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

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Rationale

- Plant with 1 GW fusion power consumes huge amount of T (55.6 kg per full power year).
- 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.
- Shortage of T significantly impacts plant operation.
- Surplus of T introduces T storage problem.
- For licensing considerations, fusion should not generate excess T than needed for plasma fuelling.
- To avoid T shortage, **Calculated TBR** must exceed unity by adequate margin, but blanket should not generate excess T.

$\Rightarrow$ **narrow tritium operating window**

Rationale (Cont.)

- **Net TBR** during plant operation could be as low as 1.01 in advanced designs, much lower than the calculated TBR*.
- Dedicate R&D program will reduce difference between **Calculated TBR** and **Net TBR**. However, remaining uncertainties could still be significant for Demo operation.
- Early generations of fusion plants may require **Net TBR** > 1.01 for shorter doubling time.
- Mature fusion system may call for 1.002 < **Net TBR** < 1.01.
- Fusion plants may not operate in uniform manner, generating more/less T during operation according to:
  - Need for variable doubling time
  - Need for higher/lower breeding over certain time period (with the same integral amount of T over blanket lifetime)
  - Availability of T recovered from detritiation system.
- For these reasons, T bred in blanket must be adjusted online – relatively easy task for liquid breeders (through ^{6}Li enrichment), but difficult to envision for solid breeder blankets*.

* **Ref**: L. El-Guebaly and S. Malang, Toward the ultimate goal of tritium self-sufficiency: technical issues and requirements imposed on ARIES advanced fusion power plants, Fusion Engineering and Design, in press.

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***

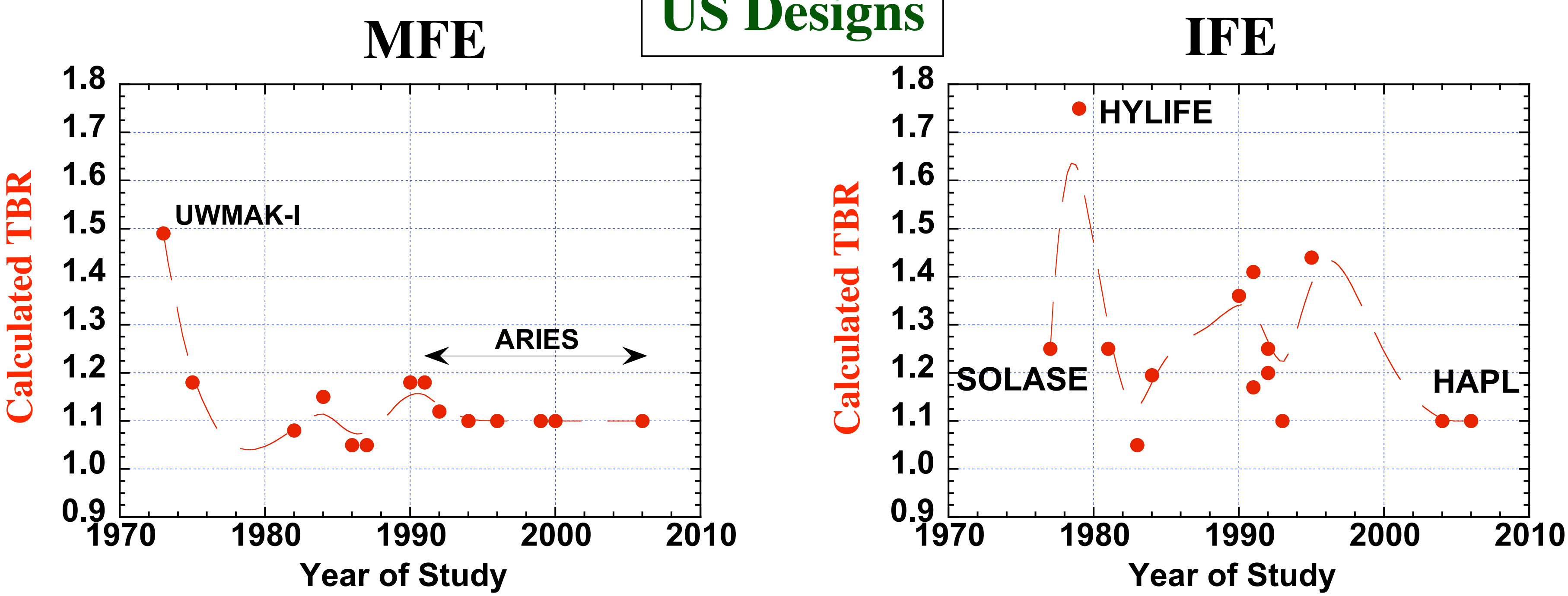
- Could T breeding be adjusted online?
  Yes, for liquid breeders through ^{6}Li enrichment

- Should 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 JA studies accord with ARIES 1.1 Calculated TBR .
- Some designs call for higher Calculated TBR with Net TBR of ~1.05.

US Designs



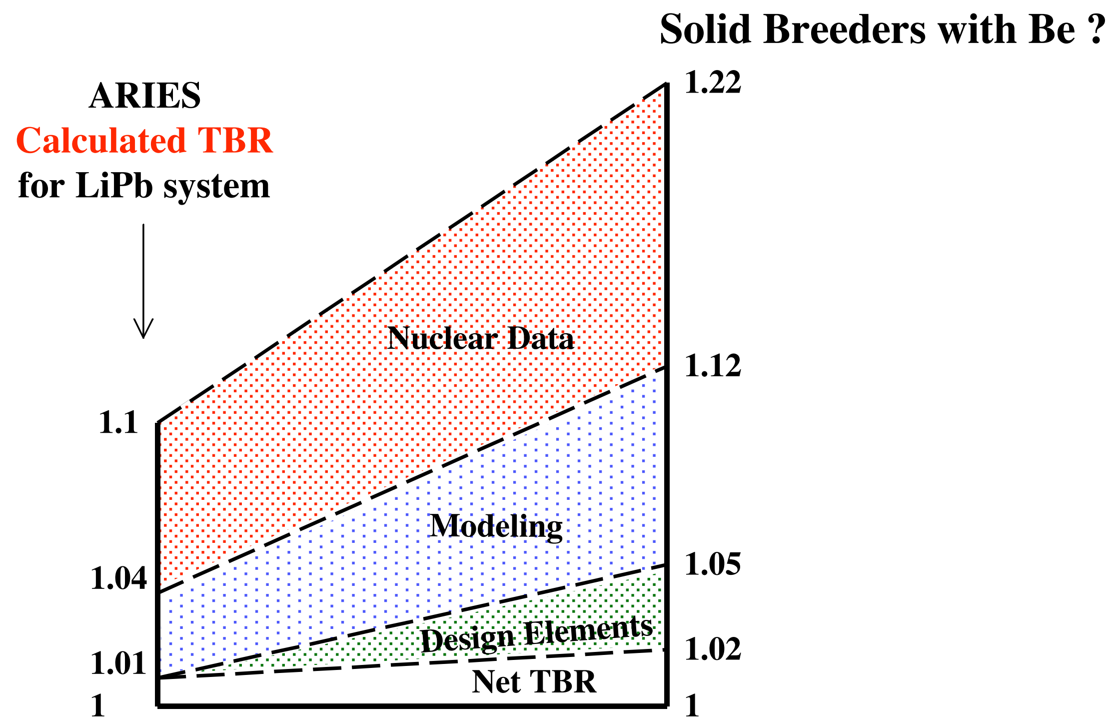
Breeding Margin

(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 items: **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 JA 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 JA and EU to validate nuclear data.
- New experiments are underway in JA and EU 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 JA and EU conduct LiPb experiments, benchmark, and publish results.

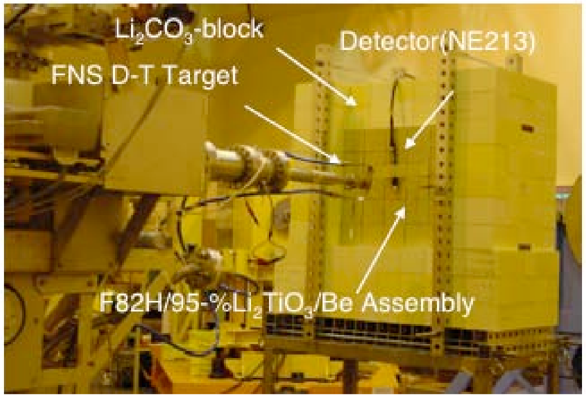
Margin for Known Deficiency in Nuclear Data (Cont.)

Solid breeder experiments:

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

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

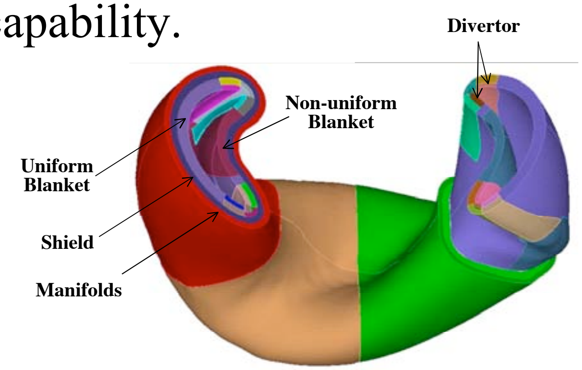
FNS Facility **(JAEA, Japan)**



FNG Facility **(ENEA, Italy)**

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



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

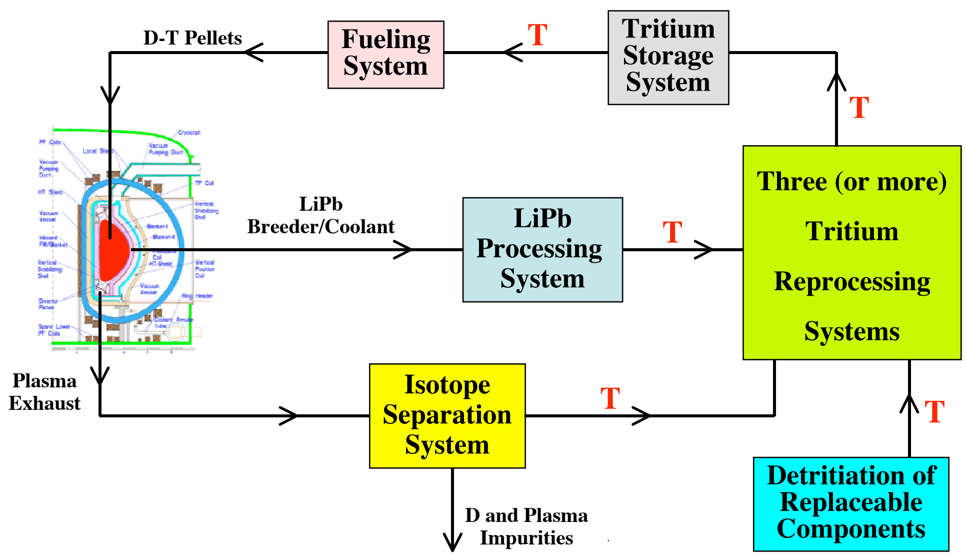
- Practically, 3-D model cannot represent real geometry, particularly complex blanket designs as very detailed blanket is too costly to model.
- Homogenization overestimates breeding level and 3-D Calculated TBR should be adjusted accordingly.
- Margin of error in Calculated TBR due to modeling could 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, stabilizing shells, 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 and/or withstand off-normal events
  - 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 strict 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.).

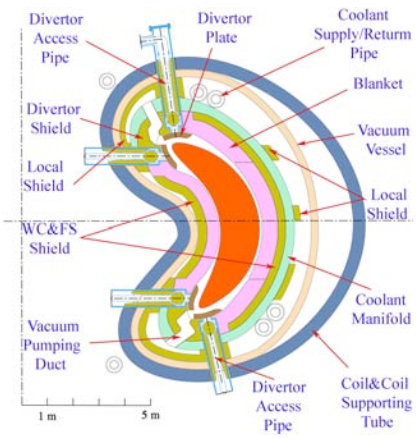


* **Ref**: L. El-Guebaly and S. Malang, Toward the ultimate goal of tritium self-sufficiency: technical issues and requirements imposed on ARIES advanced fusion power plants, Fusion Engineering and Design, in press.

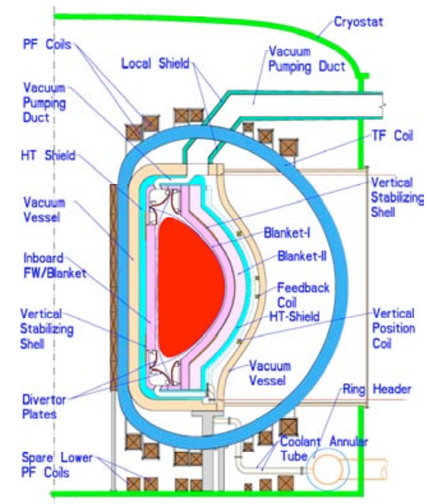
Margin for T Bred in Excess of T consumed (Cont.)

	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)



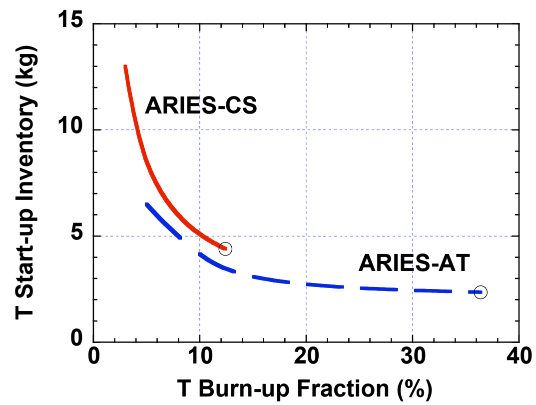
ARIES-AT (Advanced Tokamak)



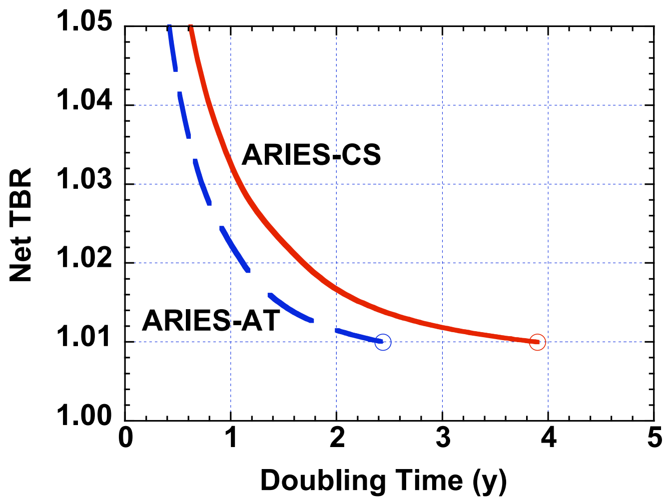
Realistic assumptions:

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

⇒ **Net TBR** ~1.01



Net TBR (~1.01%)



Early generations of fusion plants require **Net TBR** > 1.01 with shorter doubling time (needed to supply new power plant with start-up T).

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

Advanced physics and technology help keep Net TBR around 1.01

Essential requirements include:

– T burn-up fraction in plasma exceeding 10% (with high T recycling rate)
– High reliability and short repair time (< 1 day) for T processing system
– Three or more T processing system
– 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):

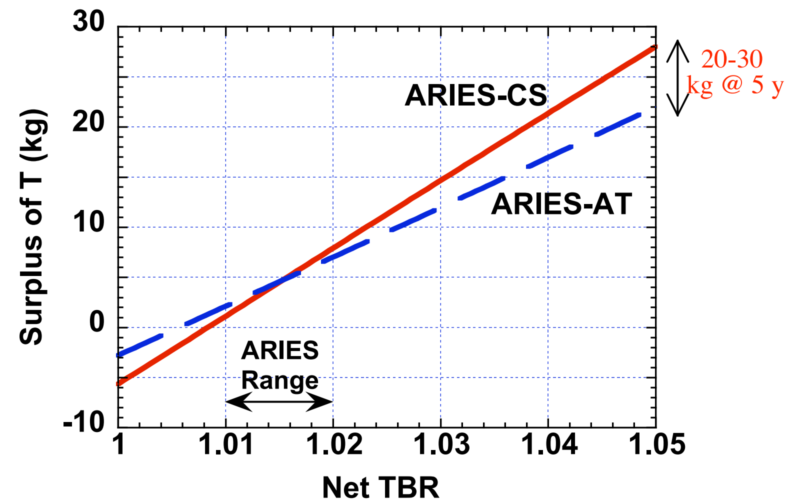
  Major design changes anticipated to raise TBR, unless reference blanket designed with ^{6}Li enrichment < 90%:
  - Thickening blanket,
  - Replacing W stabilizing shells of ARIES-AT by Al or Cu shells,
  - Lowering the structural content within the blanket,
  - Adding a beryllium multiplier to the blanket,
  - Increasing plasma aspect ratio,
  - Operating tokamaks in a single-null mode (4-5% additional breeding).
- 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 (Net TBR >1.01) Introduces 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 will reach ~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:

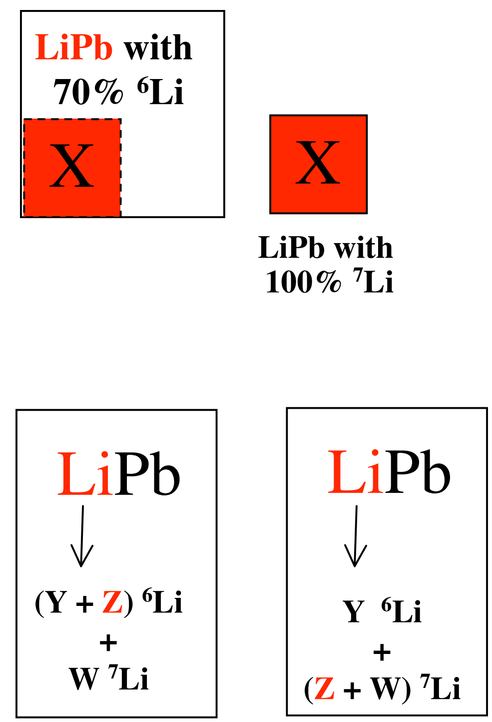
  a) Replace X tons of enriched LiPb by X tons of LiPb with 100% ^{7}Li

  (straightforward but requires additional storage for LiPb eutectic with 100% ^{7}Li).

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

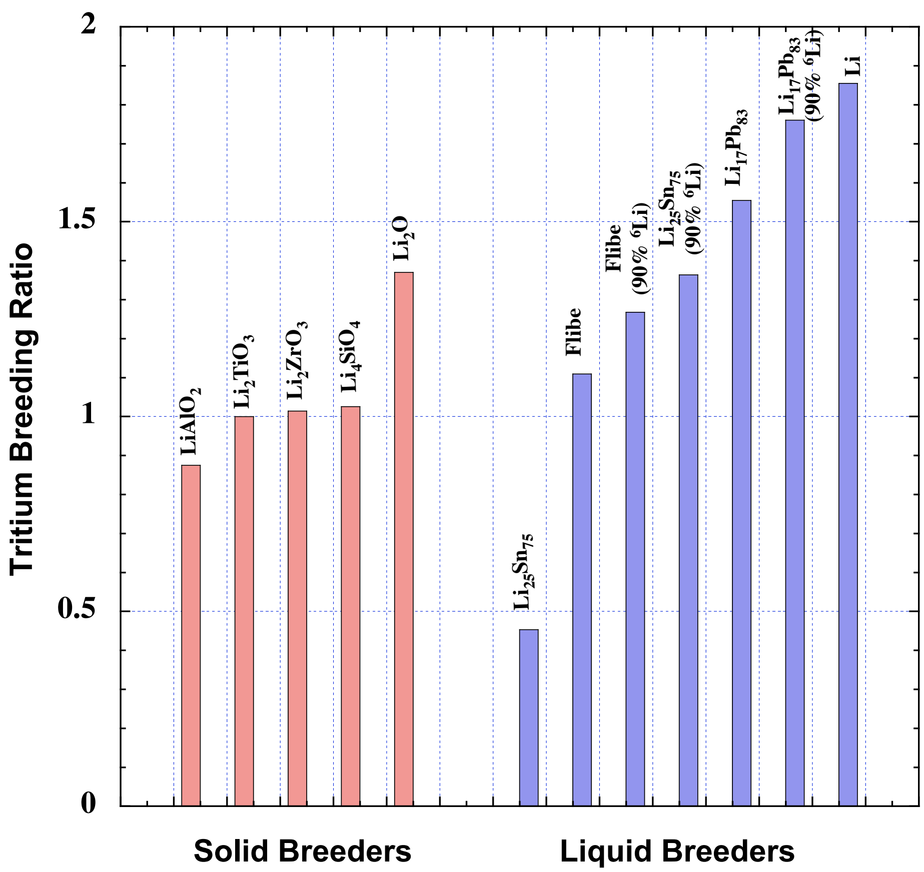
  (does not require large storage, but needs practical method* to remove Z tons of enriched Li from eutectic and feed back Z tons of 100% ^{7}Li to eutectic).

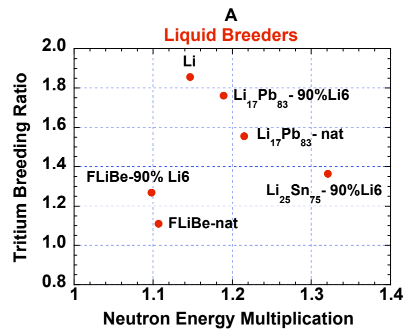
Example of Over-breeding Blanket

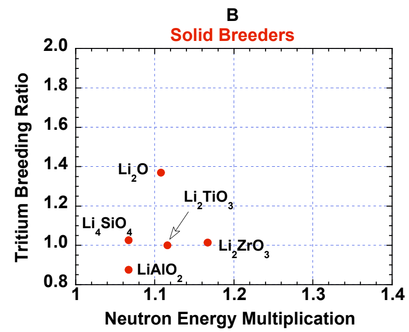


* H. Feuerstein, D.A. Wirjantoro, L. Hoerner, S. Horn, Eutectic mixture Pb-17Li - in-situ production and Li-adjustment, Fusion Technology 2 (1994) 1257-1260.
P. Hubberstey, M.J. Capaldi, F. Barbier, Replenishment of lithium lost from Pb-17Li, Fusion Technology 2 (1996) 1475-1478.

Impact of Design Elements on Breeding Capacity*



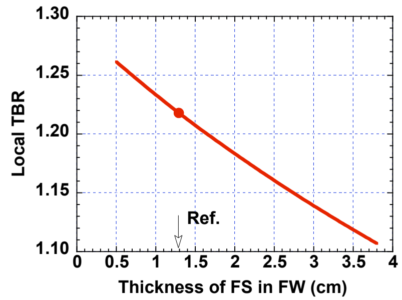


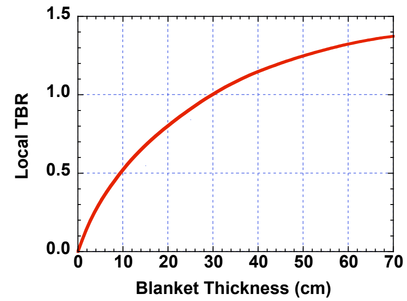


* Thick breeders; no structure; no multiplier; natural Li enrichment unless indicated.

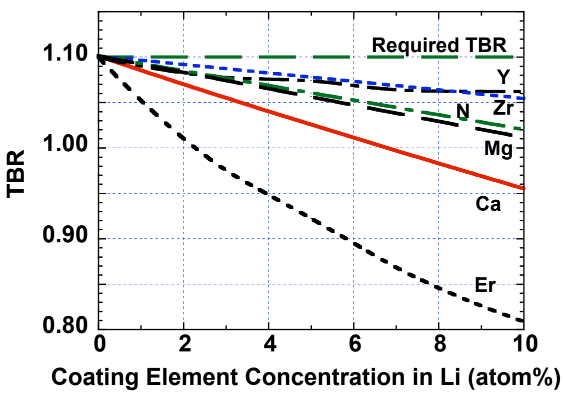
Impact of Design Elements on Breeding Capacity (Cont.)

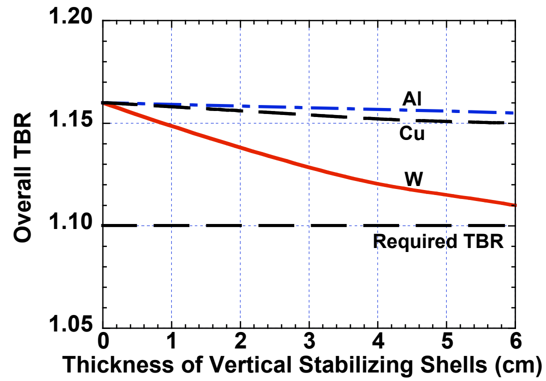
DCLL Blanket





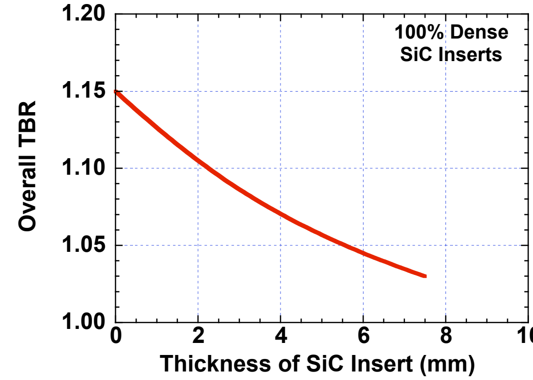
ARIES-RS
V Coating for
Li/V Blanket

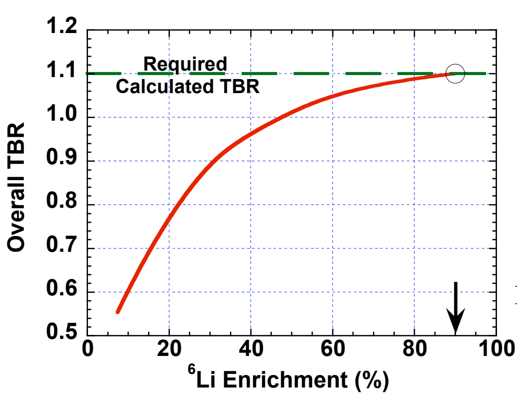




ARIES-AT Stabilizing Shells Located between LiPb/SiC Blanket Segments

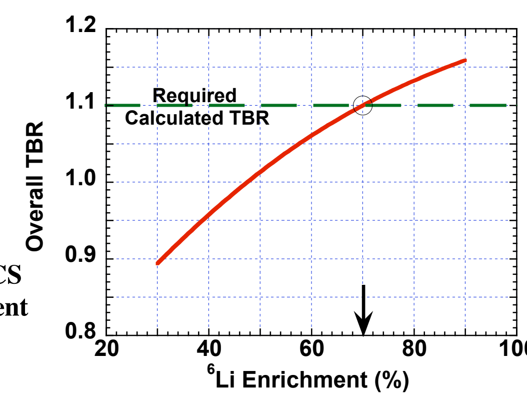
ARIES-AT DCLL Blanket





ARIES-AT Enrichment

ARIES-CS Enrichment



Conclusions

- **No universal breeding margin** (**Calculated TBR** - 1). **It is breeder and design-dependent, 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
  - Start-up T supply for new power plant.
- **Dedicated R&D program** will reduce breeding margin before Demo operation.
- **Must requirements** for fusion power plants include**:**
  - 3-D **Calculated TBR** > **Net TBR**
  - **Net TBR** very close to unity to ensure sufficient T supply without excessive T surplus
  - **LiPb** blanket parameters determined for **^{6}Li enrichment < 90%**
  - **Online adjustment of breeding** (feasible for liquid breeder blankets, but difficult to envision for solid breeder blankets).
- **Ability to adjust Li enrichment during operation mitigates concerns** about:
  - Danger of placing plant at risk due to T shortage
  - Problem of handling T surplus.