Tritium Breeding Issues for MFE and IFE

Laila El-Guebaly

Fusion Technology Institute
University of Wisconsin - Madison

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Background

- Limited T resources force fusion designs to breed all T required for plant operation in Li-containing blanket
- T self-sufficiency eliminates need for external T supply during plant operation (0.3-1 kg/d)
- External T supply will be needed at beginning of operation for short period of time (1-2 d) until plant reaches steady state production and extraction of T
- Tritium breeding ratio (TBR) is a metric for T self-sufficiency
- Required TBR is design dependent
- TBR requirements impact economics:
  - Lower TBR $\Rightarrow$ thin blanket $\Rightarrow$ compact machine $\Rightarrow$ lower COE
  - Lower TBR $\Rightarrow$ higher neutron energy multiplication $\Rightarrow$ lower COE

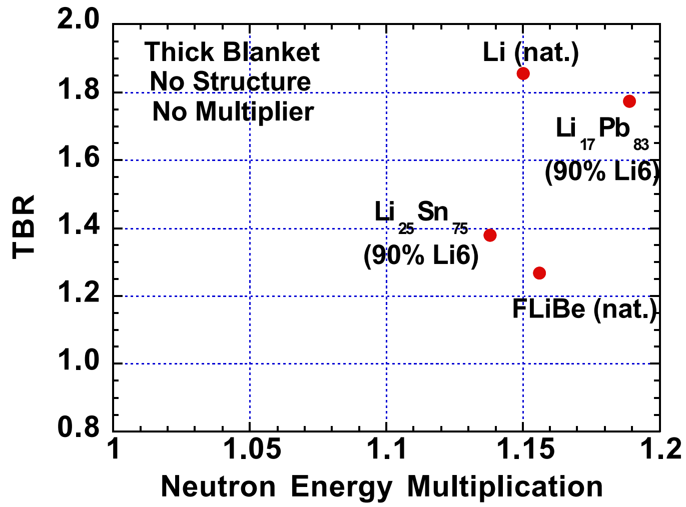
Key Factors Affecting TBR

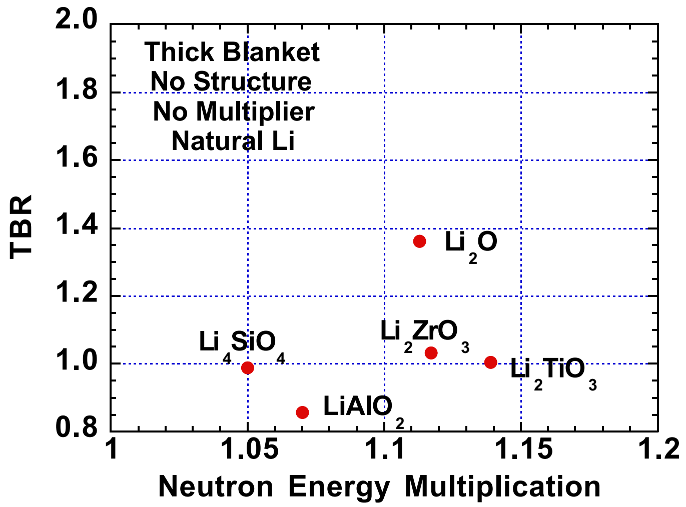
- Confinement scheme:
  - MFE (Tokamaks,ST,Spheromaks,Stellarators,RFP,FRC,Tandem mirrors)
  - IFE (Dry walls, Wetted walls, Liquid walls)
- Blanket concept:
  - Breeder (Liquid breeders, Solid breeders)
  - Structure (SiC/SiC, C/C, V, FS, Ti, W, and TZM alloys)
  - Coolant (He, H_2O, LM, SB)
  - Multiplier (Be, Pb, Be_2C, BeO)
- FW and Blanket configuration:
  - Coverage fraction, thickness, structural content
- Penetrations:
  - Divertor, plasma heating/control, diagnostics, laser/HIB beam-lines
  - Number, size, location

General Remarks on Confinement Systems

- IFE system provides > 98% blanket coverage with no restrictions on blanket size ⇒ higher breeding compared to MFE
- In tokamaks:
  - Constraints on inboard blanket thickness affect breeding
  - Double null divertor occupies 10-20% of FW area. Massive structure limits breeding behind divertor system
  - Penetrations on outboard midplane degrade breeding by 2-3%
- STs limit breeding on inboard side, forcing outboard-only blanket to provide all T required
- Stellarator blankets surround plasma entirely and offer advantage of breeding behind **thin** divertor baffles
- Linear systems offer negligible end losses

Liquid Breeders Offer Higher Breeding Potential Than Solid Breeders





- In realistic designs, TBR drops by 20-40% due to:
  - Limited blanket coverage (80-98%)
  - Penetrations (2-20% of FW area)
  - Finite blanket thickness (20-70 cm)
  - FW/blanket structure (15-20% by volume)
  - Stabilizing shells embedded in blankets of tokamaks

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Materials Selection and Design Choices Enhance Breeding

- Li and LiPb offer highest breeding w/o n multiplier
- Best combinations of breeder/structure are:

Li/V	**LiPb/SiC**
Flibe/V or W	**LiSn/V or W**
SB/V	

- FW structure degrades breeding more rapidly than blanket structure
- Water coolant reduces TBR by up to 7%
- Li enrichment enhances breeding level of LiPb, LiSn, and SB/multiplier
- In MFE, Flibe, LiSn, and SBs need n multiplier if blanket contains 10-20% structure
- In IFE, absence of large penetrations enables breeding w/o n multiplier
- Blanket concepts employing free-fall of breeders could meet breeding requirements without multiplier if structural content is limited to 1-2%
- Beryllium is best n multiplier and enhances TBR significantly
- In tokamaks:
  - Off-midplane penetrations result in less degradation in breeding
  - Single null divertor results in 3-5% higher breeding compared to double null

Breeding Requirements

- Breeding requirements are design dependent
- **ARIES project** requires **net TBR of 1.01**
- **calculated TBR** based on **3-D** analysis should be **≥ 1.1**
- 3-D analysis should model **reference** design and include:
  - Separate FW component
  - Blanket details as much as practically possible
  - Penetrations
  - Shielding components to account for n reflection
- Breeding margin (≥ 10%) compensates for:
  - Uncertainties in nuclear data (6-7%)
  - Approximation in geometric modeling (2-3%)
  - Others, in descending importance (1-2%):
    - T supply for new power plants:
      Startup inventory (2-3 kg)
      Doubling time (5 y)
    - T inventory:
      - Hold-ups in plant components (1-2 kg)
      - T thru-put and fractional burnup in plasma or target (20-40%)
      - T reserve (~0.5 kg for 2 days of operation)
    - T decay and T losses
    - T extraction process and time for repair

Advanced Subsystems Help Reduce Breeding Margin

- High T fractional burnup in plasma and target (> 30%)
- Highly reliable T processing system (> 99% reliability)
- Short time to fix failure of T processing system (< 1 d)
- Low T losses in **all** systems (<< 0.1% of T consumption, max of 1-3 Ci/d)
- Low T inventory in all components (< 1 kg)

It Is Less Problematic to Start With Overbreeding Blanket

- ±9% uncertainty means net TBR after operation will range between 1.01 and 1.2
- Overlooked uncertainties in system definition may reduce net TBR
- Net TBR will not be verified before MFE/IFE Demo operation where blanket design, T extraction and processing systems are fully integrated in single facility
- Blanket designs should be flexible and offer practical solutions to adjust net TBR to 1.01 after plant operation
- Accuracy of predicting TBR will improve considerably for second power plant generation
- In case of overbreeding (net TBR > 1.01), reduce TBR by:
  - Lowering enrichment
  - Thinning blanket
  - Reducing blanket coverage
  - Increasing structural content, porosity or packing fraction of SB
- In case of underbreeding (net TBR < 1.01), increase TBR by:
  - Adding beryllium (safety !)
  - Increasing enrichment, if < 90%
  - Thickening blanket, if effective

$\Rightarrow$ Calculated overall TBR should be $\geq$ 1.1

MFE Blankets Designed Over Past 30 y Satisfied Design Breeding Requirements

	Design	Year of Study	Blanket Composition*	Calculate TBR
Tokamaks:	ARIES-I	1991	Li_2ZrO_3/SiC/He/Be	1.18
	ARIES-IV	1993	Li_2O/SiC/He/Be	1.12
	ARIES-RS	1995	Li/V	1.1
	ARIES-ST	1998	LiPb/FS/He	1.1
	ARIES-AT	2000	LiPb/SiC	1.1
Stellarators:	UWTOR-M	1982	LiPb/FS/steam	1.08
	ASRA6C	1987	LiPb/FS/He	1.05
	ARIES-SPPS	1997	Li/V	1.1
RFP	TITAN	1990	Li/V	1.18
Tandem Mirrors:	MARS	1984	LiPb/FS	1.15
	Mini-MARS	1986	LiPb/FS/He/Be	1.05

* Breeder/structure/coolant/multiplier

IFE Blankets Designed Over Past 30 y Satisfied Design Breeding Requirements

	Design	Year of Study	Blanket Composition*	Calculate TBR
Dry Walls:	SOLASE	1977	Li_2O/C	1.25
	CASCADE	1983	$LiAlO_2$/SiC/BeO	1.05
	SOMBRERO	1992	Li_2O/C	1.25
	SIRIUS-P	1993	Li_2O/SiC#	1.1
Wetted Walls:	HIBALL	1981	LiPb/SiC	1.25
	HIBALL-II	1984	LiPb/SiC	1.195
	LIBRA	1990	LiPb/SiC	1.36
	LIBRA-LiTE	1991	Li/FS	1.41
	OSIRIS	1992	Flibe/C	1.24
	PROMETHEUS	1992	Li_2O/SiC/Pb	1.2
	LIBRA-SP	1995	LiPb/FS	1.44
Liquid Walls:	HYLIFE	1979	Li/FS	1.75
	HYLIFE-II	1991	Flibe/FS	1.17

* Breeder/structure/multiplier
# with TiO_2/C FW

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Breeding-Related R&D Goals and Challenges

- Test breeding technology in DT burning facilities:
  - Verify breeding level with integrated blanket, T extraction and processing systems
  - Show T inventory can be minimized
  - Evaluate and minimize T losses during recovery process
  - Improve reliability of T processing system
- Reduce uncertainties in nuclear data to 2-3% with materials testing and code validation using 14 MeV n sources
- Develop CAD-MCNP interface to facilitate 3-D modeling and improve accuracy of TBR calculations
- Prove high T fractional burnup can be achieved with advanced plasmas/targets
- Develop robust structural materials to minimize structural content in FW and blanket
- Develop compact systems for divertor and plasma control to minimize size of penetrations

Conclusions

- T self-sufficiency could be achieved through active interaction and integration process between neutronics, materials selection, blanket configuration, safety, and overall design
- Calculated 3-D TBR $\geq$ 1.1 ensures T self-sufficiency
- 10% (or more) breeding margin accounts for:
  - Uncertainties in cross section data
  - Approximations in geometric modeling
  - T inventory, losses, decay, hold-ups, and supply for new power plants
- R&D program and T data from **operating** fusion facilities will provide information to assess breeding margin more accurately, hence relaxing breeding requirements
- Blanket designs should offer practical solutions to adjust net TBR to ~unity after machine operation
- T self-sufficiency seems easier to achieve in IFE than in MFE primarily due to absence of large penetrations