Physics and technology conditions for attaining tritium self-sufficiency for the D-T fuel cycle Mohamed Sawan The University of Wisconsin-Madison Mohamed Abdou University of California-Los Angeles

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Objective

- Attaining tritium self-sufficiency is necessary for selfsustaining fusion plants operating on the D-T fuel cycle
- Tritium self-sufficiency in DT fusion power plants cannot be assured unless specific plasma and technology conditions are met
- ➤ We will address plasma, nuclear, material, and technological conditions in which tritium selfsufficiency can be attained





Titium Availability for DT Fusion

<u>Tritium Consumption in Fusion Is</u> <u>HUGE!</u>

55.6 kg per 1GW DT fusion power per year

<u>Tritium Supply is limited</u>

➤Inventory from CANDU Reactors peaks at 27 kg in the late 2020's with a rapid decrease thereafter due to radioactive decay and reduced production rate

> \$30M/kg (current)

Production & Cost from fission are LIMITED & EXPENSIVE!

- It takes tens of fission reactors to supply one fusion reactor
- DOE Inspector General report (12/2003) Tritium costs in the range \$84M to \$130M per kg





Tritium Self-Sufficiency

To ensure tritium self-sufficiency, the calculated achievable tritium breeding ratio should be equal to or greater than the required TBR

Required tritium breeding ratio

Is dependent on many system physics and technology parameters:

- plasma edge recycling, tritium fractional burn-up in the plasma
- tritium inventories (release/retention) in components
- efficiency/capacity/reliability of the tritium processing system

Achievable tritium breeding ratio

Is a function of technology, material and physics:

- FW thickness, amount of structure in the blanket, blanket concept
- Presence of stabilizing/conducting shell materials/coils for plasma control and attaining advanced plasma physics modes
- Plasma heating/fueling/exhaust, PFC coating/materials/geometry
- Plasma configuration (tokamak, stellerator, etc.)
- Uncertainties in nuclear data required for accurate determination of TBR



The Required TBR

The required TBR should exceed unity by a margin to:

(a) compensate for losses and radioactive decay (5.5%/year) of tritium between production and use

(b) supply inventory for startup of other reactors

(c) provide a "reserve" storage inventory for continued reactor operation during a failure in a tritium processing line

To accurately determine the required TBR, one has to consider the "dynamics" of the entire fuel cycle for the DT plant that involves many subsystems





Dynamic Modeling of Fuel Cycle

Kuan and Abdou developed detailed analytic dynamic models to describe various tritium processes and quantify the characteristic parameters of various elements of tritium fuel cycle as a tool for evaluating the required TBR

- Short-term and long-term tritium inventories as well as tritium lost through waste material are differentiated
- Maximum tritium inventory limits considered from safety and operational standpoints



[W. Kuan and M. Abdou, "A New Approach for Assessing the Required TBR and Startup Inventory in Future Fusion Reactors," *Fusion Technology*, <u>35</u>, 309 (1999)]



Simplified schematic of key elements of the fuel cycle system



Key Parameters Affecting Required TBR

- 1) doubling time for fusion power plants
- 2) tritium fractional burn-up in the plasma f_b
- "reserve time", i.e. days of tritium supply kept in "reserve" storage to keep plasma and plant operational in case of any malfunction in tritium processing system
- 4) time required for tritium processing of various tritiumcontaining streams (e.g. plasma exhaust, tritium-extraction fluids from the blanket)
- 5) parameters and conditions that lead to large "trapped" inventories in reactor components (e.g. in divertor, FW, blanket)
- 6) inefficiencies in various tritium processing schemes





Examples on Dependence of Required TBR on Key Parameters

Reference Parameters [from Table VII in Kuan/Abdou paper]

1.5 GW_f 9 kg long-term Inv. 2 kg short-term Inv.

Impact of fractional burn-up and doubling time

- Required TBR increases as f_b decreases with very rapid increase as f_b falls below ~ 2%
- Tritium fueling rate to plasma ~1/f_b and plays major role in determining some of most dominant inventories such as that in plasma exhaust, and reserve storage
- For all values of f_b, the required TBR increases with decreasing the doubling time





Calculations performed by P. Calderoni, UCLA using Kuan/Abdou model



Examples on Dependence of Required TBR on Key Parameters

Impact of fractional burn-up and Reserve time

- Required TBR increase with decreasing f_b is dramatically larger for longer reserve time
- At a low f_b of 0.5%, required TBR increases rapidly with reserve time
- At f_b of 5% or higher increase in required TBR with reserve time is relatively small



The combination of low fractional burn-up, long reserve time, and short doubling time has a compound effect on increasing the required TBR to very large values





Window for attaining self-sufficiency

- Maximum achievable TBR depends on many design conditions
- Conceptual tokamak designs have calculated TBR values ~1.15 and uncertainties in system definition, calculation procedure and nuclear data used in these studies can lead to lower TBR
- > This is used to define the "window" of parameters that can lead to tritium self-sufficiency

Physics Conditions

- Tritium fractional burn-up in plasma should be kept high (above 2% and most preferably above 5%)
- ≻Plasma edge physics modes that lead to higher tritium recycling are needed
- ➤ High tritium recycling may also lead to high alpha-particle recycling which would reduce the sustainable DT particle density in the plasma for a given stability limit of beta and hence would lower the achievable fusion power
- Therefore, schemes which lead to preferential pumping of alpha particles and preferential recycling of tritium into plasma, need to be explored





Window for attaining self-sufficiency

Technology Conditions

- Reserve tritium inventory to keep fueling plasma and continue reactor operation during periods of malfunction of tritium processing system is necessary
- > To keep reserve inventory, and required TBR, sufficiently low requires:
 - a) High tritium fractional burn-up
 - b) High reliability/availability of tritium processing system
 - c) redundancy in some of tritium processing system, especially the plasma exhaust processing line
- Retention of large tritium inventories in reactor components such as blanket, FW, and divertor can have a large impact on increasing the required TBR. Design options that minimize these inventories should be considered
- Improvements in tritium processing system to substantially shorten time between production and use need to be explored further





Window for attaining self-sufficiency

Possible Windows of Parameters

Fractional Burn-up	Reserve Time	Doubling Time
(%)	(days)	(years)
>2	<5	>10
>2	<2	>5
>5	<10	>10
>5	<5	>4



The Achievable TBR

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

- Concepts and materials used in chamber components (blanket, divertor, etc.)
- 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 achievable TBR due to system definition, modeling, and nuclear data should be accounted for when assessing the potential for achieving tritium self-sufficiency





Tritium Breeding Potential of Candidate Breeders



- Li and LiPb have highest breeding potential
- Breeders with moderate breeding potential (Li₂O, Flibe) require moderate amount of multiplier
- Ceramic breeders have poor breeding potential and require significant amount of multiplier and minimal structure content
- In realistic designs, the structure, configuration, and penetrations will degrade the achievable overall TBR below the values shown



TBR is Very Sensitive to Structure Content in Blanket











- Many considerations influence choice of structural material (compatibility, blanket thermal, mechanical, and safety performance requirements)
- Structure content should be adequate to ensure structural integrity under normal and abnormal load conditions



Achievable TBR is Very Sensitive to FW Thickness



Detailed ITER engineering design shows that the FW may have to be quite thick (~7 cm)



TBR drops by up to ~16% if FW thickness is increased to 4 cm

It is necessary to carry out *detailed structural-mechanical and thermal-hydraulics analyses* for accurate determination of practical values for FW thickness and blanket structure content





Impact of Other Blanket Components on Achievable TBR

Coolant

- Liquid breeder can serve as coolant in self-cooled concept
- He gas coolant has negligible impact on neutron economy but a thicker blanket is needed and using high pressure He gas requires larger structure content
- In typical designs, using 20% water coolant in the FW/blanket system reduces the TBR by up to 7% *Electric Insulator*
- Several oxide and nitride coatings (~10-micron layers) are considered for Li/V blankets
- For in-situ self-healing of microcracks up to ~10 atom% Ca, Y, Al, or Er added to Li. Degrades TBR by up to ~13% with Ca and ~27% with Er [L. El-Guebaly, ISFNT7]
- 5 mm thick SiC flow channel inserts are used with LiPb that degrade the TBR by ~8%
- Adding the required electrical insulators to the high electric conductivity Li and LiPb with the highest breeding potential should be assessed regarding its negative impact on the achievable TBR

Neutron Multiplier

- Be yields better enhancement in TBR than with equivalent amount of Pb
- Several issues with using both multipliers need to be resolved: compatibility, tritium production and retention in Be, Be swelling, and polonium production in Pb
- Cooling requirement for multiplier introduces added structure and limits thickness
- Preferred form for Be is pebble bed has a lower packing fraction and lower thermal conductivity





Adding Multiplier Does not Allow increasing TBR Indefinitely

Be layers in front of blanket (where nuclear heating is highest) are limited in thickness (~2 cm) and are surrounded by steel cooling plates







Impact of Confinement Concept on Achievable TBR

IFE vs. MFE

- Thicker blankets are easier to accommodate in IFE chambers
- IFE chamber configuration results in nearly full blanket coverage
- Easier to employ flowing thick liquid breeder concepts without structure
- Higher potential for achieving tritium self-sufficiency in IFE

Divertor Requirement

- Confinement schemes, such as tokamak, ST, and stellarators require a divertor system for power exhaust and particle control
- Tritium breeding will be compromised or absent in the divertor region
- Coverage fraction of divertors is 5-12% depending on whether it is single or double null with larger values in stellarators
- W PFC is a strong neutron absorber with more negative effect on TBR
- C PFC results in increasing tritium inventory and the minimum required TBR
- For the thin divertor armor, the Cu and steel used in the sizable divertor heat sink and structure have the dominant effect on TBR and severely reduce TBR contribution from a blanket placed behind them





Chamber Configuration

Tokamak:

- Due to space limitation in IB side a thinner blanket is used <u>ST:</u>
- With very low AR no breeding blanket installed in space-constrained IB side
- TBR very much influenced by material choice for the center-post shield <u>Stellarator:</u>
- External coils producing rotational transform of magnetic field required to be close to plasma imposing severe restrictions on thickness of breeding blanket
- In ARIES-CS, blanket is replaced by a highly efficient shield at locations where the external coils have to be close to plasma [El-Guebaly, FS&T, 2005]
- This approach requires careful design of the "nominal" blanket to enhance the overall achievable TBR
- Absence of disruptions allows using thinner first walls than in tokamaks **<u>FRC</u>**:
- Elongating the cylindrical chamber can reduce end losses and increase blanket coverage
- These concepts also allow for using uniformly thick blankets





Plasma Heating and CD

- Material choice for antennas and launchers employed in ICH and ECH systems could affect the achievable TBR based on their ability to reflect neutrons into the chamber rather than absorb them
- Careful choice of material and minimizing streaming path in these systems help improve potential for achieving tritium self-sufficiency
- NBI ports are relatively larger with larger streaming path



Penetrations for heating and CD are placed in OB side where local TBR is highest
In recent conceptual MFE power plant designs heating and CD penetrations take 1-3% of the FW area with net effect on the overall TBR ~2-4% reduction. This predicted small coverage fraction needs to be confirmed





Plasma Control Requirements

- To attain advanced plasma physics modes of operation with higher β and elongation, conducting shells need to be introduced in blanket
- Stabilizing shells should be located closer to plasma to have favorable impact on plasma performance (30 cm depth in ARIES-AT)
- Three candidate materials (W, Cu, Al) investigated in ARIES-AT

[L. El-Guebaly, et al., FE&D, 2005]



- > Thickness of shell depends on type of conductor, operating temperature, and time constant
- > Toroidally continuous OB stabilizing shells placed at upper/lower extremity of OB blanket
- Overall TBR reduced by 4% with 4 cm W stabilizing shells (operate hot and are passively cooled). Additional ~2% drop results from midplne1 cm thick resistive wall mode shell
- It is essential to determine from plasma control requirements the exact configuration of stabilizing shell as they influence potential for achieving tritium self-sufficiency



Uncertainties in the Achievable TBR

Uncertainties in calculating the achievable TBR are due to:

1. System definition

Achievable TBR depends on many system parameters and design considerations that are not yet well defined (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 and CD systems)

2. Modeling and calculation method

Calculation model (3-D) should accurately reflect the detailed chamber configuration including all components with detailed design and material distribution and heterogeneity and accurate source profile

3. Nuclear data

Uncertainties in measured cross section data and their processing lead in uncertainties in calculating TBR







Dual Coolant Flibe Blanket

3-D Model

- 3-D TBR 1.07 compared to 1.14 from 1-D estimate obtained by coupling the 1-D local TBR values with blanket coverage fractions [Sawan, ISFNT7]
- Combined effects of blanket and source 3-D configurations and detailed blanket heterogeniety modeling can lead to more than ~6% lower TBR compared to 1-D estimates
- Continuous energy (vs. multi-group) 3-D Monte Carlo (vs. discrete ordinates) calculation with efficient varience reduction techniques should be used





Uncertainties due to Nuclear Data

- Uncertainties are primarily due to uncertainties in measured cross sections and energy and angle distributions of secondary neutrons
- Another uncertainty arises from processing cross sections into multi-group data libraries. However, this can be greatly reduced by relying on continuous energy cross section data or using a fine energy group structure
- Cross section sensitivity/uncertainty analyses have been performed to provide estimate of uncertainty in calculated TBR in different blanket concepts and values of 2-6% were reported [M. Youssef and M. Abdou, "Uncertainties in Prediction of Tritium Breeding in Candidate Blanket Designs due to Present Uncertainties in Nuclear Data Base," Fusion Technology, 9. 286 (1986)]
- Nuclear data for fusion applications have been under continuous improvement culminated by issuing FENDL-2 in 1998
- Several fusion neutronics integral experiments have been performed in facilities that utilize 14 MeV neutron sources [e.g. FNG, FNS] using breeding blanket mock-ups to validate nuclear data and compare the calculated and measured TPR





Recent Integral Experiments Give Lower Measured TPR than Calculated





- A series of integral experiments was performed recently in the FNS facility on blanket mock-ups containing F82H, Li₂TiO₃, and Be layers [ISFNT7]
- A SS316 steel source reflector utilized to simulate fusion reactor environment
- Calculation of TPR overestimated experimental value by an average factor of ~1.14 [Y. Verzilov, S. Sato, et al., 2004]
- While there is uncertainty of ~5% in measuring TPR, the large overestimate from calculation is alarming and implies that an intensive R&D program is needed to validate and upgrade nuclear data to improve our ability to accurately predict the achievable TBR





R&D Needs to Assess Potential for Achieving Tritium Self-Sufficiency

- Parallel and interactive R&D programs in plasma physics, plasma control technologies, chamber technology, materials science, safety, and systems analysis are necessary to determine "phase-space" of conditions in which tritium selfsufficiency can be attained
- ITER TBM program will be the first integrated experimental verification of several principles necessary for assessing tritium self-sufficiency
 - TBM having its own integrated loops and systems for tritium breeding, tritium processing, heat extraction, etc will provide information (e.g., tritium mean residence time, tritium inventory, reliability and efficiency of tritium processing system, etc) that allow better determination of the minimum required TBR
 - TBM testing will provide information that helps better define practical blanket design parameters (e.g., FW thickness, structure content, and coolant conditions
 - Testing in ITER TBM, along with dedicated 14 MeV neutron integral experiments, help validate the predictive capabilities (nuclear data and codes) used for calculating the achievable TBR
- Research involving extensive modeling of materials and plasma chamber phenomena and experiments in various laboratoryscale testing facilities and fission reactors will be necessary to supplement ITER testing





R&D Needs to Assess Potential for Achieving Tritium Self-Sufficiency (continued)

- Blanket and material research should be closely interactive with plasma physics research
- R&D for subsystems that involve penetrations such as impurity control/exhaust and plasma auxiliary heating should focus on design options that result in minimum impact on TBR
- Design choices that necessitate use of large neutron absorbing materials imbedded in blanket region for plasma stabilization and attaining advanced plasma modes should be examined regarding their implication on tritium self-sufficiency
- Plasma physics experimental and theoretical research is needed to assess potential for operating in high plasma-edge recycling mode to attain high tritium fractional burn-up in plasma





R&D Needs to Assess Potential for Achieving Tritium Self-Sufficiency (continued)

- ➤An experimentally verified, comprehensive fuel cycle dynamics model needs to be developed to predict tritium behavior, transport, and inventories in all system components such as plasma exhaust, plasma facing components, blankets, and tritium processing
- ➤Tritium retention and release in chamber components as a function of operating conditions need to be fully understood and material choice should take into consideration the need to minimize the tritium inventory

➤To increase prospect of achieving tritium self-sufficiency, R&D program should aim at reducing uncertainties associated with achievable and required TBR

- Better definition of the system parameters
- Continued data improvement and validation in integral experiments





Summary and Conclusions

- No practical external source of tritium available for DT fusion development beyond ITER
- Tritium self-sufficiency in DT fusion systems cannot be assured unless specific plasma and technology conditions are met
- Plasma edge physics modes that lead to higher tritium recycling and high tritium fractional burn-up need to be explored
- > High reliability/availability and redundancy in tritium processing system is required
- Design options that minimize tritium inventories in reactor components are needed
- Practical FW thickness and blanket structure content based on detailed structuralmechanical and thermal-hydraulics analyses need to be well defined
- 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
- It is necessary to establish without delay an extensive parallel and highly interactive R&D program in plasma physics, control technologies, chamber technology, materials science, safety, and systems analysis to determine the "phase-space" of conditions in which tritium self-sufficiency can be attained



