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 $^6$Li 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.
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%) → **design dependent**

![Diagram showing the breakdown of breeding margin into different categories]
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.
Solid breeder experiments:

- Recent **FNS** results for Li$_2$TiO$_3$/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.
• 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.

- 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.)

<table>
<thead>
<tr>
<th></th>
<th>ARIES-CS</th>
<th>ARIES-AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net output power (MWₑ)</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Fusion power (MW)</td>
<td>2436</td>
<td>1759</td>
</tr>
<tr>
<td>Burn-up fraction of T in plasma</td>
<td>12.4%</td>
<td>36.4%</td>
</tr>
<tr>
<td>T consumption: in kg/FPY</td>
<td>135</td>
<td>97.8</td>
</tr>
<tr>
<td>in kg/day</td>
<td>0.37</td>
<td>0.268</td>
</tr>
<tr>
<td>T throughpup (kg/day)</td>
<td>3</td>
<td>0.74</td>
</tr>
<tr>
<td>T holdups in LiPb breeder (kg)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>T holdups in structure (kg)</td>
<td>~1</td>
<td>~0.8</td>
</tr>
<tr>
<td>T inventory in reprocessing system (kg)</td>
<td>1.5</td>
<td>0.37</td>
</tr>
<tr>
<td>T build-up outside FPC (kg)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Stored T for malfunctions (kg)</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>T decay (kg/y)</td>
<td>0.33</td>
<td>0.16</td>
</tr>
<tr>
<td>T losses to environment (g/y)</td>
<td>&lt; 4</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>Start-up inventory (kg)</td>
<td>~4</td>
<td>~2</td>
</tr>
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Realistic assumptions:
- 3 fuel reprocessing systems
- 1 day T reserve to allow unperturbed plasma refueling
- Doubling time < 5 y
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).

* $Y << X$
Impact of Design Elements on Breeding Capacity
Impact of Design Elements on Breeding Capacity (Cont.)

ARIES-RS
V Coating for Li/V Blanket

ARIES-AT DCLL Blanket

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

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 **6Li 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 6Li enrichment of breeder, but **difficult to envision for solid breeder blankets.**