

Tritium Fuel Cycle, **Tritium** Inventories,
and Physics and Technology R & D Challenges for:
1) Enabling the startup of DEMO and future Power Plants
AND
2) Attaining Tritium Self-Sufficiency in Fusion Reactors

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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 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 area requires detailed Dynamic Modelling of the T fuel Cycle

This Presentation will focus on Topics 1 and 2. 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 only be achieved by “effective partnership” between plasma physicists and fusion technologists (e.g. in area of plasma fueling, tritium processing, blanket)

Note: Tritium Safety will not be addressed in this presentation. Other presentations in this ISFNT address safety.

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 constructed > 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

Dynamic Modelling of Fuel Cycle (See Refs 1-7)

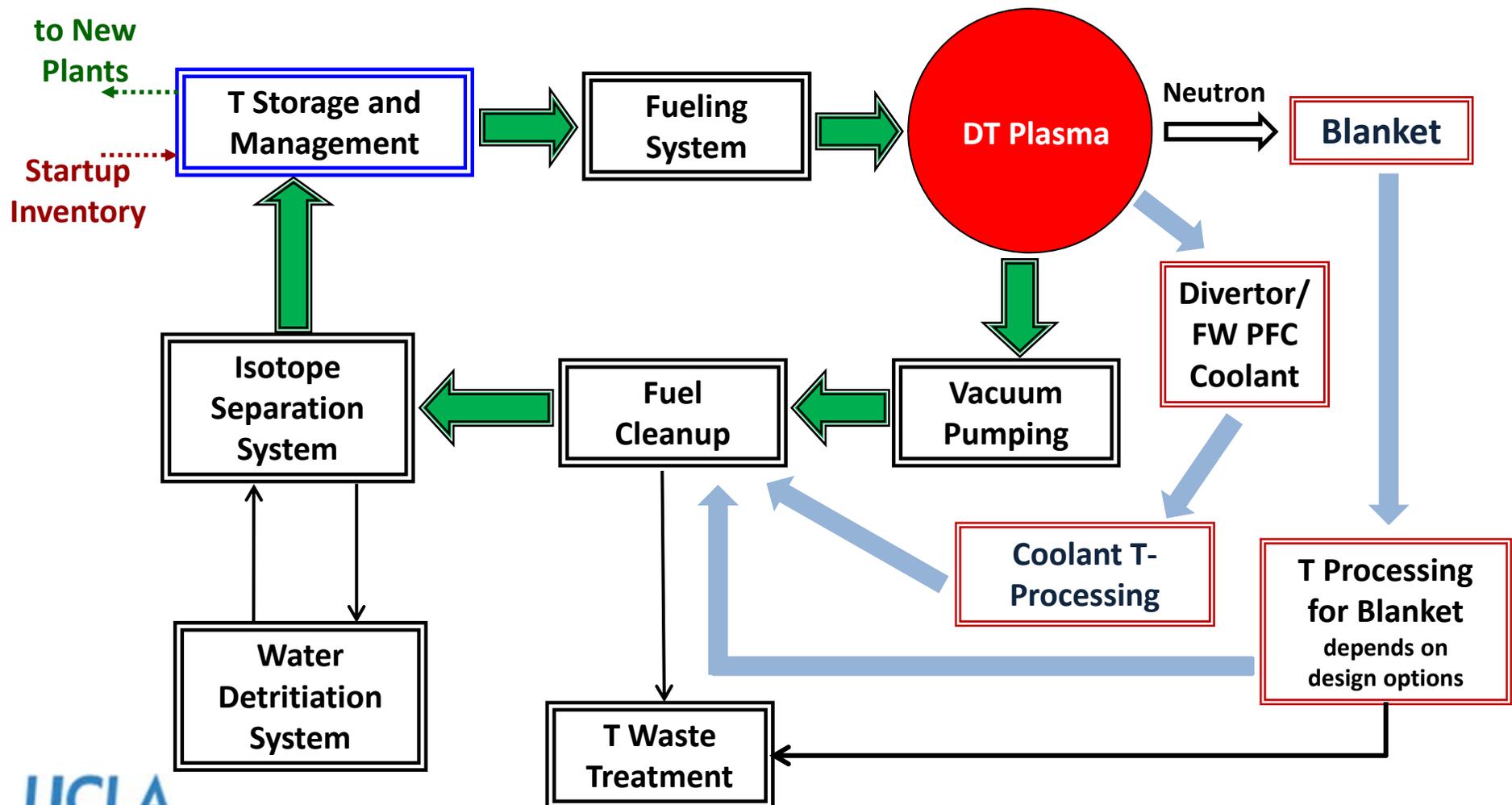
- Dynamic Modelling and Analysis of the Tritium Fuel Cycle was started (at UCLA) 30 years ago and **is still ongoing** because it has huge impact on the R&D for physics, fueling, tritium processing, safety, as well as blanket design and breeding requirements
- This Dynamic Modelling/analysis went through major improvements in 1986, 1999, 2011, 2015, 2016, and 2017
- The most 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. This was the subject of IAEA workshop in KIT in November 2016
 - But **much more challenging advances are still needed**. These can be realized only by **intense R&D coordinated worldwide among plasma physicists, plasma support technologists, and FNST scientists/engineers**.

Quantifying the requirements for this R&D is the primary motivation behind this presentation

Dynamic fuel cycle models have been developed to calculate time-dependent tritium flow rates and inventories and required TBR

(Dynamic Fuel Cycle Modelling: Abdou/Kuan/Liu et al. 1986, 1999, 2011, 2015, 2016, 2017; See Refs 1-7)

Simplified Schematic of Fuel Cycle



Tritium self-sufficiency condition:

$$\text{TBR}_a \geq \text{TBR}_r$$

TBR_a = **Achievable** tritium breeding ratio

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

TBR_r = **Required** tritium breeding ratio

TBR_r should exceed unity by a margin required to:

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

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

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**” depend strongly on tritium burn fraction (f_b), tritium fueling efficiency (η_f), and tritium processing time (t_p)

Required Startup Inventory

$I_0 < 7\text{KG}$

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

And $t_p < 2\text{hr}$

$I_0 > 20\text{kg}$

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

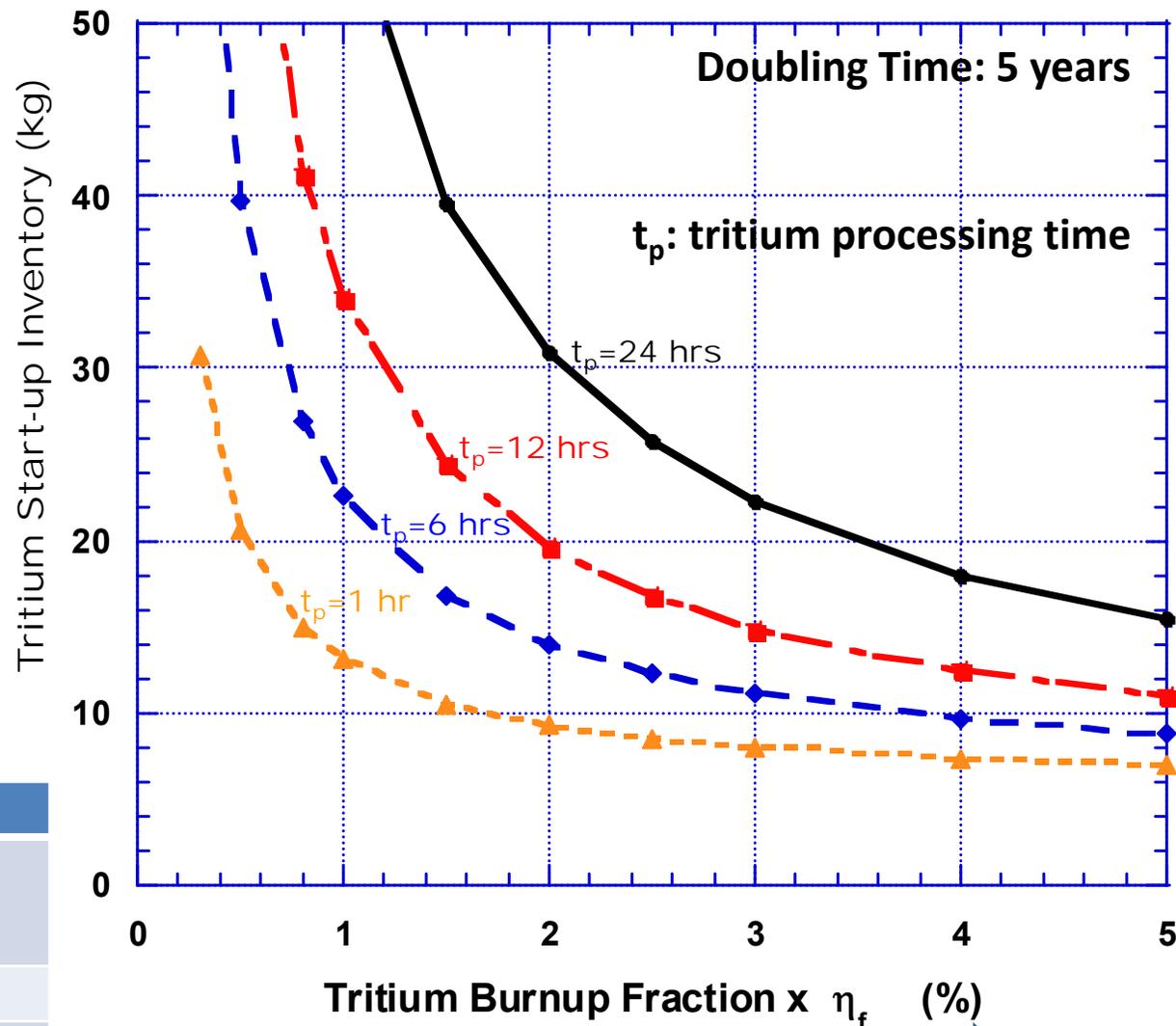
And $t_p > 6\text{ hr}$

Fusion Power = 3000 MW

Reserve time for outage x fraction of tritium plant failing= 0.25 day

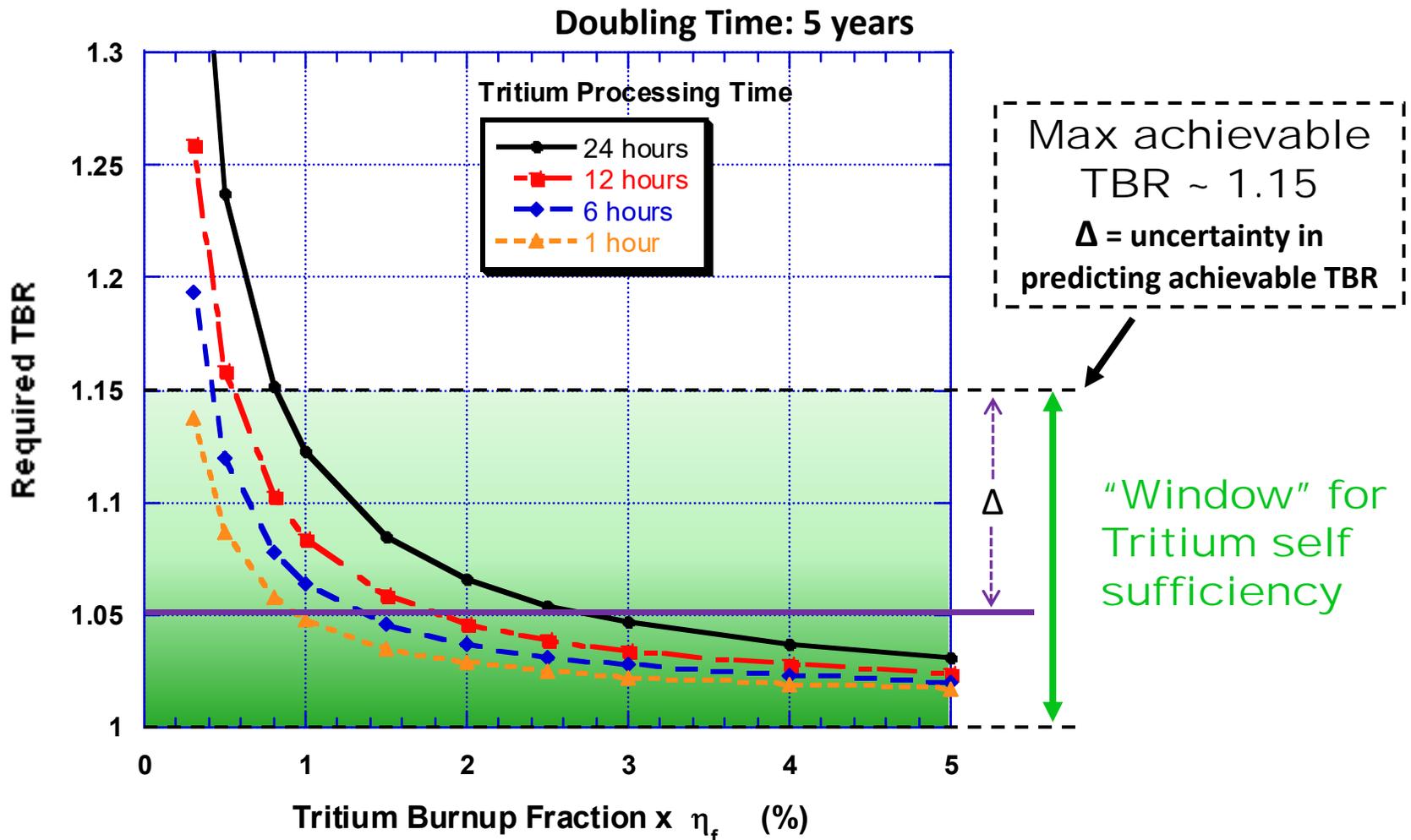
Inefficiency, $\varepsilon = 0.01\%$

Blanket mean residence time = 10 days



Physics x Technology Advances

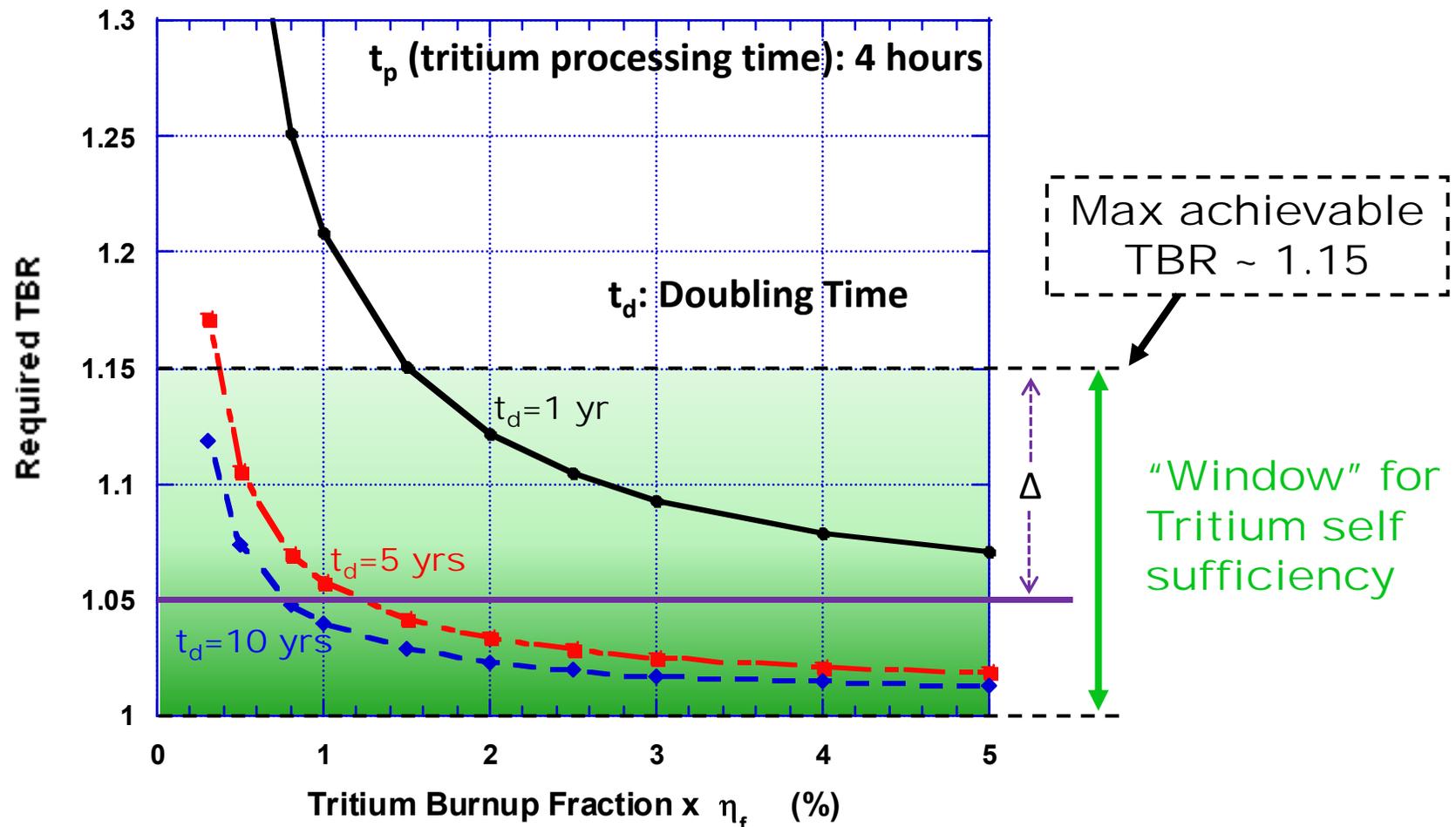
Required TBR and Achieving T Self-Sufficiency are strongly dependent on $f_b \times \eta_f$ and t_p



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

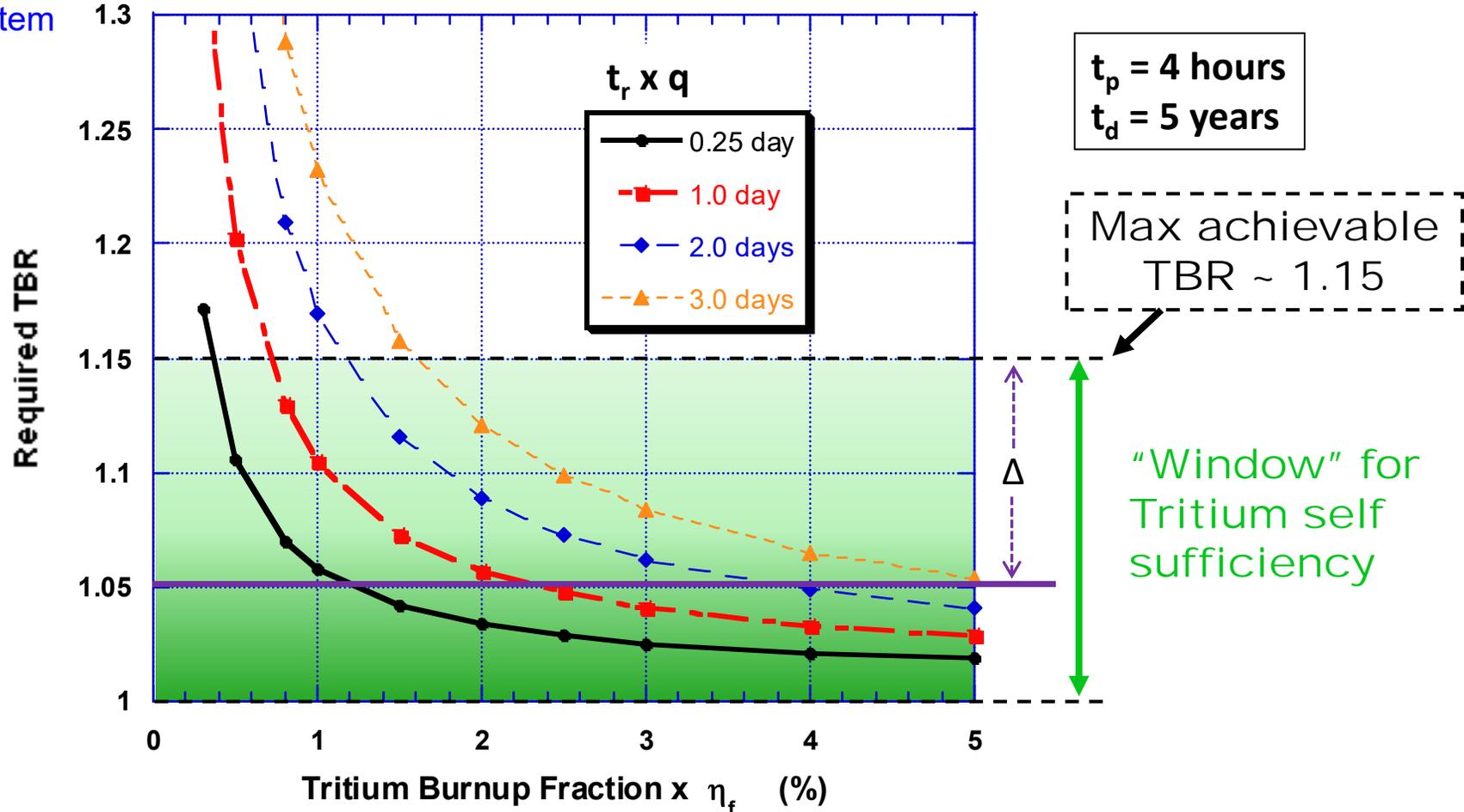


- For Mature Power Industry, typical doubling time is ~7 years
- For Fusion from demonstration to initial commercialization stage, relatively short doubling time (e.g. 1 year) is needed
- This will not be possible if $f_b \times \eta_f < 1\%$ even if $t_p \sim 4$ hrs. It is attainable with higher $f_b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

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

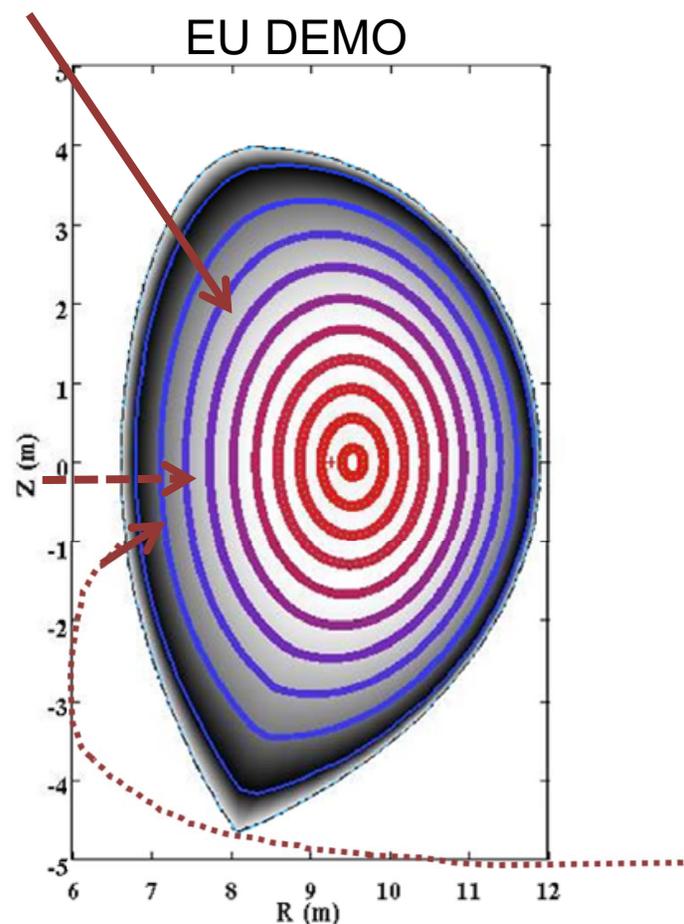
What is the State-of-the-Art for η_f , f_b , and t_p ?

And What Should be the Goals for R&D?

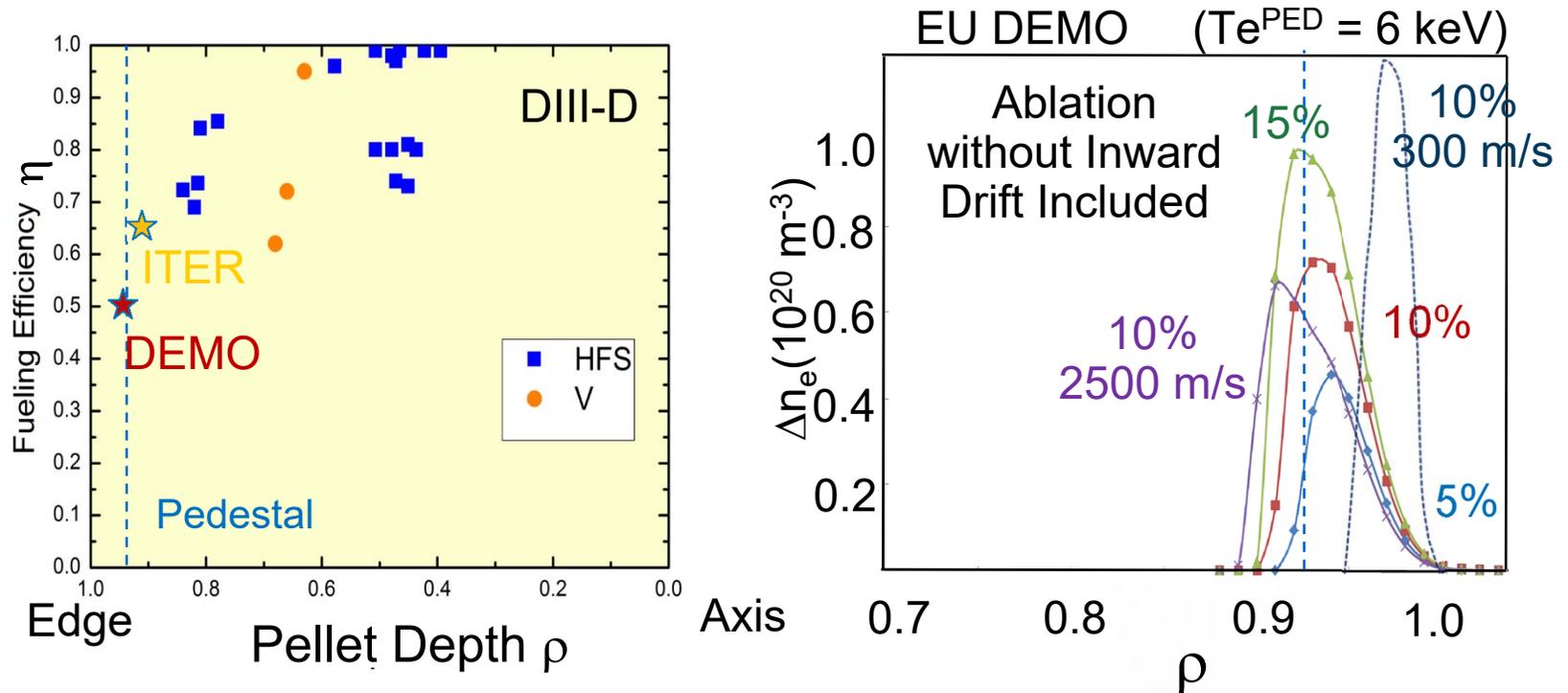
Fusion Fueling Efficiency Summary

(Summary from Larry Baylor 1/2)

- Gas fueling/recycling expected to be highly inefficient: recycling coefficient $R \sim 0$
- High fueling efficiency $> 50\%$ can possibly be achieved with suitable high speed High-Field Side (HFS) pellet injection in a tokamak DEMO
 - A stellarator DEMO would also need high speed pellets
- ELM impact on HFS pellet fueling efficiency remains an open question
- Calculations of pellet penetration for DEMO conditions show penetration to the pedestal top is possible with HFS injection – optimal location under study



Fueling Efficiency **Extrapolation** from Deep to Shallow Penetrating Pellets Expected in ITER and DEMO is **Highly Uncertain** but can Possibly Exceed 50% (Summary from Larry Baylor 2/2)



- **Extrapolation from present small tokamaks to ITER and DEMO is highly uncertain, η is likely less in DEMO than ITER from more shallow penetration.**
- Ablation profiles (no drift included) show penetration possible to pedestal top with high speed pellets (% density perturbation), but not with slow speed from inner wall.

Tritium Burn Fraction (f_b)

f_b = fusion reaction rate / tritium fueling rate

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

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
$$f_b = 1 / \left(1 + \frac{2}{n \tau^* \langle \sigma v \rangle} \right)$$

$\tau^* = \tau / (1 - R)$ 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: $R \sim 0$**
- Reactor studies must change the unfounded assumption of $R \sim 0.95$ to $R \sim 0$ and confront the issue of extremely low R , low f_b
- **For ITER, $f_b \sim 0.3\%$** 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 10% (at least 5%) 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 .** Loarte and others reported on new ideas in the IAEA DEMO workshop in Nov 2016

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 $\text{Pam}^{-3}\text{s}^{-1}$) 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)

- $\Gamma_{\text{T}}^{\text{burn}} = 0.35 \text{ Pam}^{-3}\text{s}^{-1}$ $\Gamma_{\text{T}}^{\text{fueling}} = 100 \text{ Pam}^{-3}\text{s}^{-1}$

$$\Gamma_{\text{T}}^{\text{burn}} / \Gamma_{\text{T}}^{\text{fueling}} = 0.35 \%$$

Very conservative → 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 $130 \text{ Pam}^{-3}\text{s}^{-1}$ → requirements for He exhaust are less demanding ($\sim 40 \text{ Pam}^{-3}\text{s}^{-1}$ out of a maximum of $200 \text{ Pam}^{-3}\text{s}^{-1}$)
- **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**
 - $\Gamma_{\text{T}}^{\text{burn}} = 0.35 \text{ Pam}^{-3}\text{s}^{-1}$, $\Gamma_{\text{T}}^{\text{fueling}} = 15\text{-}30 \text{ Pam}^{-3}\text{s}^{-1}$ →
 $\Gamma_{\text{T}}^{\text{burn}} / \Gamma_{\text{T}}^{\text{fueling}} = 1.2 - 2.3 \%$

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 :
 - ✓ Required edge density (and associated gas fueling) to achieve power load control (i.e. power e-folding length λ_p)
 - ✓ 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 maybe reduced due to more likely triggering of ELMs after injection of fueling pellets
 - ✓ Higher core radiation and associated edge impurity density can cause pedestal inwards DT pinch which can improve net efficiency of gas fueling in DEMO compared to ITER

Tritium Processing Time, t_p

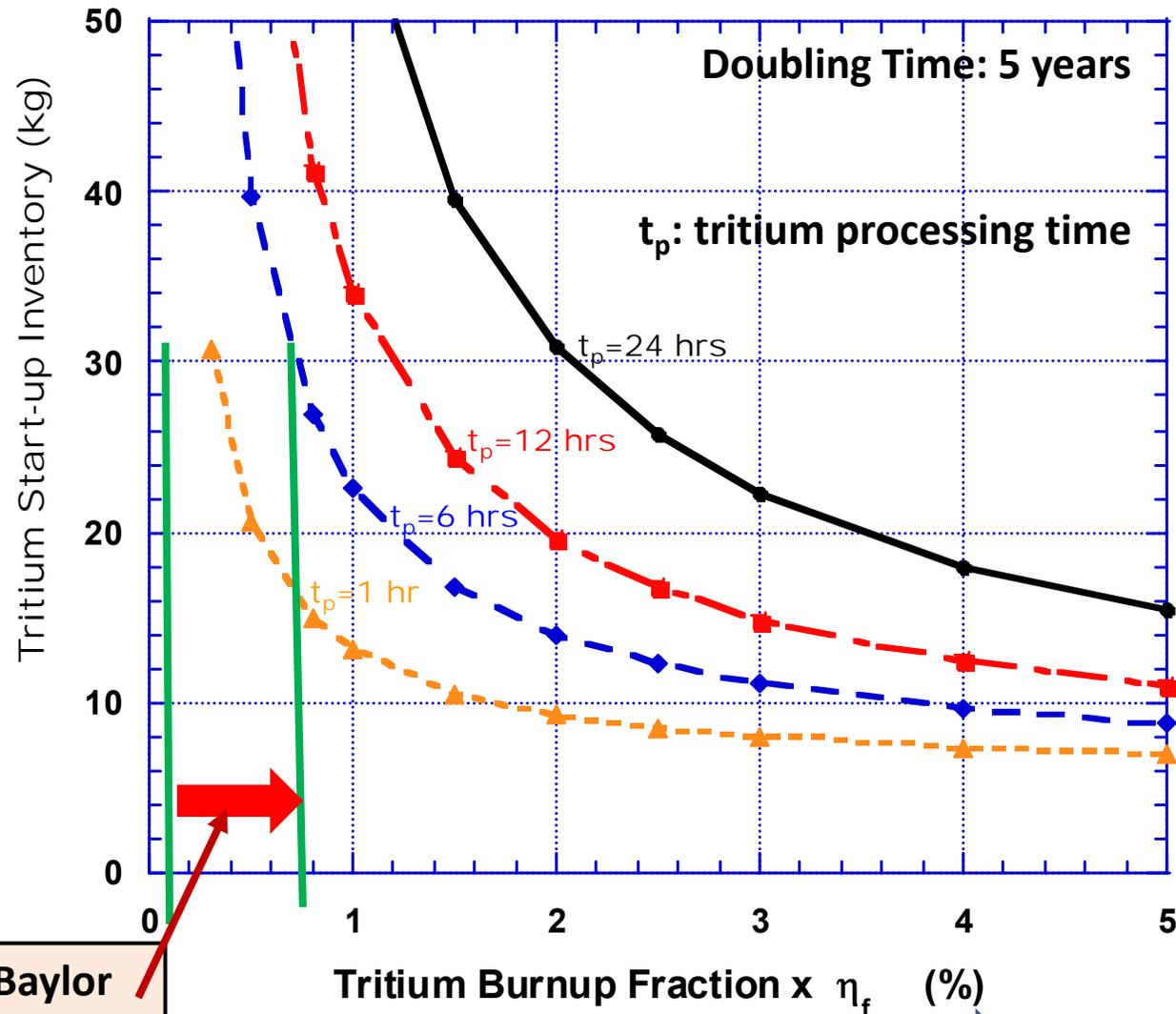
- In 1986, **TSTA** at LANL demonstrated tritium processing time, $t_p \sim 24$ hours
- Reactor Design Studies in the 1970's to 2000's assumed t_p similar to that from TSTA
- **ITER** has a tritium fuel cycle comparable to DEMO for plasma exhaust processing but with big differences in plasma duty cycle 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 $t_p \sim 1$ hr if achievable.
- **State-of-the-art prediction for DEMO and beyond:**
 - $t_p \sim 2-6$ hr likely achievable

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

Burn fraction
 ~ 1.5%
 HFS fueling efficiency
 ~ 50%
 $t_p \sim 2 - 6$ hrs

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

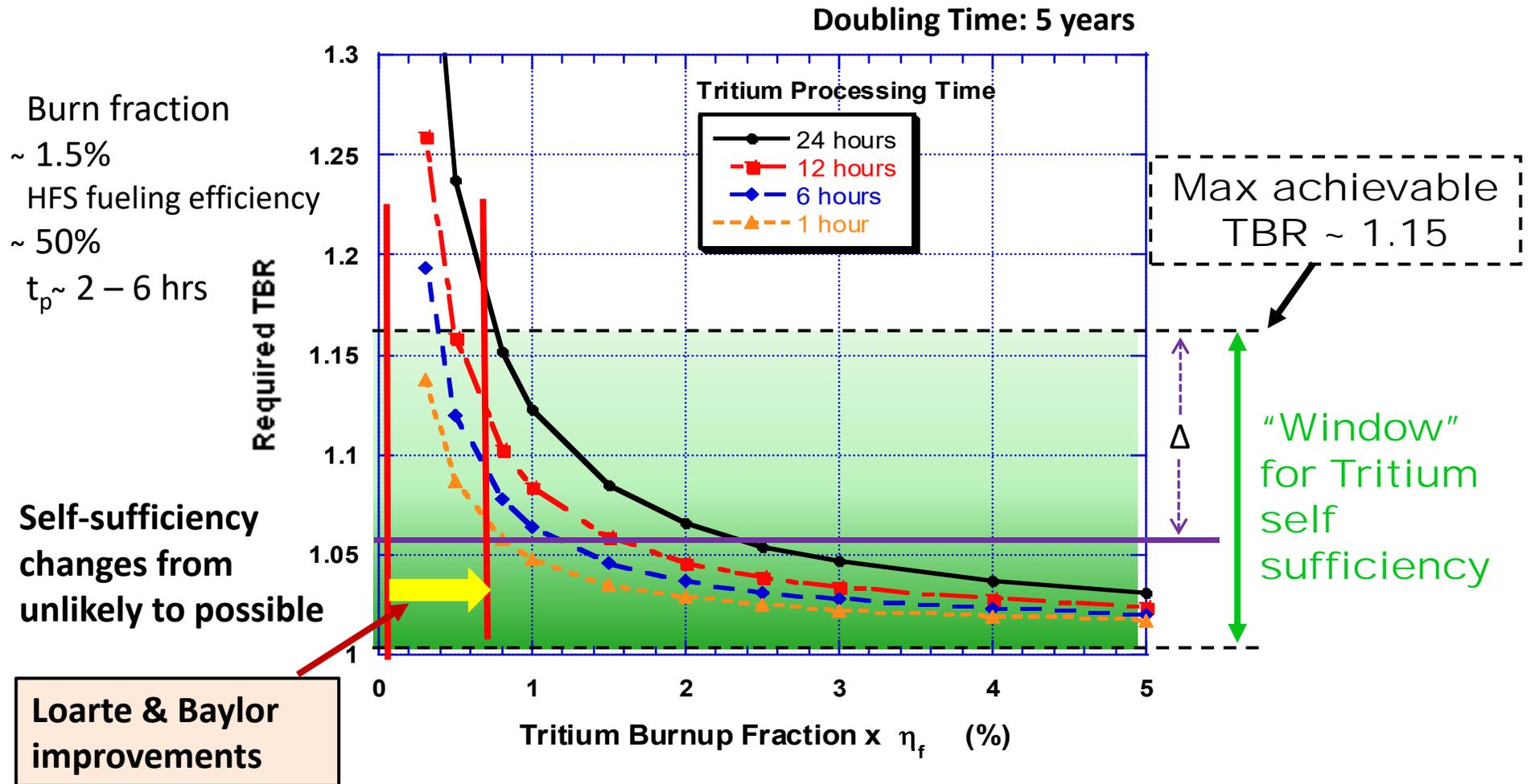
Remarkable Progress but Major improvements are still needed!!



Loarte & Baylor improvements

Physics x Technology Advances

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 also **improve confidence in achieving tritium self-sufficiency**



Major improvements still needed for attaining Tritium Self Sufficiency with higher confidence level.

The goal for R & D should be to achieve:

- UCLA** T burnup fraction (f_b) \times fueling efficiency (η_f) $> 5\%$ (not less than 2%)
- T processing time (in Plasma exhaust/fueling cycle) < 6 hours

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 to ~5 kg
- 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 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)

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

The Issue of External Tritium Supply from non-fusion sources is Serious and has Major Implications on Fusion Development Pathway

Tritium Consumption in Fusion is HUGE! Unprecedented!

55.8 kg per 1000 MW fusion power per year

Production in fission is much smaller & Cost is very high:

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

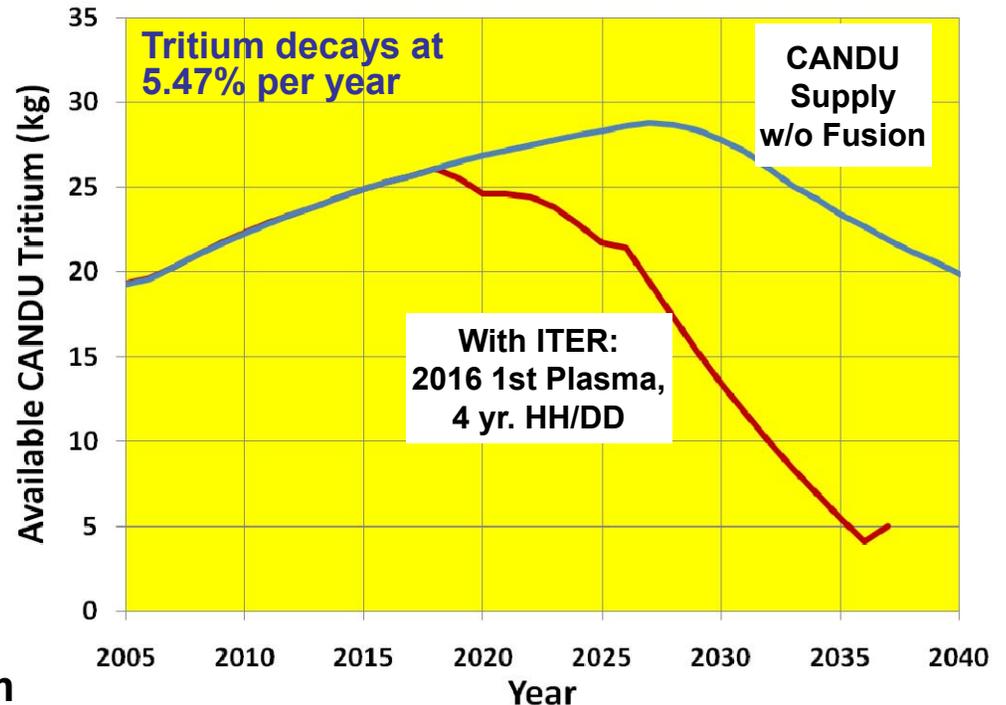
Typical CANDU ~ .2 Kg per GWe per fpy

CANDU Ontario: With production/ decay over 40 years of operation, supply will **peak at 27 kg** in 2027

Future Supply from CANDU depends on whether current reactors can be licensed to extend life by 20 years after refurbishment. There are many political, national policy, and practical issues with both CANDU and LWR

Other non-fission sources (e.g. APT (proton-accelerator) proved totally uneconomical.

- **A Successful ITER will exhaust most of the world supply of tritium**
- **Availability of External Supply of Tritium beyond ITER is highly uncertain:**
 - If ITER DT were to start in 2020, there would be ~ 5 Kg left in 2035
 - With ITER DT current plan to start 2036, there may be no T left after ITER completion



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:

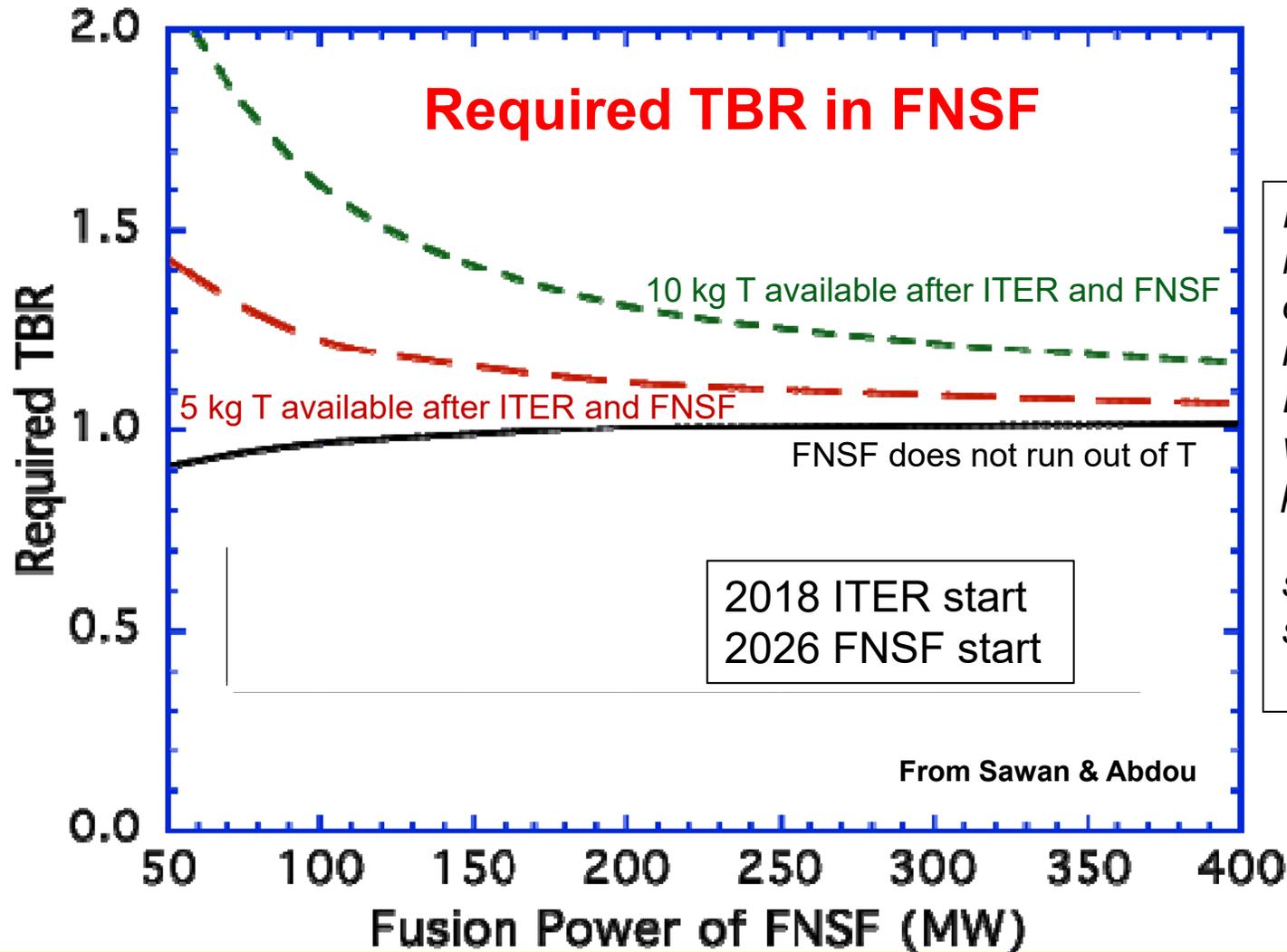
1. Provide startup T inventory for 2 or 3 DEMOs plus other facilities such as FNSF and CFETR
2. Provide replacement for any shortfall in satisfying T self-sufficiency in large power fusion devices

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** 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**

FNSF should be designed to breed tritium to:

- Achieve T self sufficiency, **AND**
- Accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO



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

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

Concluding Remarks (1 of 2)

- The development of Comprehensive **Dynamic Fuel Cycle Model** started 30 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. ~ 1 yr) in the critical stage from demonstration to initial commercialization

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)

Thank you

APPENDIX

Achievable TBR

The achievable TBR depends on many **technology, material, and physics design and operating conditions:**

- Concepts and materials used in chamber components (blanket/FW, divertor, etc.)
- FW thickness, amount of structure and non breeding materials
- Presence of stabilizing shells and conducting coils for plasma control and attaining advanced plasma physics modes
- Size and materials used in plasma heating and current drive components and fueling and exhaust penetrations
- Confinement scheme, primarily due to the impact on breeding blanket coverage and possible limitation on blanket thickness
- Uncertainties in predicting the achievable TBR should be accounted for when assessing the potential for achieving tritium self-sufficiency

Uncertainties in the Achievable TBR

Uncertainties in calculating the achievable TBR are in *three areas*:

1. System definition

Achievable TBR depends on many system parameters and design considerations that are not yet well defined (e.g. amount and configuration of structure, required FW thickness, using separate coolant and/or neutron multiplier, need for electric insulator, chamber penetrations, absorbing materials in stabilizing shells, divertors, and plasma heating/CD systems)

2. Modeling and calculation method

Uncertainties due to limitations of Calculation method (Monte Carlo, Sn) and the accuracy of the model (3-D) simulation of the detailed chamber configuration including all components with detailed design and material distribution and heterogeneity and accurate neutron source profile

3. Nuclear data

Uncertainties in measured cross section data, secondary neutron energy and angular distributions and their processing

Uncertainties in the Achievable TBR (Cont'd)

- **Uncertainties due to nuclear data, modeling, and calculation methods:**

Integral neutronics experiments in Japan and the EU showed that **calculations** of TBR **OVERESTIMATE** **experiments** by an average factor of **~1.14**

- The largest uncertainties in achievable TBR are due to shortcomings in **system design definition** associated with uncertainties in what is achievable in plasma physics and technological components

Achievable TBR

Analysis of current worldwide FW/Blanket concepts shows that achievable TBR ≤ 1.15 (see refs 3-6)

- But we must account for uncertainties.

Accounting for Uncertainties

- **At present there are uncertainties in predicting the Achievable and the Required TBR. Both are currently based on calculations and modelling, not measured in prototypical experiments**
- **A thorough statistical treatment of uncertainties in tritium fuel self-sufficiency is a complex area that was addressed in Ref.1**
- **At this early stage of fusion development, we propose that fusion physics and technology R & D should have the following guideline: **Estimated Achievable TBR should exceed the estimated Required TBR by a margin, Δ . Current estimates suggest Δ of $\sim 10\%$****
- **This margin does not account for uncertainties due to major changes in design definition**

Conclusions on Tritium Self-Sufficiency

We have identified a “phase space” of physics and technology conditions in which tritium self-sufficiency can be attained. Our R & D in plasma physics, blanket technology, and fuel cycle must aim at ensuring tritium self-sufficiency. In particular, our **R & D Goals** should:

Minimize Tritium Inventories and Reduce Required TBR

- T burnup fraction x fueling efficiency > 5% (not less than 2%)
- Tritium processing time (in plasma exhaust/fueling cycle) < 6 hours
- Minimize Tritium Inventories in Blanket, PFC, other components
- Minimize tritium processing time in breeder and coolants cycles

Ensure Achievable TBR is not significantly below the currently calculated value of 1.15

- Avoid Design choices that necessitate use of large neutron absorbing materials in blanket and divertor regions (challenges: **thickness of first wall** and divertors and blankets structure to handle **plasma off-normal** conditions such as disruptions, and ELMS; **passive coils** inside the blanket region for plasma stabilization and attaining advanced plasma physics mode)
- Aim the R & D for subsystems that involve **penetrations** such as impurity control/exhaust and plasma auxiliary heating to focus on design options that result in minimum impact on TBR

When Can We Accurately Predict , Verify, and Validate Achievable TBR?

ONLY After we have:

1. Detailed, accurate definition of the design of the in-vessel components (PFC, First Wall/Blanket, penetrations, etc.). This can be realized only after actual blankets are tested in the real fusion nuclear environment.
2. Prototypical accurate integral neutronics experiments:
 - This can be achieved only in DT-plasma-based facility
 - Current integral experiments are limited to point neutron source with $S < 5 \times 10^{12}$ n/s. Does not allow a) accurate simulation of angular neutron flux, b) complex geometry with subsystem details and heterogeneity. (Efforts on such experiments showed that calculations differ from experiments by ~10%)

Analysis has shown that at least a “full sector” testing in fusion facility is required for accurate measurement of achievable TBR.

(Uncertainties in extrapolation in the poloidal direction from module is larger than the required accuracy.)

Role of ITER in Resolving Tritium Fuel Cycle Issues and Demonstrating the Principles of Tritium Self-Sufficiency

- ❑ We will learn from ITER (and other physics devices) what tritium burn fraction and fueling efficiency are achievable.
 - **ITER must explore methods to increase f_b and η_f .**
- ❑ Work on ITER fuel processing systems will help quantify inventories, flow rates, and processing times required in fusion at near reactor scale (for plasma exhaust/fueling cycle).
- ❑ **ITER TBM will provide important information on some aspects related to the achievable TBR : initial verification of codes, models, and data (but not reliable prediction of the achievable TBR)**

Demonstration of tritium self-sufficiency requires another DT fusion facility (e.g. FNSF), in addition to ITER, in which full breeding blankets, or at least “**complete sectors**”, efficient plasma fueling, fast plasma exhaust processing, and fully integrated tritium processing systems can be tested.

Tritium Control and Management

- Tritium control and management will be one of the most difficult issues for fusion energy development, both from the technical challenge and from the “public acceptance” points of view.
- Experts believe the T-control problem is underestimated (maybe even for ITER!)
- ***The T-control problem in perspective:***
 - ***The scale-up from present CANDU experience to ITER and DEMO is striking:***
The quantity of tritium to be managed in the ITER fuel cycle is much larger than the quantities typically managed in CANDU or military reactors (which represents the present-day state of practical knowledge).
 - ***The scale-up from ITER to DEMO is orders of magnitude:***
The amount of tritium to be managed in a DEMO blanket (production rate ~400 g/day) is several orders of magnitude larger than that expected in ITER, **while the allowable T-releases could be comparable.**

For more details, see:

- W. Farabolini et al, “Tritium Control Modelling in an He-cooled PbLi Blanket...” paper in ISFNT-7 (this conference)
- Papers and IEA Reports by Sze, Giancarli, Tanaka, Konys, etc.

Why is Tritium Permeation a Problem?

- Most fusion blankets have high tritium **partial pressure**:
LiPb = 0.014 Pa ? Flibe = 380 Pa
He purge gas in solid breeders = 0.6 Pa
 - The **temperature** of the blanket is high (500–700°C)
 - Surface area of heat exchanger is large, with thin walls
 - Tritium is in **elementary form**
- These are perfect conditions for tritium permeation.***
- The allowable tritium loss rate is very low (~10 Ci/day), requiring a partial pressure of $\sim 10^{-9}$ Pa.
- Challenging!***
- *Even a tritium permeation barrier with a permeation reduction factor (PRF) of 100 may be still too far from solving this problem!*

Tritium Permeation will Depend Strongly on blanket concept/behavior including many phenomena in the blanket/FW that **we do not yet know or understand**

Example 1: Detailed analysis of tritium permeation that considers details of fluid flow show that T permeation in HCLL is much larger than DCLL because :

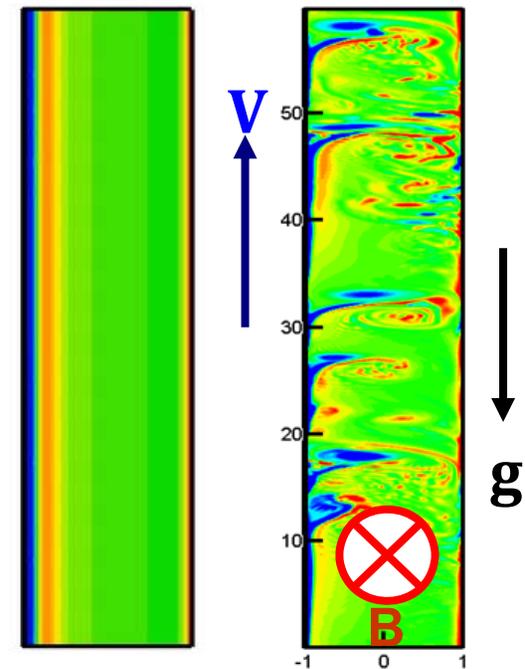
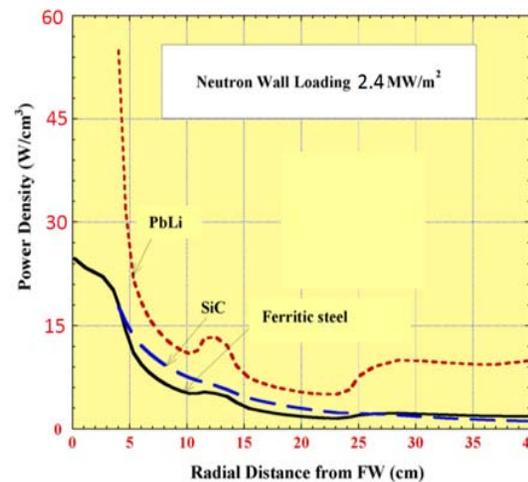
1. higher flow speed of PbLi in DCLL results in lower T partial pressure
2. the SiC flow channel insert acts as T barrier

Example 2:

New UCLA Discovery that LM MHD flow is “mixed convection” (not laminar as previously assumed) means new instabilities will strongly affect tritium transport and tritium permeation.

The mixed convection phenomena will be examined in new MaPLE upgrade facility at UCLA (joint collaboration with EUROfusion). Results are expected in ~2 years. These results will substantially alter our predictions of tritium permeation.

Vorticity Field shows new instabilities that affect transport phenomena (Heat, T, Corrosion)



UCLA

Information and key References on the development of the Dynamic Modeling of the tritium fuel cycle and the physics and technology requirements for Tritium Self-Sufficiency

1. M. Abdou, et. al., "Deuterium-Tritium Fuel Self-Sufficiency in Fusion Reactors", *Fusion Technology*, 9: 250-285 (1986).

This was the first and remains the primary reference in the field. It is a comprehensive paper that described the results of very detailed model development and serious investigation of conditions for T self-sufficiency:

- Detailed description of comprehensive dynamic model to predict time-dependent T flow rates and inventories and detailed derivation of Required TBR as a function of physics and technology parameters
- Developed quantitative conditions for attaining T self-sufficiency
- Evaluated Required TBR and Achievable TBR for a wide range of physics and technology parameters and conditions
- Developed statistical model to evaluate and quantify uncertainties
- Defined a phase space of physics and technology conditions for satisfying T self-sufficiency conditions, compared the state of the art and derived recommendations for R&D (e.g T burn fraction , fueling efficiency, T processing time, materials and configurations for blanket/FW/divertor,)
- **This paper motivated many initiatives in physics, fusion technology, T processing Technology in US, EU & Japan over 3 decades and recently sparked new research in China, Korea, and India**

Information and key References(cont'd)

2. W. Kuan and M. Abdou, "A New Approach for Assessing the Required Tritium Breeding Ratio and Startup Inventory in Future Fusion Reactors", *Fusion Technology*, 35: 309-353 (1999).

(part of Kuan PhD Thesis with Abdou & Willms)

- Developed detailed models for all subcomponents of the tritium processing systems (e.g. Impurity separation, ISS, ..) to derive expressions for “mean residence time” for use in the Ref 1 model.
- Detailed analysis that confirmed results of Ref 1

3. M. Sawan, M. Abdou, "Physics and Technology Conditions for attaining Tritium Self-Sufficiency for the DT Fuel Cycle", *Fusion Engineering & Design*, 81:(8–14), 1131–1144 (2006).

- Summarized model and results of Ref 1
- Added specific evaluation of likely achievable TBR in current blanket concepts and systems

Information and key References(cont'd)

4. M. Abdou, H. Liu, A.Ying “Plasma physics and technology R&D requirements to attain tritium self-sufficiency and reduce tritium inventories and fusion systems” to be submitted soon for journal publication.

- More details were added to the model of reference 1 and added explicit treatment of additional parameters in the tritium processing system
- Added very explicit treatment of the start-up inventory as well as tritium inventories in various components
- Performed very detailed analysis to predict time dependent tritium inventories and flow rates, start-up inventory, required TBR as a function of many physics and technology conditions and parameters
- Derived the phase space and the required R&D for many key parameters that have impact on tritium self-sufficiency, start-up inventory and safety

5. M. Abdou et al "Blanket Technology, Fuel Cycle and Tritium Self-Sufficiency", presented for the JASON Study on Tritium Production in Fusion, San Diego, CA, June 27-28, 2011.

- This was comprehensive PPT presentation that summarized the state of the art and required R&D

Information and key References(cont'd)

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

- Section 3.1 summarizes all the recent results from reference 4 (good summary until reference 4 gets submitted and published)

7. Ni Muiyi, et al. Tritium supply assessment for ITER and DEMOnstration power plant. Fusion Eng. Des. 88(9-10) 2013, 2422-2426.

- PhD. Thesis of Muiyi Ni developed dynamic modeling of the tritium fuel cycle for China following the methodology of reference 1
- In reference 7 he made important assessment of the tritium supply issue

There are of course many publications and presentations in the field relating to various aspects of the tritium fuel cycle, tritium breeding, etc. The above references are the key references related to the development of the Dynamic Modeling of the tritium fuel cycle and the physics and technology requirements for realizing low T inventories, low startup inventory and achieving Tritium Self-Sufficiency