others) have been aware from the early stages of ITER design of the results of the Dynamic Fuel Cycle Modelling that show the extreme importance of achieving short t_p. They worked hard to minimize t_p
  - They set an ambitious goal of t_p~1 hr if achievable.
- **State-of-the-art prediction for DEMO and beyond:**
  - **t_p~2-6 hrs likely achievable**

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

Fueling Efficiency, η

- **Extrapolation shows pellet fueling (from HFS)**

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

Tritium Burn Fraction (TBF) , f_b

- 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

Achievable TBR

Maximum achievable TBR with the current concepts is 1.05-1.15

(The range is due to uncertainties in calculations and data. This does not include uncertainties in the system definition that may substantially lower the Achievable TBR)

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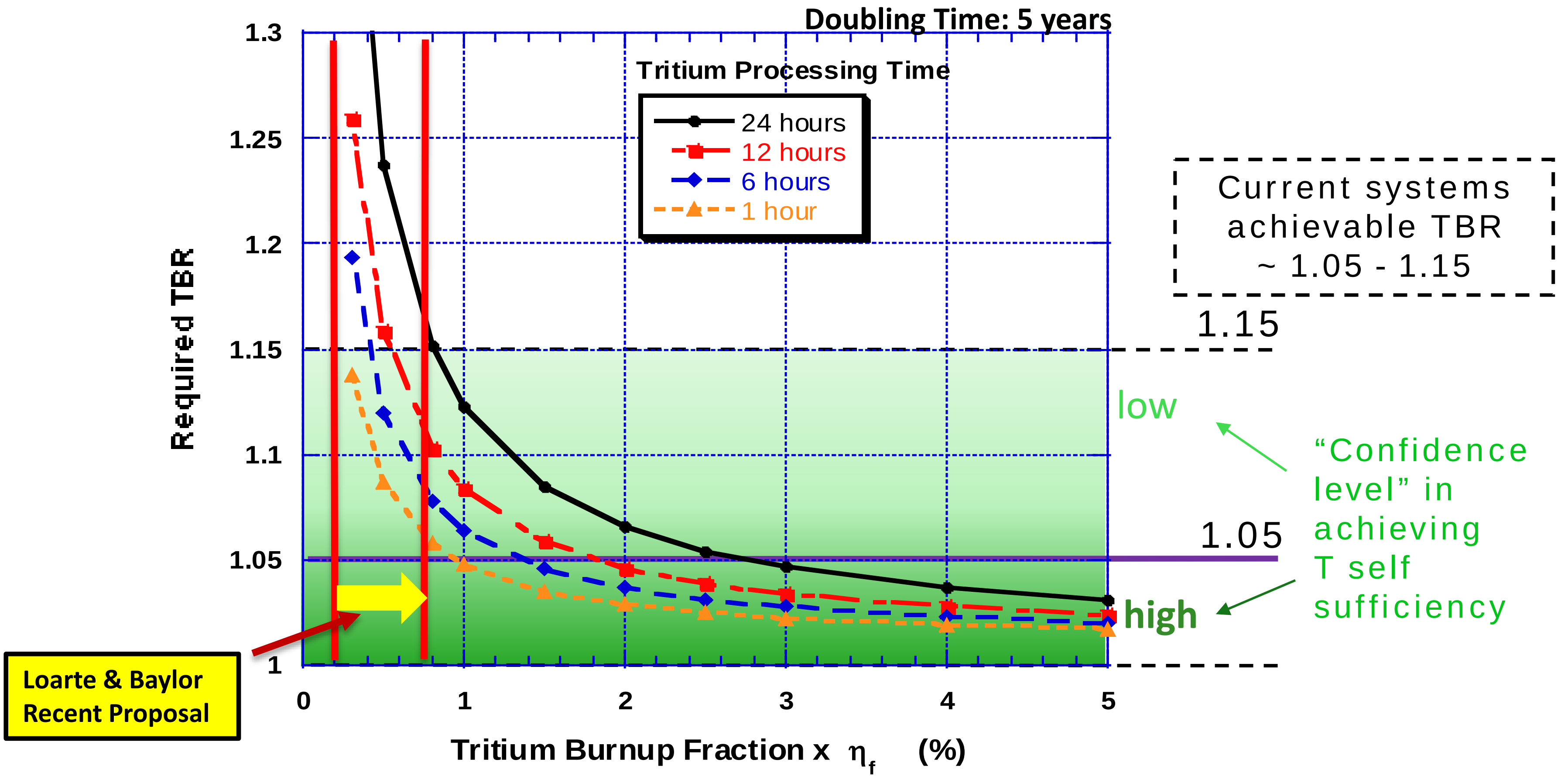
There are large uncertainties in achieving T Self-Sufficiency
The required R&D is challenging



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 x η_f > 5% and t_p< 6 hours **(how to get there?)**
- **Increase Achievable TBR:** Reduce structure and non breeding materials, etc.

Recent advances in fueling efficiency, potential advances from ITER physics innovative ideas to increase burn fraction, and promising advances in tritium processing time from the plasma exhaust lead to lower requirements for the DEMO startup tritium inventory

But Major Improvements are still needed/mandatory – Not clear how

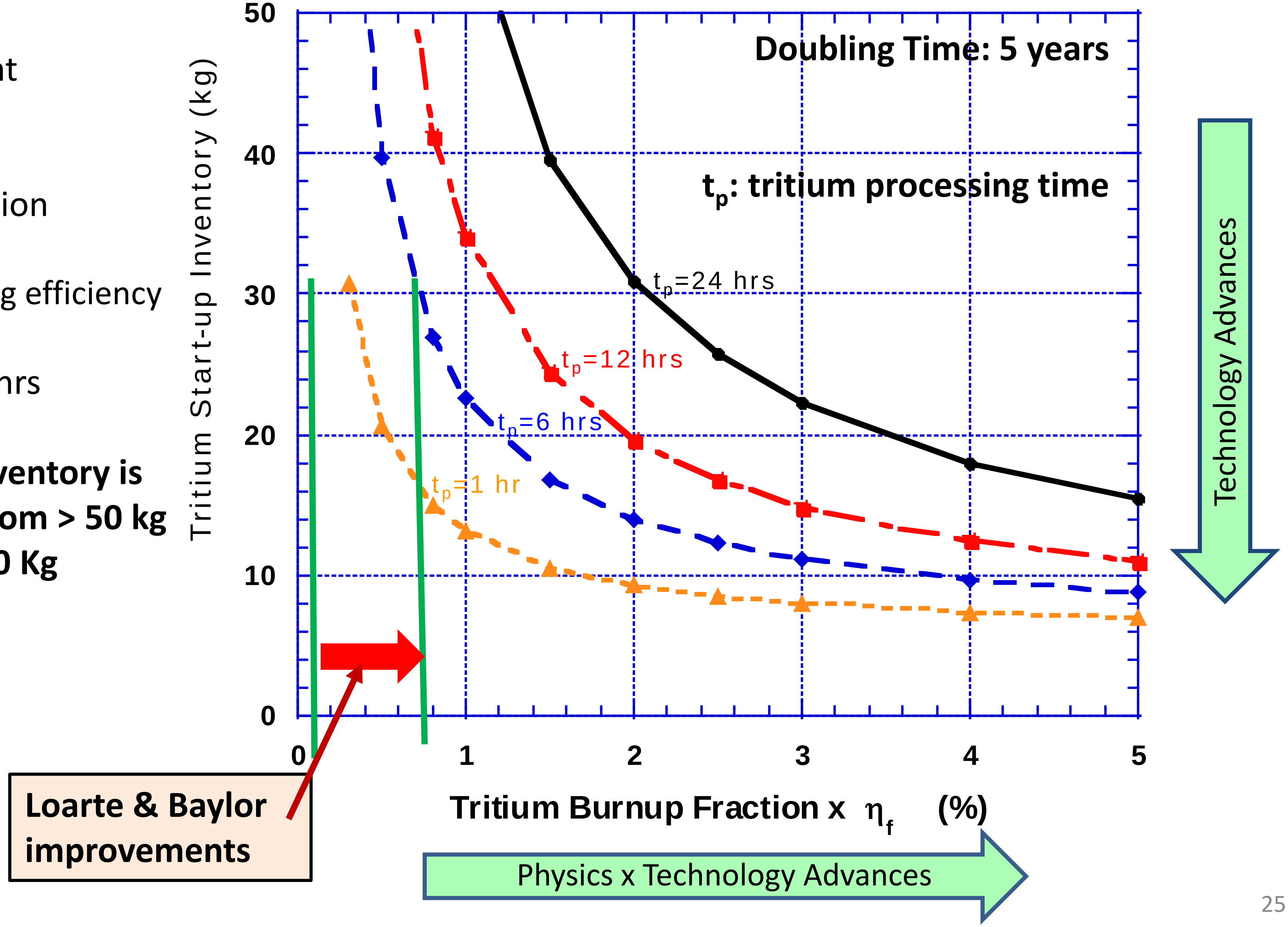
With recent advances:

-Burn fraction ~ 2.3 %

- HFS fueling efficiency ~ 25 %

- t_p ~ 2 – 6 hrs

Startup inventory is lowered from > 50 kg to: ~ 15- 30 Kg



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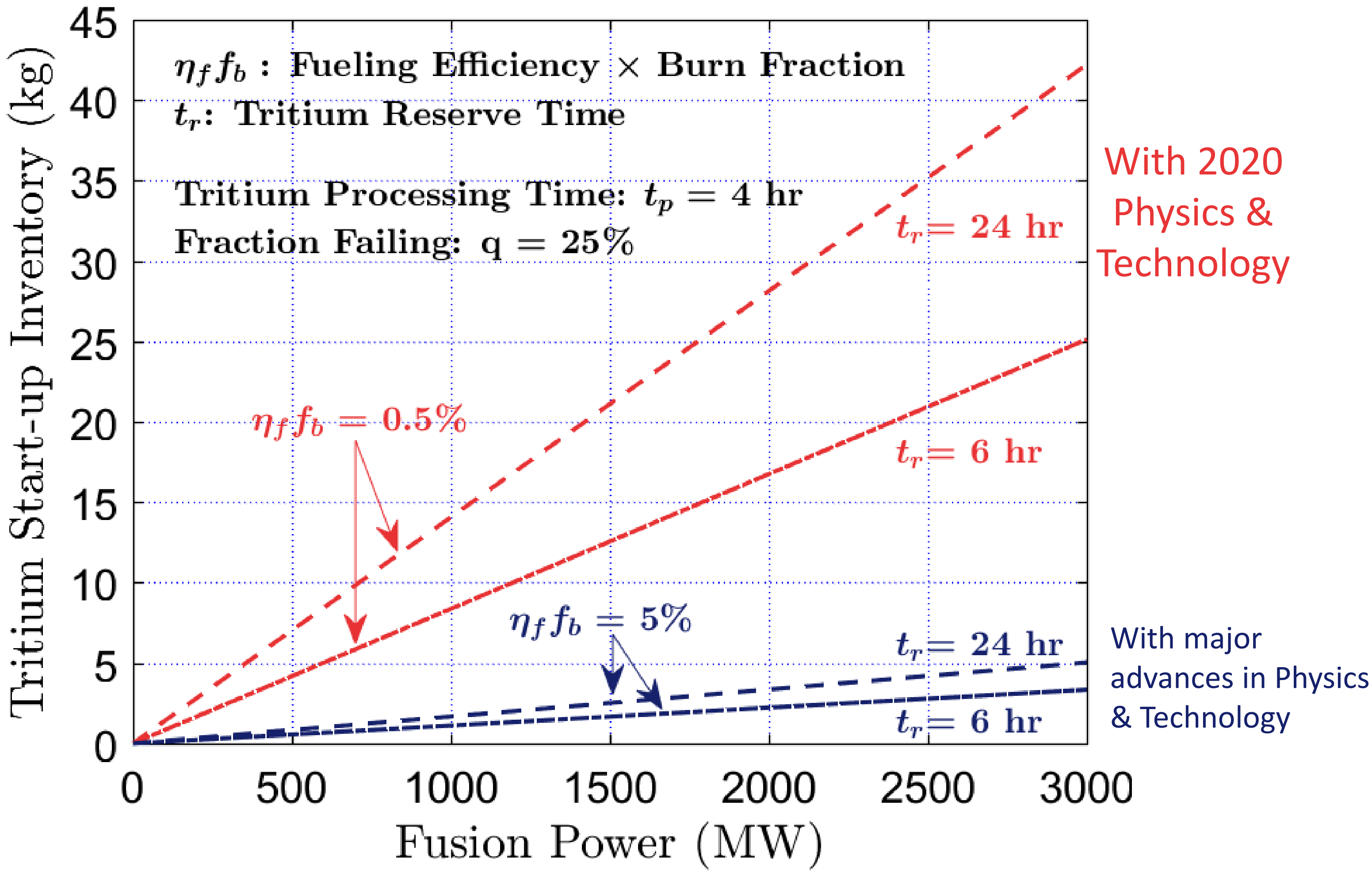
Required tritium Start-up Inventory

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.



Components other than Plasma Exhaust/Fueling System:
Blanket Tritium Inventory, Breeder & Coolant Processing time; PFC Tritium inventories and coolants processing; etc.

Blanket/Breeder/Coolant

- Tritium Inventory in Breeding Blanket is < 1 kg
  - This is based on calculations and some experiments
  - Radiation- induced sintering for CB may increase T inventory
  - There are proposals/designs for the tritium processing systems from breeders (LM & CB) and coolants. But no detailed engineering design or experimental verification yet
- Based on available information, tritium inventories in such systems are < 1 kg and tritium processing time < 24 hours
  - **Much smaller impact on Required Startup Inventory and Required TBR compared to impact of inner cycle (plasma exhaust/fueling cycle)**

PFC (First Wall, Divertor)

- T trapping inventories in solid materials can be large for some materials (e.g. C), but the Fusion Program is moving away from such materials
- Tritium Permeation to First Wall and Divertor coolants from the plasma side can be large resulting in significant T inventories.
  - But the impact on Required Startup Inventory and Required TBR appears insignificant since such inventories would come out of the plasma exhaust/processing system (which is already accounted for in detail)

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Note: If $f_b \times \eta_f > 5\%$ and $t_p < 4$ hrs, the tritium inventory in the plasma exhaust system becomes small (2-3 kg) and T inventory in other components may become more dominant

Reliability/Availability/Maintainability/Inspectability
RAMI

No time in this talk to address the RAMI issue for the T fuel Cycle.
Details are provided in the J. Nuclear Fusion paper mentioned earlier.

- The Need for much higher reliability and much faster maintainability in all components of the T fuel cycle beyond what is currently predictable is shown to be essential for the feasibility of the DT Cycle.

  (Again: RAMI is the Achilles' Heel issue for fusion!!)

- Results also show strong dependence of the potential to attain self-sufficiency in fusion devices on the Device availability factor when it is lower than ~30%.

Confronting the Consequences of Fusion Tritium Consumption being large and the lack of adequate external non-fusion supply of T beyond ITER is critical for the development of fusion

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

1. **Provide startup T inventory for 2 or 3 DEMOs and other facilities that are being planned around the world**
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** as discussed earlier in this presentation (e.g. Higher Burn fraction, higher fueling efficiency, shorter T processing time, minimization of T inventory in all components)
- **Minimize failures in tritium processing systems** and required reserve time
- No DT fusion devices other than ITER can be operated without a full breeding blanket
- Development of breeding blanket technology must be done in low fusion power devices (e.g. low fusion power, small size FNSF)
- Find ways to use devices such as FNSF to Accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO

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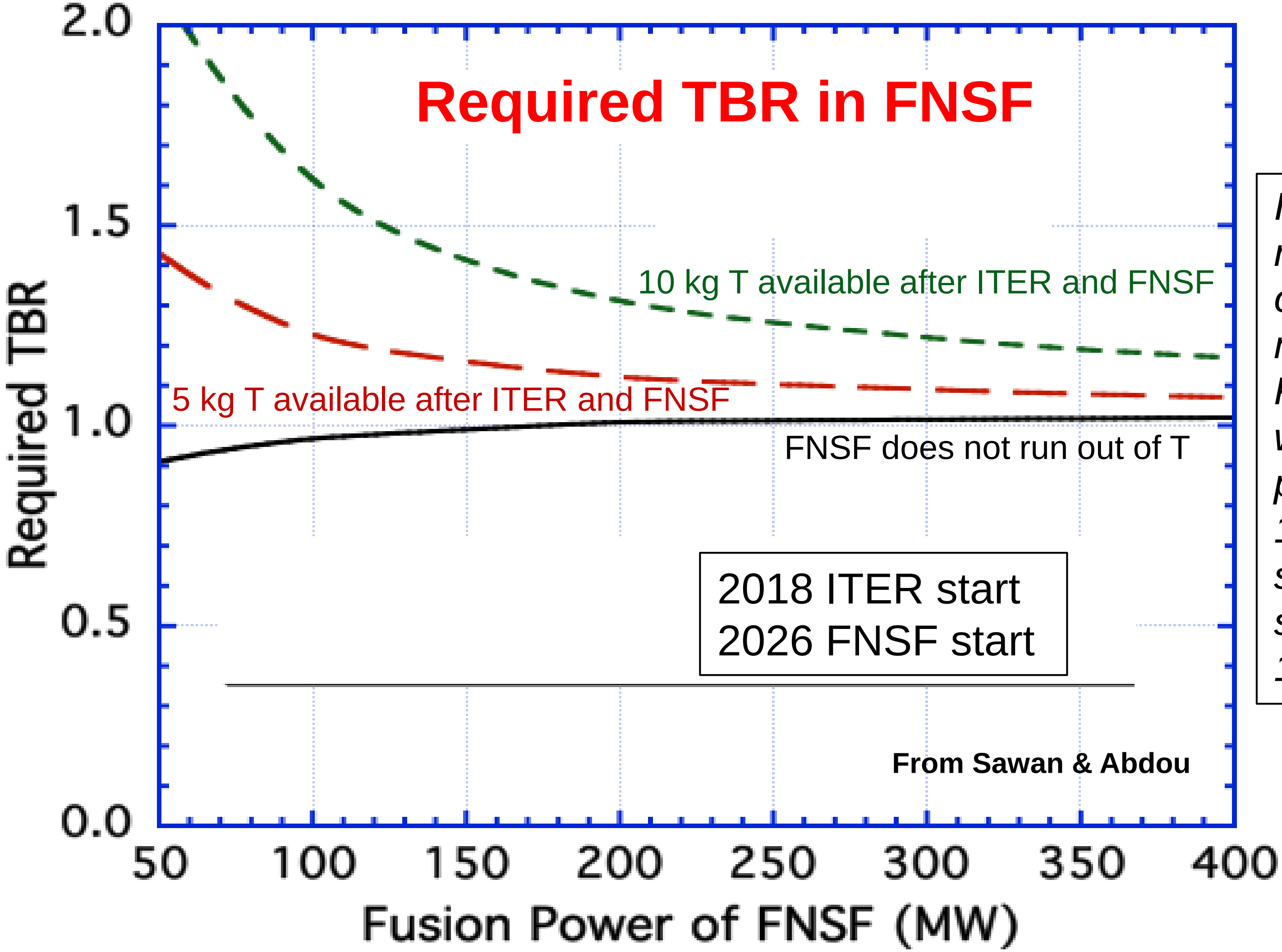
FNSF should be designed to breed tritium to:

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

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



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

The situation we are running into with breeding blankets:

What we want to test (the breeding blanket) is by itself An ENABLING Technology

Concluding Remarks (1 of 2)

- The development of Comprehensive Dynamic Fuel Cycle Model started 35 years ago, and still ongoing, has played a major role in revealing plasma physics and fusion technology parameters and conditions that have the most impact on tritium inventories, startup inventory, tritium self-sufficiency, and safety.
  - Defining Quantitative Goals for plasma burn fraction (f_b), fueling efficiency (η), tritium processing time (t_p) and other parameters and conditions AND Continued direct interactions with plasma physicists, tritium processing experts, and fueling technology developers resulted in achieving important successes in some areas, and proposing promising solutions in other areas
  - **But more challenging advances are still needed**
  - **Need intense R&D coordinated worldwide** among plasma physicists, fueling technology developers, tritium processing experts, FNST scientists and engineers, fusion facilities designers, and Dynamic Fuel Cycle developers/analysts.

- The state-of-the-art for f_b, η_f , t_p **is not acceptable** because it:
  1) Results in too large T startup inventory that cannot be provided from any tritium-producing non-fusion sources
  2) Makes it unlikely (or cause low-confidence) in achieving tritium self-sufficiency
  3) Denies fusion the opportunity to have short doubling time (e.g. ~1yr) in the critical stage from demonstration to initial commercialization

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Concluding Remarks (2 of 2)

- **Recommended R&D Goals:**

T burn fraction (f_b) x fueling efficiency (η_f) > 5% (not less than 2%)
T processing time (in Plasma exhaust/fueling cycle) < 6 hours

  - Minimize tritium inventories in all components (Blankets, PFC, etc.)
  - Tritium Processing systems (particularly in the plasma exhaust system) must be designed and developed with high reliability and redundancy

- Fusion development is taking decades (much longer than we anticipated). We still do not have critical data with which we can confidently design and predict performance of key components (e.g. behavior of blankets in the fusion nuclear environment with multiple/synergistic effects, reliable predictions of T burn fraction in the plasma, etc.)
  - We should focus on accelerating R&D for the most important issues, particularly for FNST (prompt response for minutes/days/weeks should be higher priority than long life issues)
  - We must encourage young researchers and newcomers to fusion (even if they are seniors with much experience in other fields) to learn the complex interactive issues of fusion and read papers/reports that are decades old but are still valid and have the fundamentals of fusion systems that are not available in more recent papers/reports. (Cautionary note: Not all old literature is still valid; and not all new literature is correct)

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Thank you