Toward the Ultimate Goal of Tritium Self-Sufficiency: Technical Issues and Requirements Imposed on Fusion Power Plants

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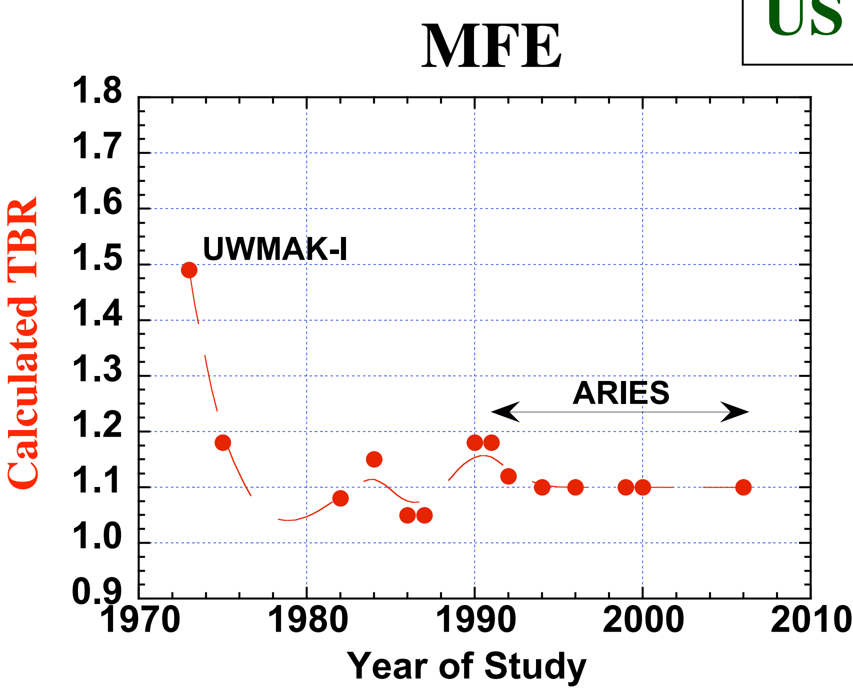
Background Info

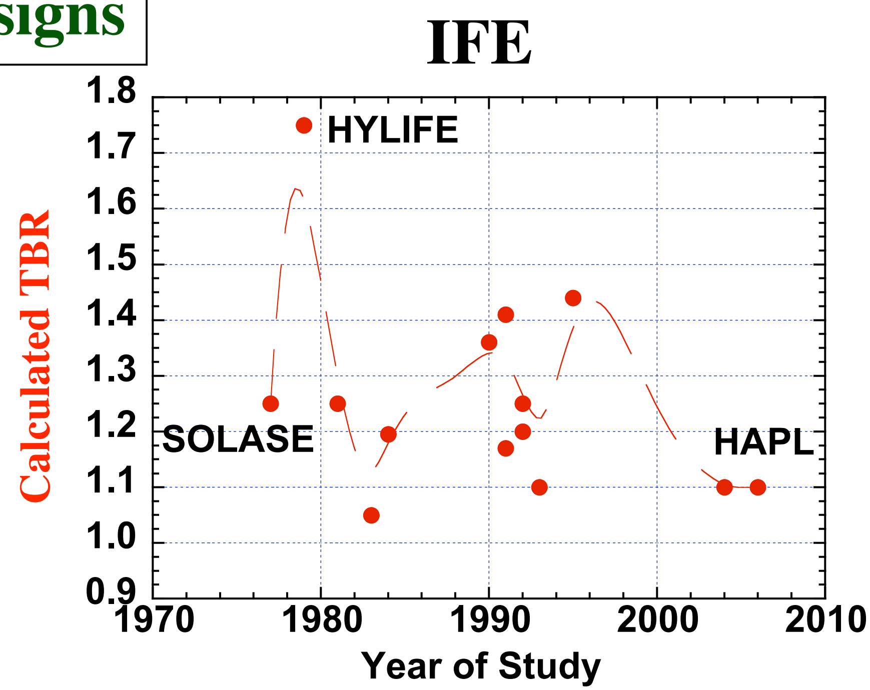
- There is no practical external source of tritium (T).
- D-T fuelled fusion power plants must breed their own tritium.
- Plant with 1 GW fusion power consumes huge amount of T (55.6 kg per full power year).
- Shortage of T **and** surplus of T significantly impact plant operation and T storage.
- For licensing considerations, fusion should not generate excess T than needed.
- T bred in blanket should be accurately estimated as 1% uncertainty translates into 1-2 kg of T/FPY for 2-3 GW P_f
- For advanced designs, Net TBR is close to 1.01.
- Calculated TBR must be greater than Net TBR.
- **Key questions**:
  - How high should Calculated TBR be? *Design and breeder dependent*
  - What elements determine breeding margin (Calculated TBR-1) ? *Four main elements*
  - Does this margin evolve with time? *Yes*
  - Could T breeding be adjusted online? *Yes, for liquid breeders through ^6Li enrichment*
  - Could design over-breed or under-breed? *Less risky to over-breed*

Calculated TBR Evolves with Time and is Design and Breeder Dependent

- There is no general consensus within fusion community on what the Calculated TBR should be.
- Advanced **ARIES** designs considered Calculated TBR of 1.1 for liquid breeders
- Other US projects (IFE **HAPL** @ NRL, Demo @ UCLA, IFE @ LLNL) along with some EU and J studies accord with ARIES 1.1 Calculated TBR .
- Some designs call for higher Calculated TBR with Net TBR of ~1.05.

US Designs





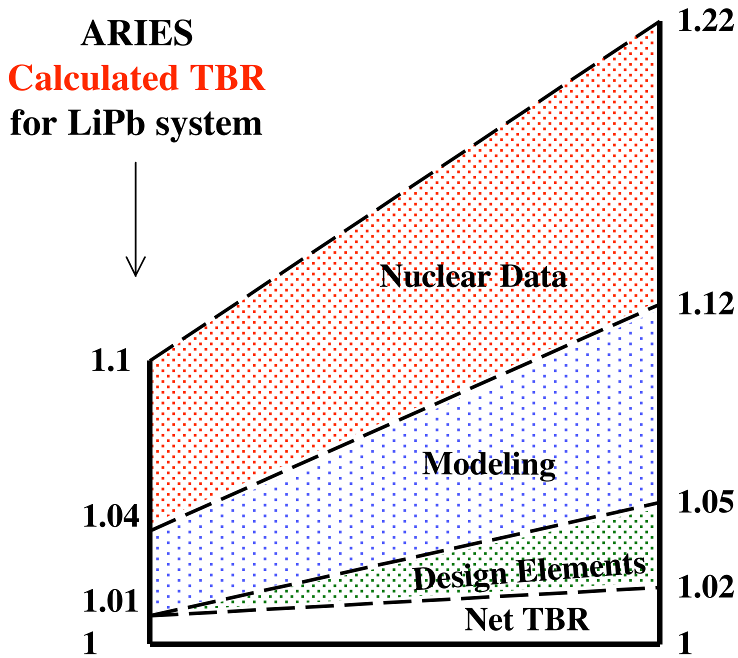
Breeding Margin

(Calculated TBR – 1)

Can be divided into **4 distinct categories**:

- Margin for known deficiencies in nuclear data (6-10%) ← **breeder dependent**
- Margin for known deficiencies in modeling (3-7%)
- Margin for unknown uncertainties in design elements (0-3%)
- Margin for T bred in excess of T consumed in plasma (1-2%)

(The last three categories: **design dependent**)



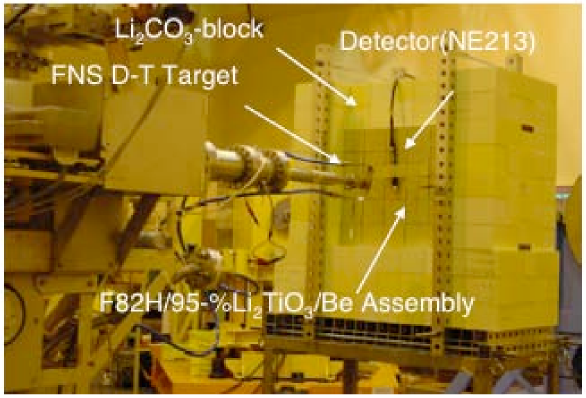
Margin for Known Deficiency in Nuclear Data (6-10%)

- T production is highly sensitive to neutron energy spectrum that is controlled by nuclear data evaluation for numerous isotopes (e.g., 20-30 isotopes in ARIES blankets) and cross-sections, not only (n,t).
- Several organizations in US, EU, and J developed nuclear data libraries for fusion applications.
- IAEA FENDL library is widely used worldwide as data were carefully selected from several national libraries.
- Despite high fidelity in IAEA evaluation, FENDL-2.1 version is far from perfect. Issuing new version takes years of extensive experimental program combined with data re-evaluation, then data validation.
- Impact of uncertainties in nuclear data evaluation on calculated TBR was assessed numerically @ UCLA for several breeders (~6% for LiPb).
- Few integral experiments (with 14 MeV neutron source) exist in J and EU to validate nuclear data.

Margin for Known Deficiency in Nuclear Data (Cont.)

Solid breeder experiments:

FNS Facility **(JAEA, Japan)**



- Recent **FNS** results for Li_2TiO_3/Be/FS blanket indicated calculations overestimate T production rate by up to 10-20%.

FNG Facility **(ENEA, Italy)**

- **FNG** experiment indicated T production is predicted within 5-10% uncertainty for solid breeding blankets with Be multiplier.

Margin for Known Deficiency in Nuclear Data (Cont.)

- New experiments are underway in Japan and Europe for helium-cooled **LiPb** blanket (more relevant to ARIES).

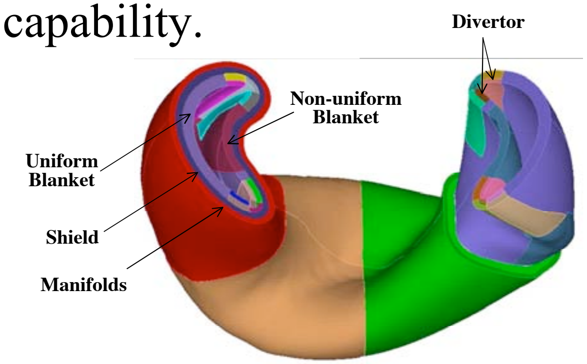
- Several iterations between data evaluation and experimental validation will continue until good agreement is reached.

- ARIES will continue including adequate breeding margin (~6%) in Calculated TBR of LiPb system to account for nuclear data deficiency until J and EU conduct LiPb experiments, benchmark, and publish results.

- Only ITER TBM and CTF will accurately measure T production in prototypical fusion environment (neutron spectrum, surrounding components, etc.), contributing to validation of TBR calculations.

Margin for Known Deficiency in Modeling (3-7%)

- Calculating TBR for any fusion system requires advanced neutronics tools. Newly developed CAD-MCNPX approach provides such capability.



Example: UW CAD/MCNPX approach applied to ARIES-CS

- Ideally, 3-D model should include essential components that impact breeding significantly: FW, blanket, divertor, stabilizing shells, penetrations, and assembly gaps.

- Practically, 3-D model cannot represent real geometry, particularly for a complex blanket designs as very detailed blanket is too costly to model.

- Homogenization overestimates breeding level and 3-D Calculated TBR should be adjusted accordingly.

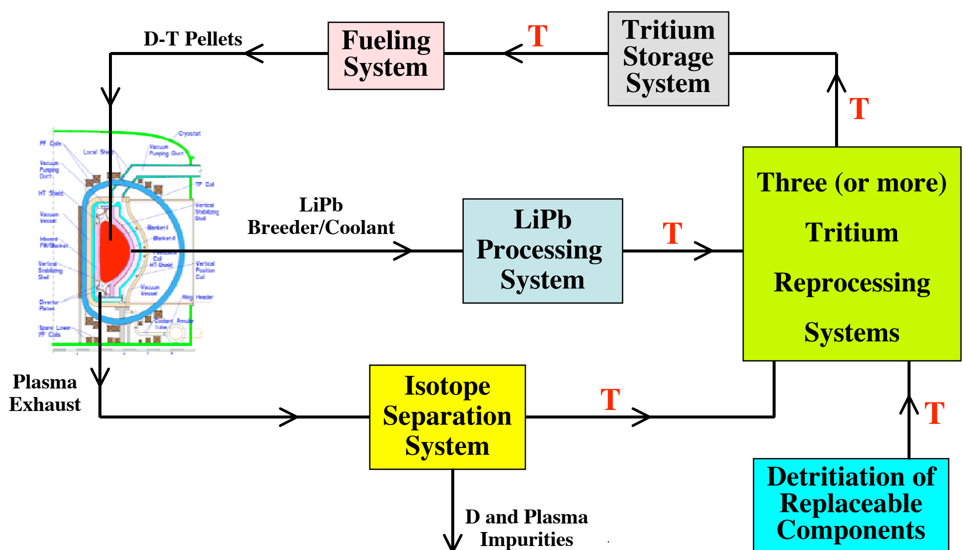
- Margin of error in Calculated TBR due to modeling could range between 3 and 7%, depending on how crude 3-D model is.

Margin for Unknown Uncertainties in Design Elements (0-3%)

- Normally, TBR is calculated for conceptual designs where major elements that degrade breeding (such as FW, blanket structure, and penetrations) are included in 3-D model.
- As design develops further approaching construction phase, several **future** design changes may negatively affect breeding, calling for larger breeding margin during conceptual phase.
- Such changes include:
  - Adding few mm W armor on FW to enhance plasma performance
  - More supporting structure for FW and blanket
  - Thicker SiC insulator for DCLL blanket concept
  - Larger stabilizing shells
  - Sizable penetrations
  - Wider assembly gaps.
- In ARIES, no provision was made to account for future design changes.
- Such changes will require higher enrichment and/or redesigning blanket to meet breeding requirement.

Margin for T Bred in Excess of T consumed (1-2%)

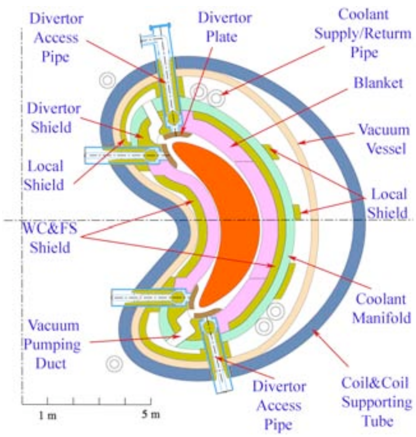
- Divided into three main categories:
  1. T required to provide start-up inventory for new fusion power plant:
     a. T build-up in power core materials (especially in breeder, multiplier, structural materials) and T recovery system for blanket
     b. T build-up in fuel reprocessing system (especially in cryo-panels, getters, molecular sieves)
     c. T build-up in detritiation systems for coolants, building atmosphere, and vacuum pumping system
     d. T to be stored in getters as reserve to continue plasma operation in case of temporary malfunctions of T reprocessing system
  2. T necessary to compensate for decay of total T inventory
  3. T lost to environment (atmosphere, cooling water, etc.).



Margin for
T Bred in Excess of T consumed (Cont.)

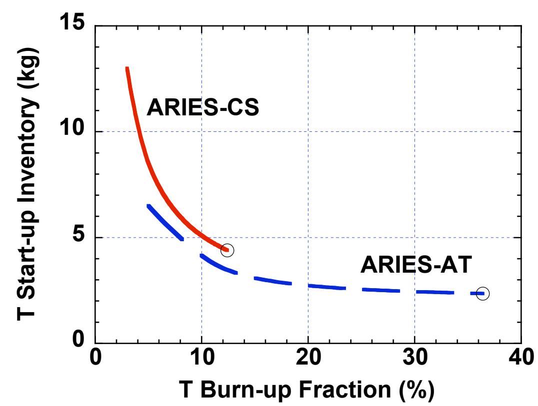
	ARIES-CS	ARIES-AT
Net output power (MW_e)	1000	1000
Fusion power (MW)	2436	1759
Burn-up fraction of T in plasma	12.4%	36.4%
T consumption: in kg/FPY	135	97.8
in kg/day	0.37	0.268
T throughput (kg/day)	3	0.74
T holdups in LiPb breeder (kg)	0.1	0.1
T holdups in structure (kg)	~1	~0.8
T inventory in reprocessing system (kg)	1.5	0.37
T build-up outside FPC (kg)	0.5	0.5
Stored T for malfunctions (kg)	1	0.25
T decay (kg/y)	0.33	0.16
T losses to environment (g/y)	< 4	< 4
Start-up inventory (kg)	~4	~2

ARIES-CS
(Compact Stellarator)

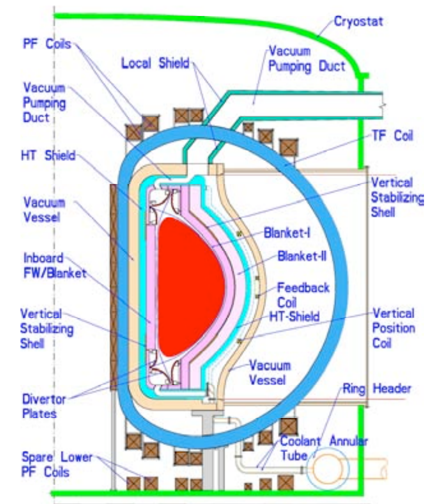


Realistic assumptions:

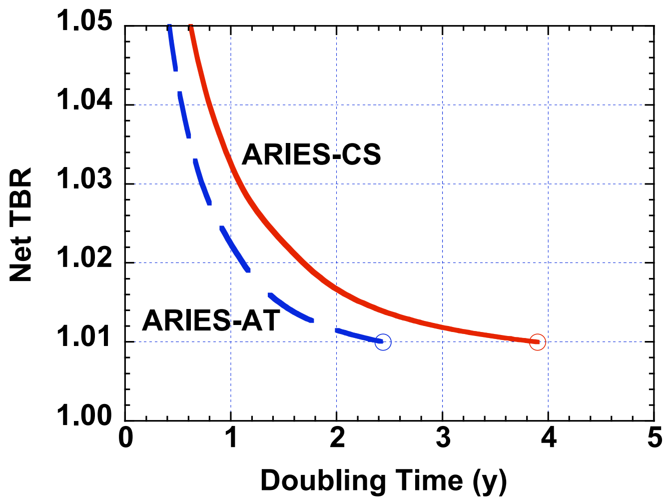
- 3 fuel reprocessing systems
- 1 day T reserve to allow unperturbed plasma refueling
- Doubling time < 5 y



ARIES-AT
(Advanced Tokamak)



Net TBR



Doubling time needed to supply new power plant with start-up T.

Mature fusion plants call for **Net TBR** ≤ 1.01.

Early generations of fusion plants require **Net TBR** > 1.01 with shorter doubling time.

Advanced physics and technology help keep Net TBR around 1.01

Essential requirements include:

- T burn-up fraction in plasma exceeding 10%
- High reliability and short repair time (< 1 day) for T processing system
- Three or more T processing system
- T and α particles recycled at high rates
- Low T inventory in all subsystems
- Extremely low T losses to environment (< 4 g/y).

Over-Breeding or Under-Breeding?

- Net TBR will not be verified till after Demo operation with fully integrated blanket and T extraction and processing systems.
- Existing blanket will be redesigned accordingly.
- All blankets should be flexible and accept few changes to deliver a Net TBR of 1.01.
- **Over-breeding blanket** (Net TBR > 1.01):
  - For liquid breeders, most practical solution is to adjust the ^{6}Li enrichment online,
  - For ceramic breeders, adjust ^{6}Li enrichment after first blanket change-out or replace few breeding modules by shield.
- **Under-breeding blanket** (Net TBR < 1.01):

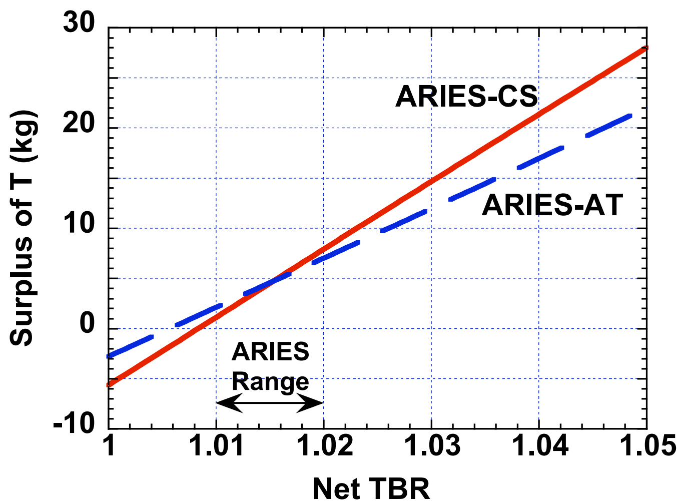
  Major design changes anticipated to raise TBR, unless reference blanket designed with ^{6}Li enrichment < 90%:
  - Thickening blanket,
  - Replacing W stabilizing shells of ARIES-AT by Al or Cu shells,
  - Lowering the structural content within the blanket,
  - Adding a beryllium multiplier to the blanket,
  - Increasing plasma aspect ratio,
  - Operating tokamaks in a single-null mode.
- It is **less risky to design over-breeding blanket** (with Net TBR of 1.01 - 1.02) and develop feasible scheme to adjust breeding shortly after plant operation.
- Surplus of T could be excessive if Net TBR exceeds 1.01.

Excessive Breeding Represents T Storage Problem

- **Without online adjustment of breeding**, surplus of T generated over blanket lifetime (~5 y) would be significant if Net TBR exceeds 1.01 (after subtracting start-up inventory for new plant (with 5 y doubling time) and account for T decay).

- For comparison, total T accumulated from all CANDU reactors reaches ~30 kg by 2025.

- T breeding should be controlled with accuracy better than 1% to ensure T self-sufficiency without storage problem for surplus of T



Proposed Scheme for Online Adjustment of LiPb Breeding

- Two practical methods are feasible through combining two LiPb eutectics with different enrichments:

a) **Replace X tons of enriched LiPb by X tons of LiPb with 100% ^{7}Li**

(straightforward but requires additional storage volume for eutectic).

b) **Remove Y* tons of enriched Li from LiPb eutectic and replace it with Y tons of ^{7}Li**

(does not require large storage, but needs practical method to remove enriched Li from eutectic and feed Li back with 100% ^{7}Li).

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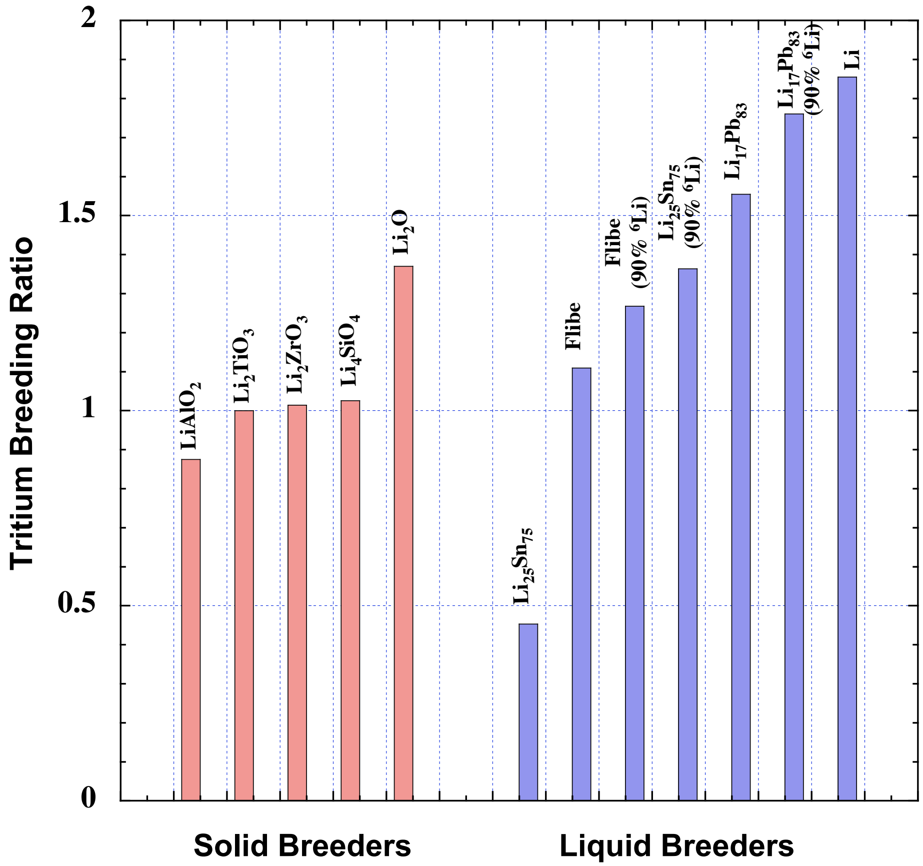
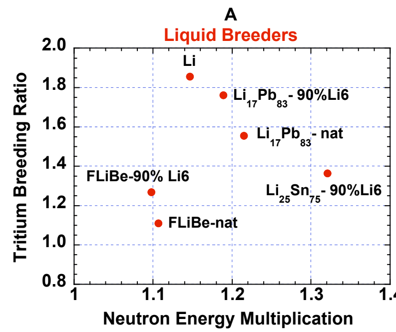
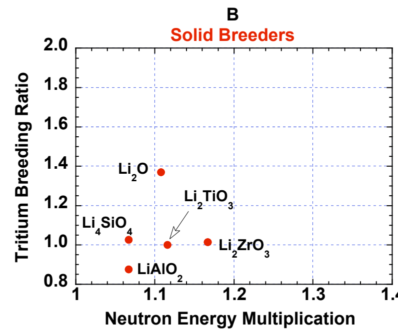
* Y << X

Impact of Design Elements on Breeding Capacity

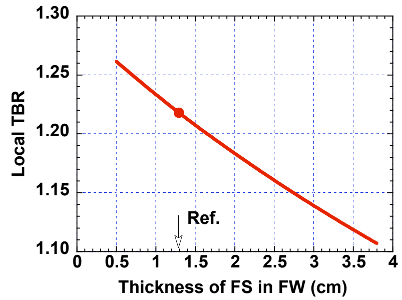


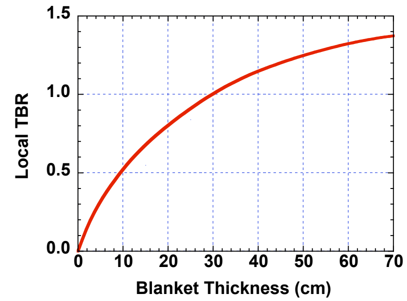




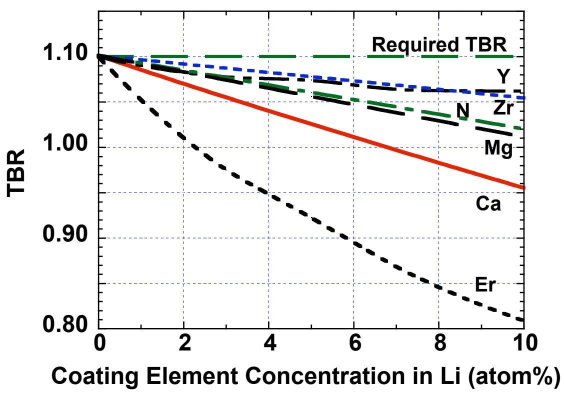
Impact of Design Elements on Breeding Capacity (Cont.)

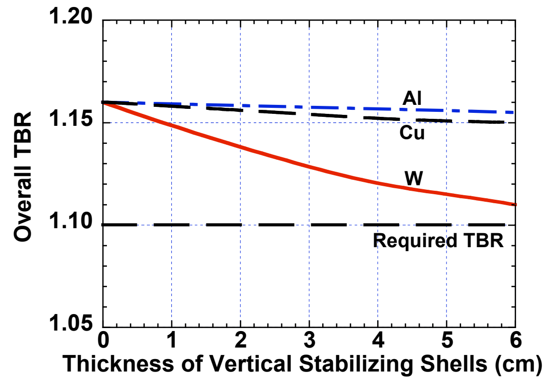
DCLL Blanket





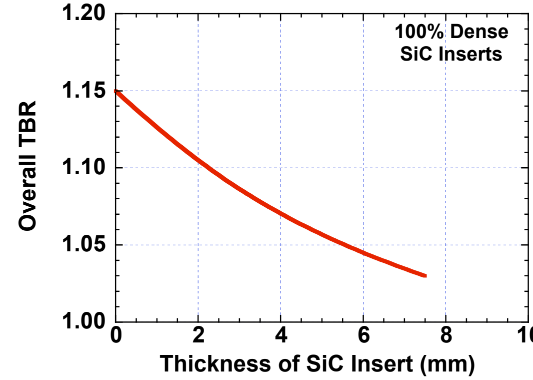
ARIES-RS
V Coating for
Li/V Blanket

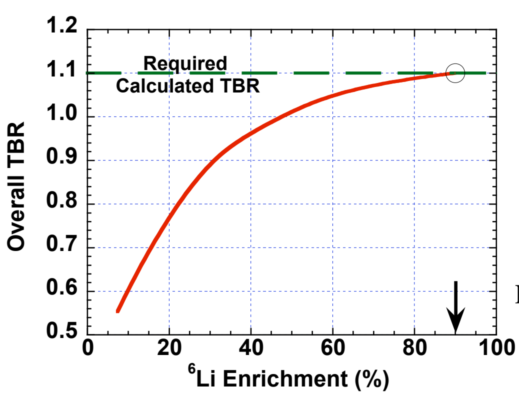




ARIES-AT Stabilizing Shells
Located between LiPb/SiC
Blanket Segments

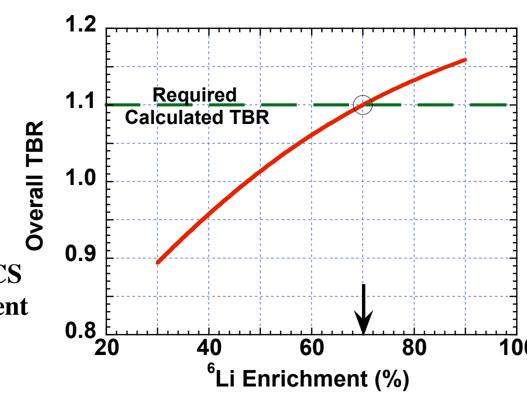
ARIES-AT DCLL Blanket





ARIES-AT
Enrichment

ARIES-CS
Enrichment



Conclusions

- **Breeding margin** (calculated TBR-1) **is breeder and design-dependent**. It **evolves with time** and accounts for know deficiencies in calculated TBR due to data and 3-D modeling, unknown uncertainties in design elements, possible malfunctions during plant operation, and start-up T supply for new power plant.
- 3-D Calculated TBR must be greater than Net TBR. 1% uncertainty translates into 1-2 kg T/FPY (for 2-3 GW fusion power), causing shortage or surplus of T.
- Net TBR must be very close to unity in order to ensure sufficient T supply without generating excessive T surplus.
- **Dedicated R&D program** will reduce breeding margin.
- **LiPb** blanket parameters should be determined for **^{6}Li enrichment < 90%.**
- **Online adjustment of breeding is *must* requirement** for Demo and power plants.
- Such online adjustment is **feasible for liquid breeder blankets** through adjusting ^{6}Li enrichment of breeder, but **difficult to envision for solid breeder blankets.**