Introduction to the Tritium Workshop Day and

Overview of the Tritium Fuel Cycle and Conditions for Tritium Fuel Self- Sufficiency and Other Tritium Issues

Mohamed Abdou

4th IAEA DEMO Programme Workshop
November 15th-18th, 2016 - Karlsruhe, Germany

Tritium Workshop Day

Session Chair: Mohamed Abdou, Co-Chair: Scott Willms
Poster Session Coordinator: Paul Humrickouse

Goals:

The Tritium Workshop day presentations and discussions will focus primarily on the plasma physics and fusion technologies parameters and conditions required to attain Tritium Self-Sufficiency in fusion DEMO and Power Plants.

Speakers and discussions among workshop participants will:

A. Identify the key plasma physics and fusion technology conditions that will have the largest impact on the “required TBR” and the “achievable TBR”,

B. Evaluate the current status of the relevant key areas in physics and technology and predictions for ITER,

C. Provide Predictions for DEMO and Power plants and needed improvements, and

D. Identify required R&D.

Agenda Tritium: Topic 1

Tuesday, November 15th 2016

09:20	Introduction and overview of the tritium fuel cycle and conditions for self sufficiency	Mohamed Abdou (UCLA)	40	20
10:20	Coffee/Tea break		20	
10:40	The plasma physics aspects of the tritium burn fraction and the prediction for ITER	Alberto Loarte (ITER)/ David Campbell (ITER)	40	20
11:40	Predictions for plasma fueling efficiency based on experiments and modelling	Larry Baylor (ORNL)	20	10
12:10	Lunch + posters		100	
13:50	Tritium technology for ITER	Scott Wilms (TTER)	30	15
14:35	T Technology R&D for DEMO and required extrapolations beyond ITER	Christian Day (KIT)	30	15
15:20	Tritium Transport, Permeation and Control	Paul Humrickhouse (INL)	30	15
16:05	Coffee/Tea break		20	
16:25	Availability of tritium	Michael Kovari (CCFE)	30	15
17:10	Tritium discussion	Mohamed Abdou and ALL		30
17:40	adjourn			

Tritium Posters

POSTER TITLE:	AUTHOR:	AFFILIATION:
Tritium permeation to cooling water and environments for DEMO	Kazunari Katayama	AEES, Kyushu University, Japan
Research Activities Related Tritium Processing for Fusion Energy in Korea	Min Ho Chang	Fuel Cycle Technology Team, ITER KOREA, NFRI, Korea
A Hierarchical Approach for Dynamic Tritium Modeling Development for a Blanket System	Alice Ying	UCLA, USA
Yttria as a Tritium Permeation Barrier in Fusion Components	Jan Engels	Institut für Energie- und Klimaforschung – Plasmaphysik, Germany
Technical Challenges of Fusion Tritium Self-sufficiency under Debate	Muyi Ni	INEST, China
Tritium issues from the perspective of DEMO system design	Someya Youji	National Institutes for Quantum and Radiological Science and Technology, Japan
Safety in the Fusion Nuclear Science Facility	Paul Humrickhouse	INL, USA

Tritium Issues

1. Tritium Fuel Cycle and Tritium Self-Sufficiency
    a. Conditions for attaining tritium self sufficiency
    b. Dynamic modeling of the tritium fuel cycle
    c. Tritium Burn Fraction (in the plasma) and fueling efficiency
    d. Time required for Processing tritium in plasma exhaust & other streams
    e. Tritium inventories and Start-up requirements
    f. Required TBR: Dependence on plasma physics and technology
    g. Achievable TBR: Predictions and Uncertainties
    h. Phase Space of Physics and Technology Parameters and Conditions
    i. How, where and when tritium self sufficiency can be demonstrated
2. Tritium Extraction and Processing
3. Tritium Permeation and Control
4. Availability of External Tritium Supply for “startup” of early DT devices beyond ITER, e.g. FNSF and DEMO

Tritium Consumption and Production

Physical constants

- Half life of tritium: 12.32 years
- Mean life of tritium: 17.77 years
- Tritium decay rate: 5.47 %/yr

Tritium Consumption in Fusion Systems

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

Production and Cost in Fission Reactors

Fission Reactor (with special designs for T production): **~0.5-1 kg/year**

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

www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf

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

Successful ITER will consume almost all externally available tritium supply from CANDUs

Tritium self-sufficiency condition:
$\mathrm{TBR}_a \geq \mathrm{TBR}_r$

TBR_a= Achievable tritium breeding ratio

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

TBR_r = Required tritium breeding ratio

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

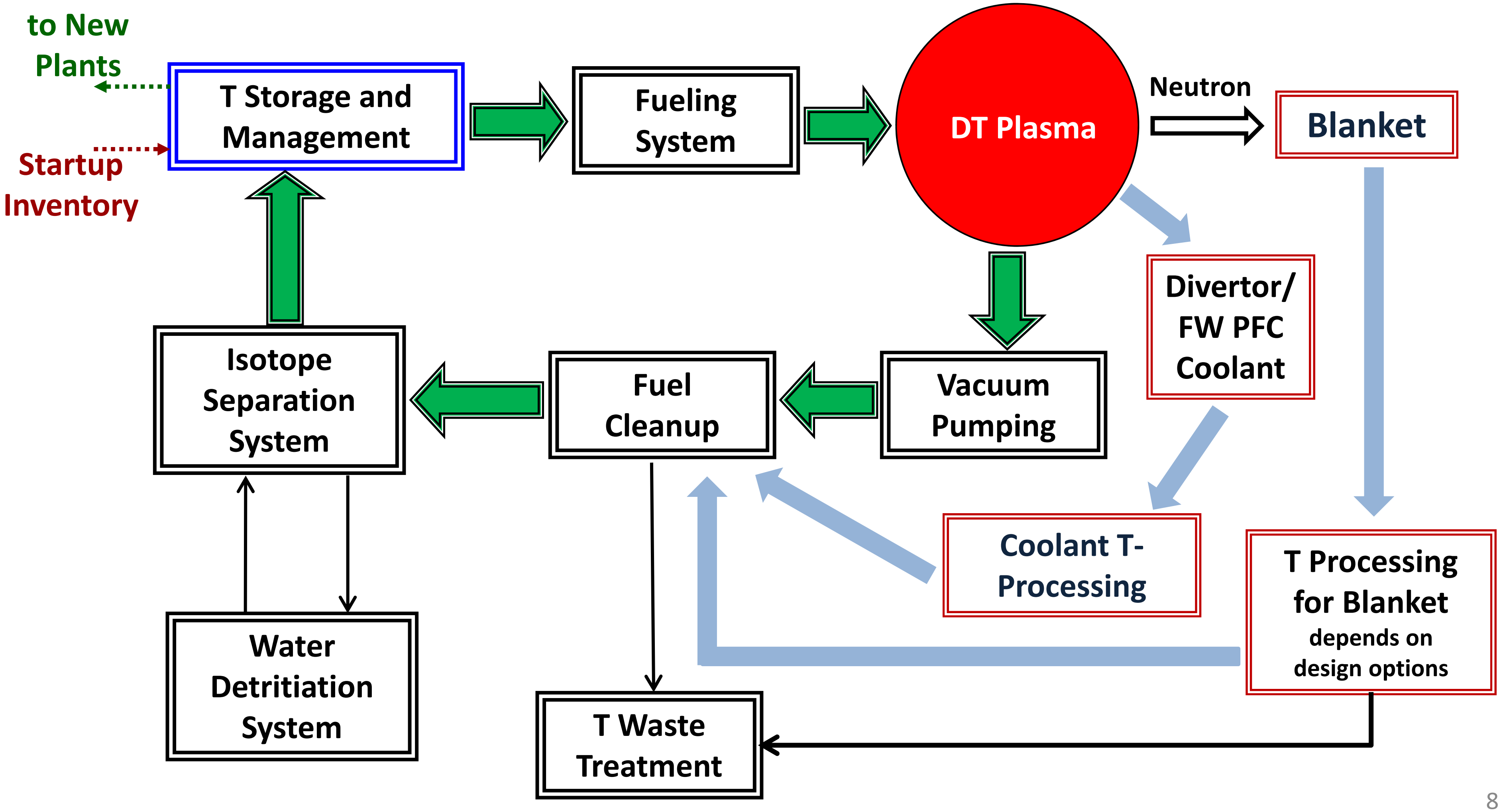
1) *Compensate for losses and radioactive decay (5.47% per year) of tritium between production and use*
2) *Supply tritium inventory for start-up of other reactors (for a specified doubling time)*
3) *Provide a "reserve" storage inventory necessary for continued reactor operation under certain conditions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

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

(Dynamic Fuel Cycle Modelling: Abdou/Kuan/Liu et al. 1986, 1999, 2015; **See Refs 1-6**)

Simplified Schematic of Fuel Cycle



Results show that the Key Parameters Affecting Tritium Inventories, and Hence, 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_{tp}
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, blanket)
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)

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

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

τ = particle confinement time

Status

η_f: Recent results: gas fueling is not efficient (η_f ~5%). (See Larry Baylor Talk)

Pellet fueling: η_f ~90% on high-field side, 50% for low-field side injection.

Results on ineffectiveness of gas fueling imply significantly smaller R, and hence much lower f_b than that assumed in rector studies

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f_b : ITER: ~0.3% estimated by ITER & others (See Alberto Loarte presentation)

Reactors? depends on assumptions on R (hope to learn a lot more on this TODAY)

Impact of Tritium Burn Fraction, Fueling Efficiency, and Tritium Processing Time on Tritium Inventory

$$I = I_{fe} + I_c$$

$I_{fe} \equiv$ Tritium inventory in systems associated with the plasma (fueling, exhaust, etc.)

$$I_{fe} = f\left(\mathrm{t_p} / \mathrm{f_b}\eta_\mathrm{f}\right)$$

t_p is the time for tritium processing (to go through the vacuum pumping, impurity separation, ISS, fuel fabrication and injection). Function of technology, design/cost trade-off

$I_c =$ Tritium inventory in other components, e.g. blanket, PFC

Fusion Program must aim at minimizing tritium inventories

Why large tritium inventory is unacceptable

- Safety
- "Start-up" inventory becomes large (not available from external sources)
- Required tritium breeding ratio becomes much higher

Status on Tritium Processing Time, t_p

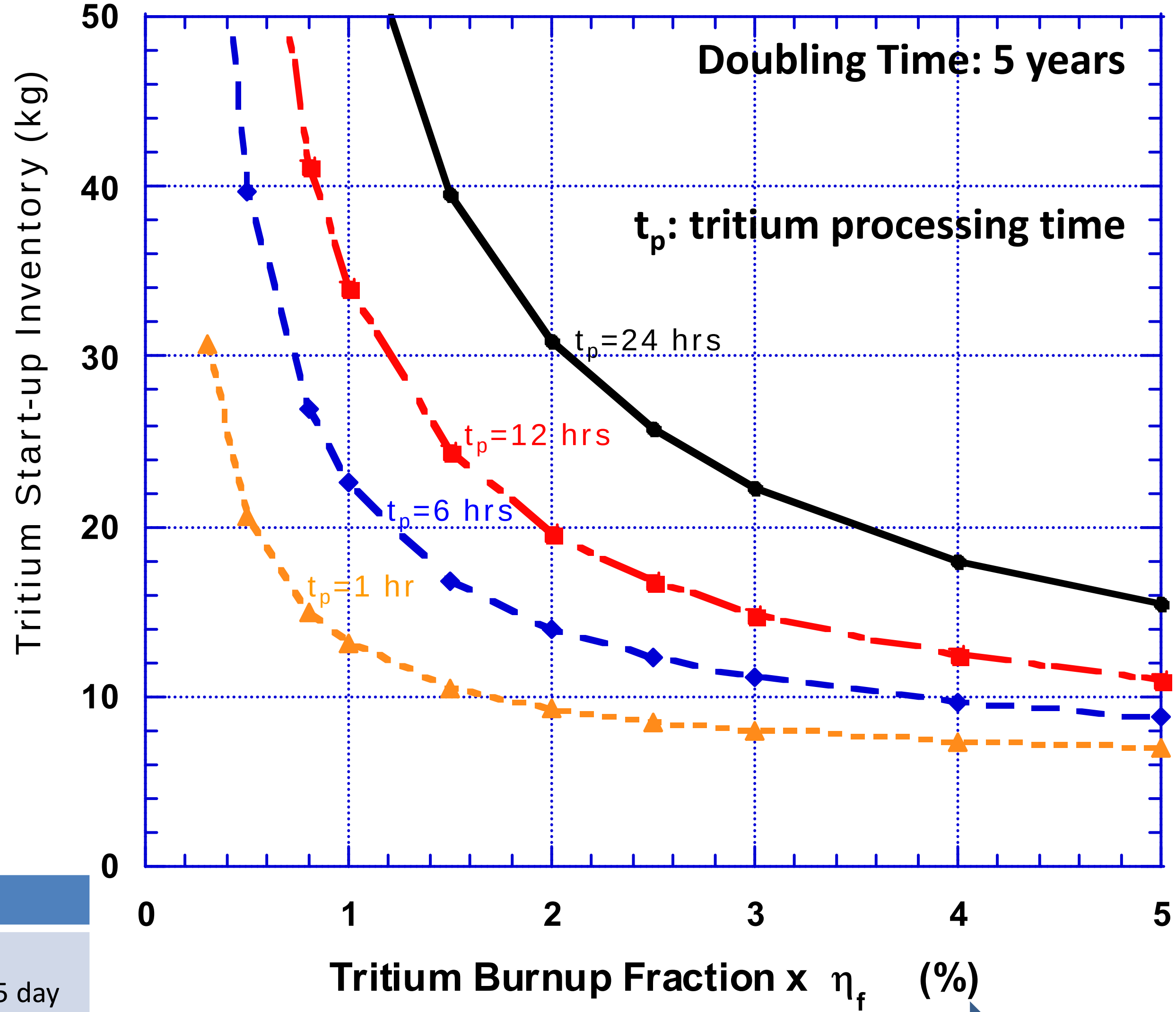
1970's-80's Reactor Designs (ANL, FED, etc) : 24 hours ; 1986 TSTA demonstrated < 24 hours

Current ITER Goal is t_p ~ 2 hour

Reactor: no reliable estimate yet, probably somewhere between ITER and TSTA

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

"Initial" Inventory ≡ "Start-up" Inventory



Technology Advances

Physics x Technology Advances

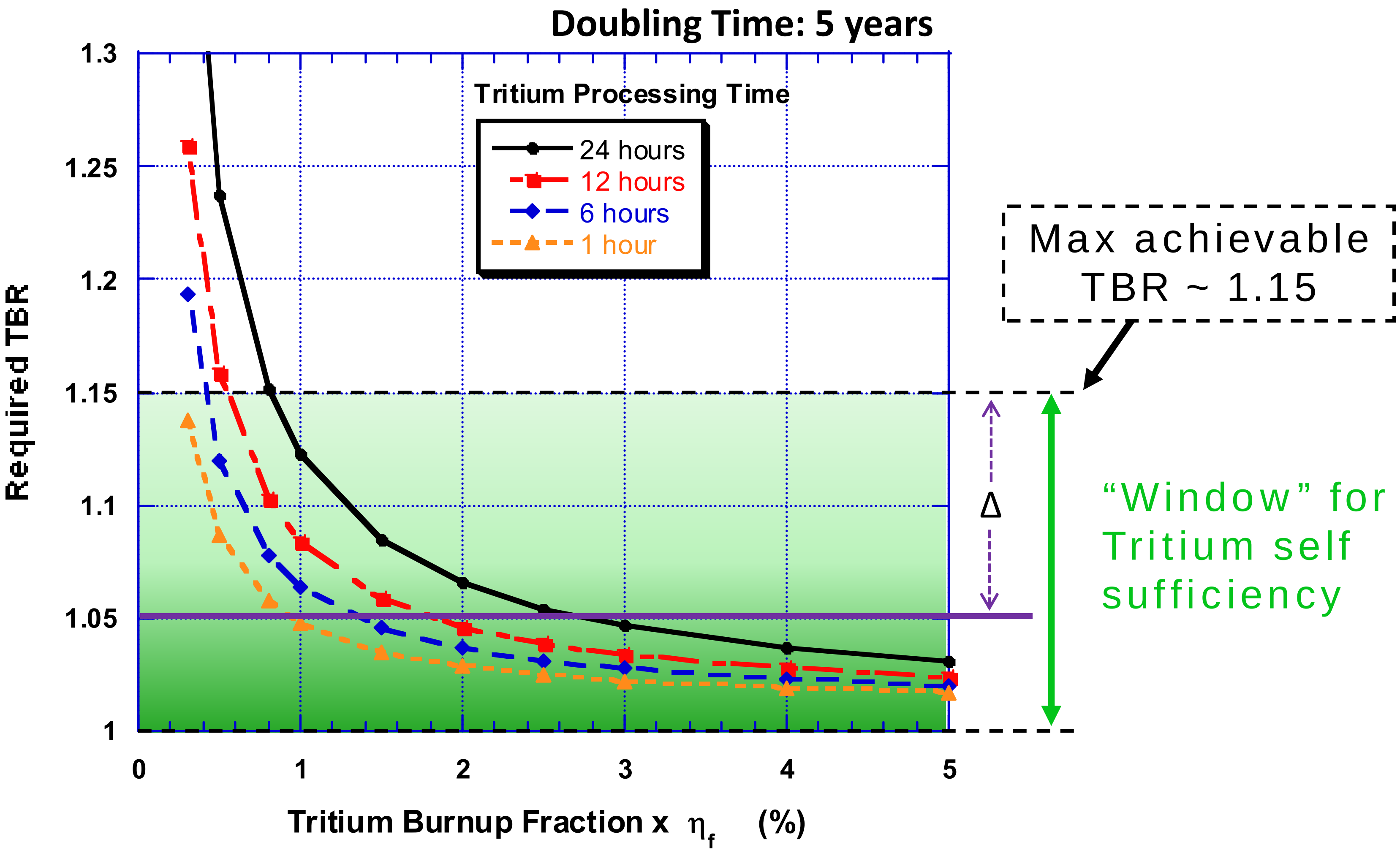
Fusion Power = 3000 MW

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

Inefficiency, ε = 0.01%

Blanket mean residence time = 10 days

Variation of Required TBR with f_b x η_f, and t_p



Max achievable TBR ~ 1.15

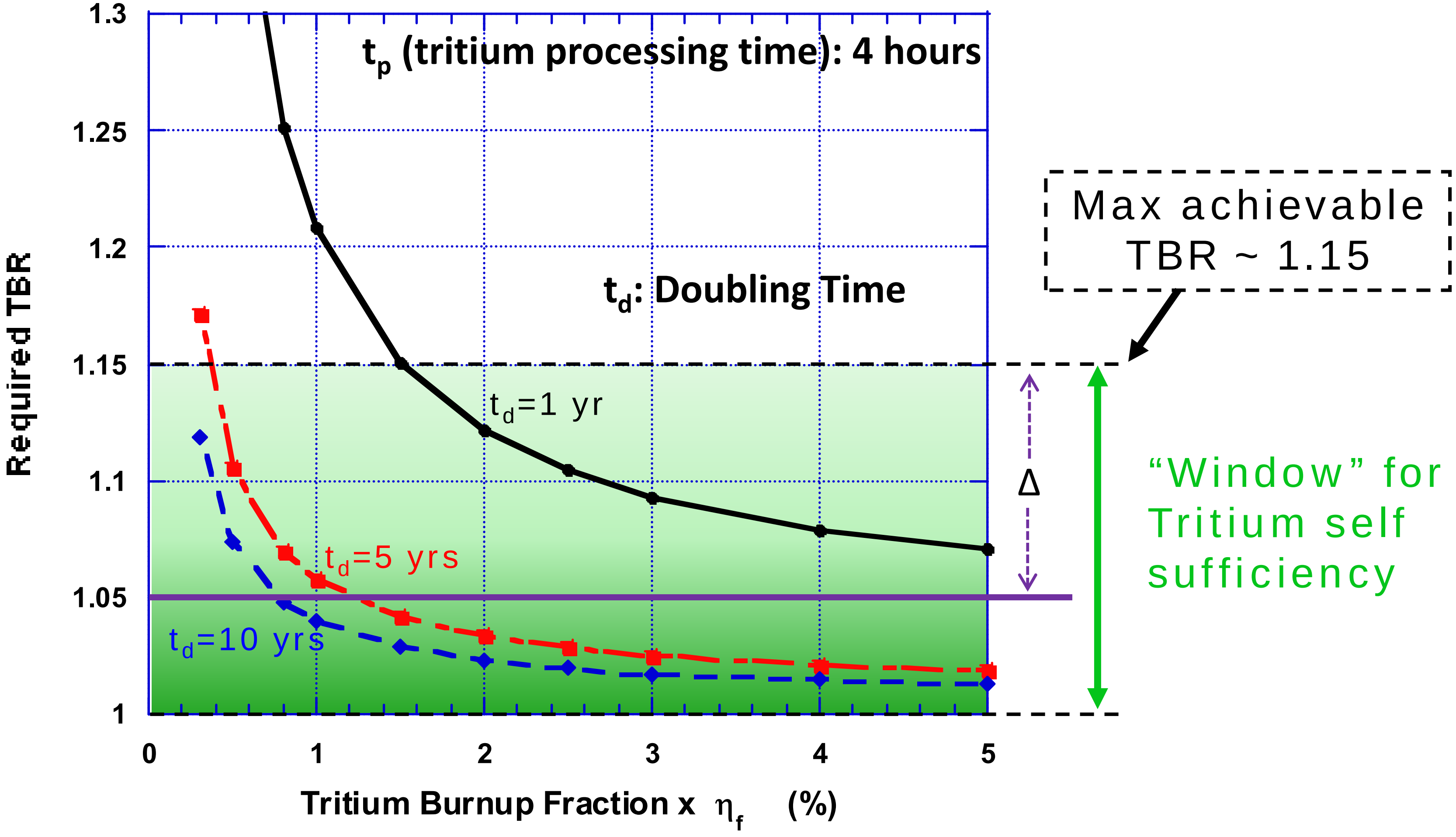
"Window" for Tritium self sufficiency

Attaining Tritium Self Sufficiency in DT Fusion Imposes Key Requirements on Physics and Technology. **The goal for R & D should be to achieve:**

T burnup fraction (f_b) x fueling efficiency (η_f) > 5% (not less than 2%)

T processing time (in Plasma exhaust/fueling cycle) < 6 hours

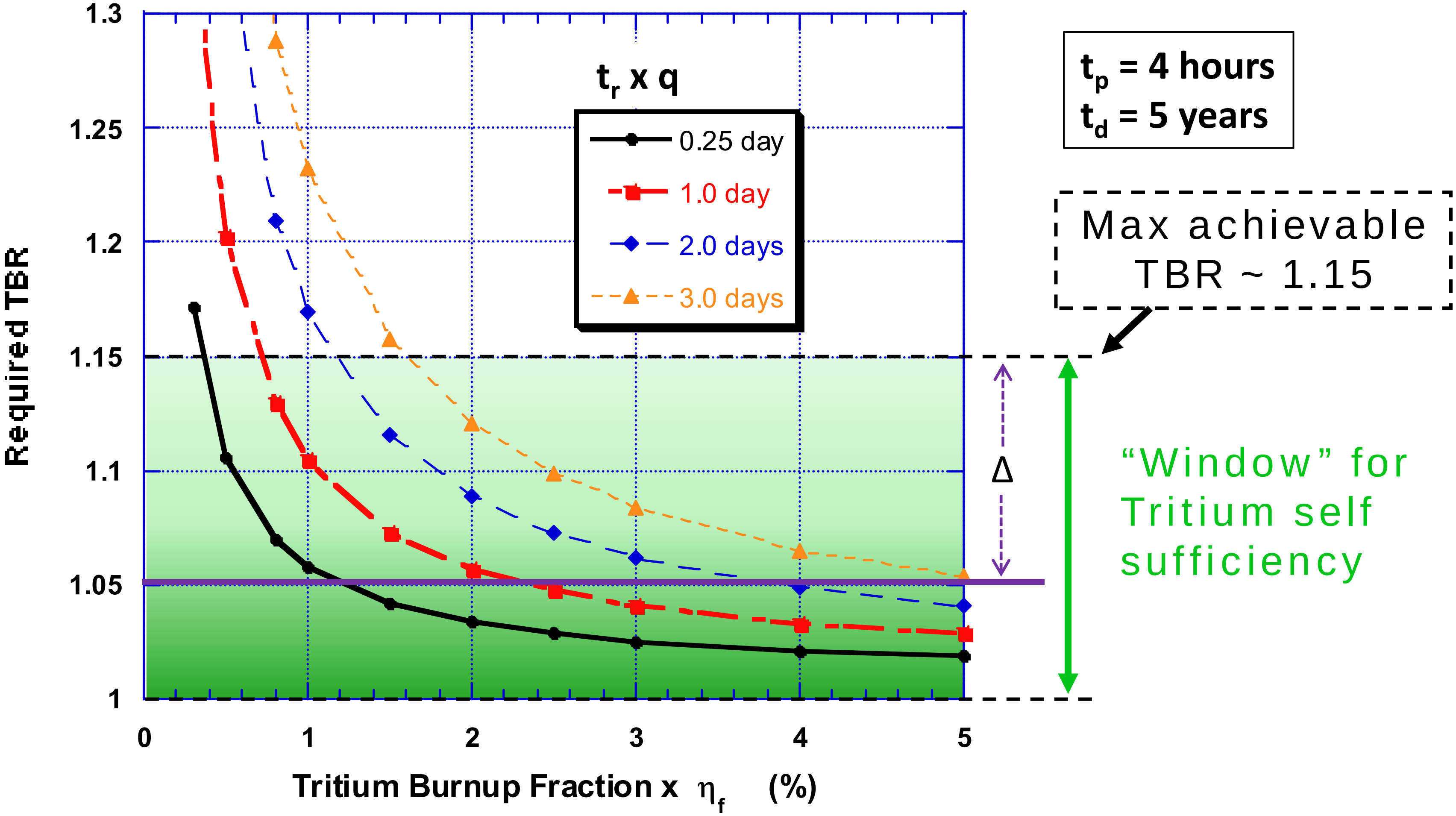
Variation of Required TBR with $f_b \times \eta_f$ and doubling time for short tritium processing time



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 as a function of f_b x η_f for different t_r x q values

t_r = reserve time for outage (days) q = fraction of the T processing system that has failure



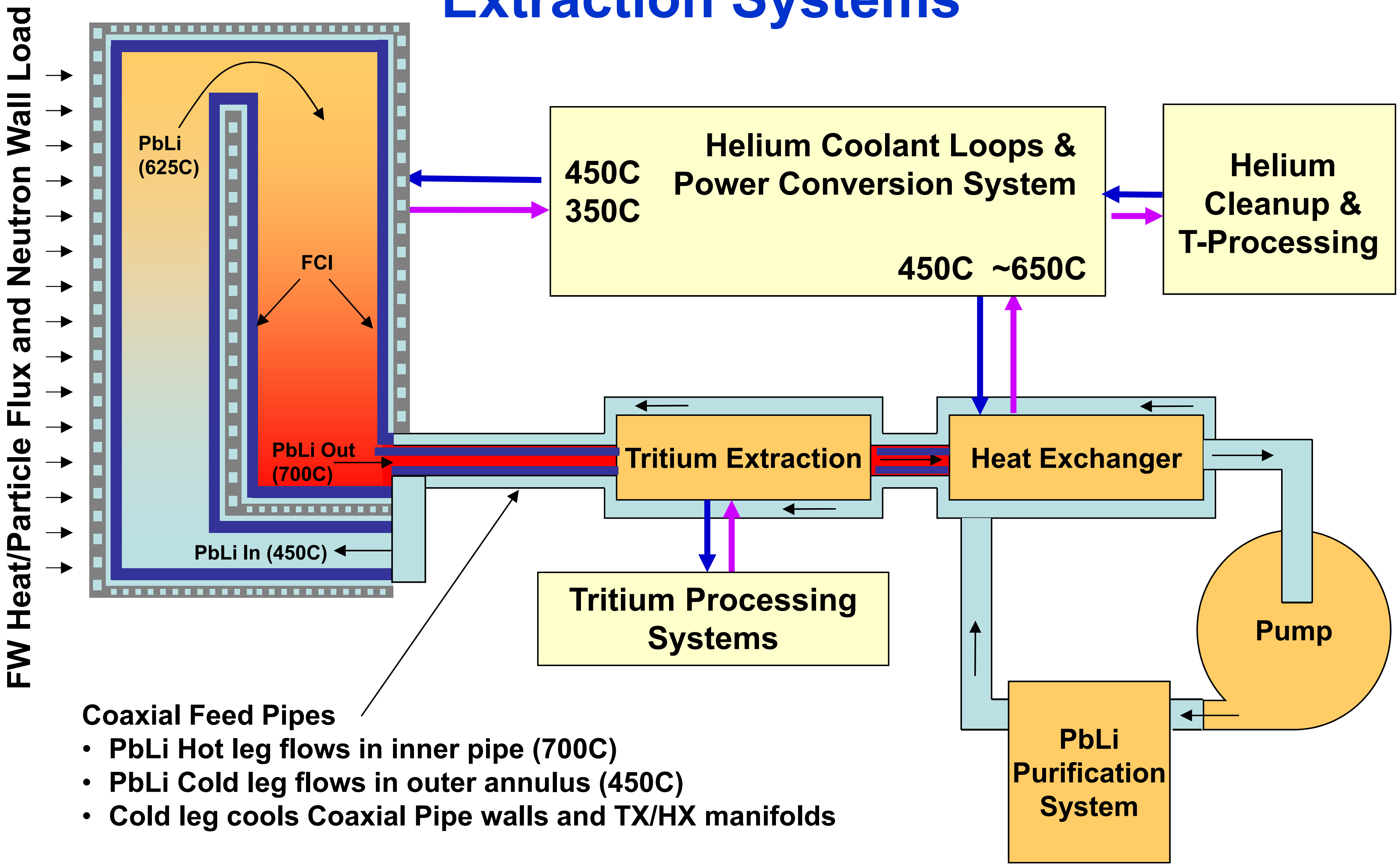
t_p = 4 hours
t_d = 5 years

Max achievable TBR ~ 1.15

“Window” for Tritium self sufficiency

- 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

A Simplified DCLL PbLi Transport and Tritium Extraction Systems



FW Heat/Particle Flux and Neutron Wall Load

PbLi (625C)

FCI

PbLi Out (700C)

PbLi In (450C)

450C
350C

Helium Coolant Loops & Power Conversion System

450C ~650C

Helium Cleanup & T-Processing

Tritium Extraction

Heat Exchanger

Tritium Processing Systems

Pump

PbLi Purification System

Coaxial Feed Pipes
- PbLi Hot leg flows in inner pipe (700C)
- PbLi Cold leg flows in outer annulus (450C)
- Cold leg cools Coaxial Pipe walls and TX/HX manifolds

Blanket Tritium Inventory, Breeder & Coolant Processing time; PFC Tritium inventories and coolants processing; and processes other than plasma exhaust/fuel T processing

Blanket/Breeder/Coolant

- Tritium Inventory in Breeding Blanket is <1 kg
  - This is based on calculations and some experiments
  - Radiation- induced sintering for ceramic breeder may increase T inventory to ~ 5 kg
- There are proposals/designs for the tritium processing systems from breeders, helium purge, and coolants. But no detailed engineering design or experimental data/verifications for such systems
- Based on available information, tritium inventories in such systems are < 1 kg and tritium processing time < 24 hours
  - **Much smaller impact on 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 TBR appears insignificant since such inventories would come out of the plasma exhaust/processing system (which is already accounted for in detail)

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 ~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.

The Issue of External Tritium Supply is Serious and Has Major Implications on FNST (and Fusion) Development Pathway

Tritium Consumption in Fusion is HUGE! Unprecedented!

55.6 kg per 1000 MW fusion power per year

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

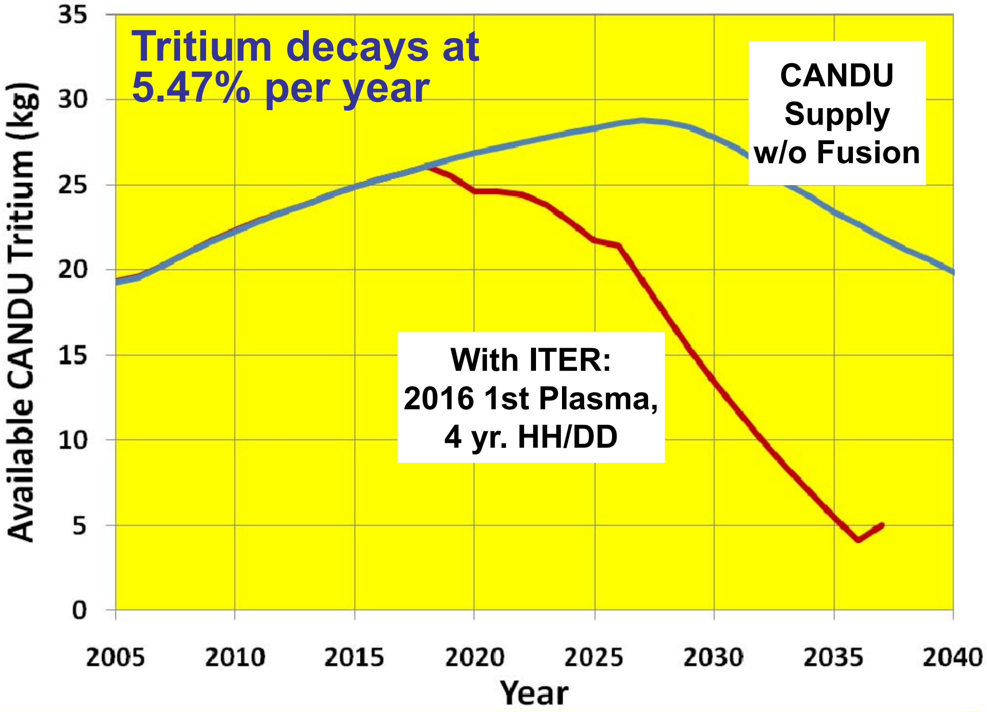
Fission reactors: ~0.5-1 kg/year

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

*www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf

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

- **A Successful ITER will exhaust most of the world supply of tritium**
- **No DT fusion devices other than ITER can be operated without a breeding blanket**
- **Development of breeding blanket technology must be done in small fusion power devices.**



Two Issues In Building A DEMO:

1 – Need Initial (startup) inventory for each DEMO of 8-12 kg (or much higher depending on T burn fraction, fueling efficiency and T processing time)

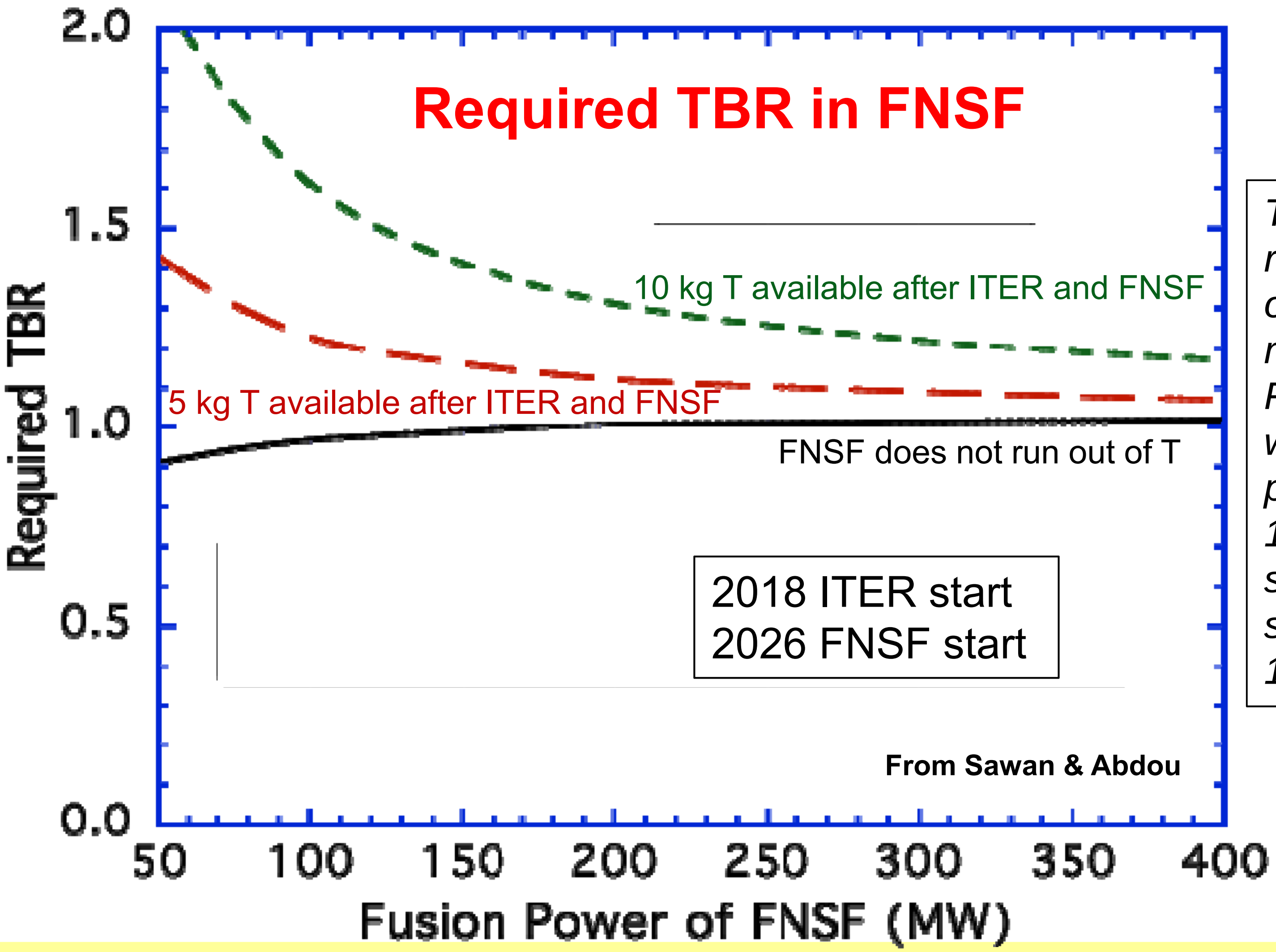
(How many DEMOs will the world build? And where will startup tritium come from?)

2 – Need Verified Breeding Blanket Technology to install on DEMO

M. Abdou April 2013

FNSF should be designed to breed tritium to:

a) Supply most or all of its consumption
b) Accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO



This is 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

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 (500–700ºC)
- 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 ~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 :

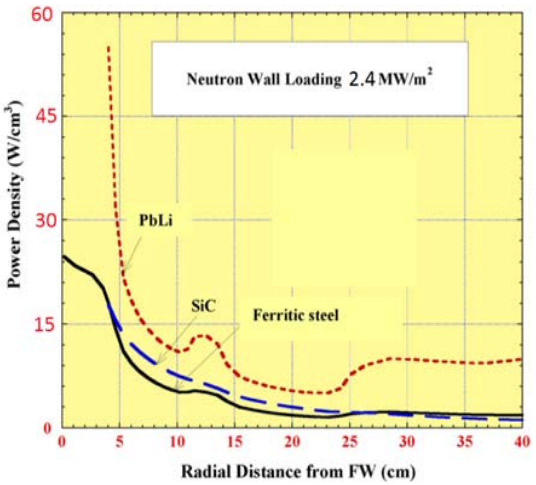
1. higher flow speed of PbLi in DCLL results in lower T partial pressure
2. the SiC flow channel insert acts as T barrier

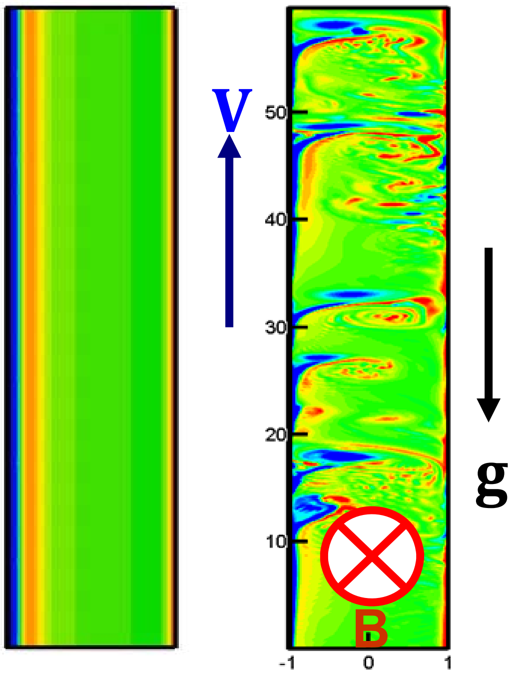
Example 2:

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)





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

- PhD. Thesis of Muyi 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 Tritium Self-Sufficiency

Summary (1 of 2)

- A **comprehensive dynamic model** has been developed to predict time-dependent tritium flow rates and inventories in the fuel cycle as well as the required TBR and dependence on plasma physics, and technology parameters and conditions.
  - Tritium inventories in the plasma fueling and exhaust systems and required TBR are very sensitive to many physics parameters, e.g. tritium burn fraction and fueling efficiency, and tritium processing time.

- The **achievable TBR** is sensitive to many system parameters and design considerations that need to be well defined. Present blanket designs in conceptual tokamak designs have estimated TBR values < 1.15
  - There is uncertainty in predicting achievable TBR of ~10% due to uncertainties in calculation methods, models, and nuclear data

Attaining Tritium Self Sufficiency in DT Fusion Imposes Key Requirements on Physics and Technology. The goal for R & D should be to achieve:

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

Summary (2 of 2)

- The **“start-up” tritium inventory** required for any reactor or DEMO is also a strong function of many physics and technology parameters, particularly T burn fraction, fueling efficiency and tritium processing time.
  - This start-up inventory is 8-12 kg for relatively optimistic values of these parameters and it can be prohibitively large if no advances are made beyond state-of-the-art

- There is no practical external source of tritium available for fusion development beyond ITER (definitely not for multiple DEMOs around the world)
  - A scheme to generate start-up inventory for DEMO using FNSF has been proposed

- Use of stabilizing shells and conducting coils for plasma control and attaining advanced plasma physics modes and material choice for plasma heating and CD components and divertors should be examined carefully to minimize impact on tritium breeding

- Tritium control and management will be one of the most difficult issues for fusion energy development

- Tritium permeation depends strongly on many phenomena in the blanket/FW that we do not yet know or understand

Thank you