Tritium Breeding Ratio Requirements

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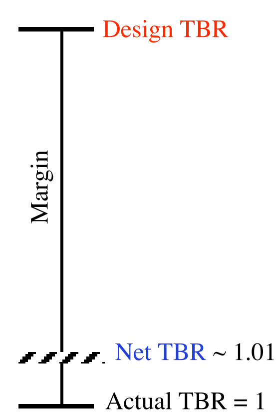
General Requirements

- There is no practical external source of tritium.
- Fusion power plants must breed their own tritium (55.6 kg/FPY per 1 GW P_f).
- For licensing considerations, fusion plants should not generate excess T than needed.
- For advanced designs, Net TBR must be close to 1.01:
  - Early generations of fusion plants may require Net TBR > 1.01 for shorter doubling time.
  - Mature fusion system may call for 1.004 < Net TBR < 1.01. Exact value depends on T inventory, doubling time, etc.
  - Fusion plants may not operate in uniform manner, generating more (or less) T during operation* ⇒ operating LiPb system at enrichment < 90% is highly desirable
- Online adjustment of breeding is mandatory. This is easily achieved for liquid breeders with fine tuning of enrichment.
- Design TBR must be greater than Net TBR by a margin to account for known deficiencies in nuclear date and modeling and unknown uncertainties in design elements.
- This margin evolves with time as nuclear data improves, more sophisticated 3-D neutronics modeling tools develop, and detailed engineering designs become available.



* Due to need for variable doubling time, need for higher/lower breeding over certain time period with same integral amount of T over blanket lifetime, Li burn-up of ceramic breeders, etc.

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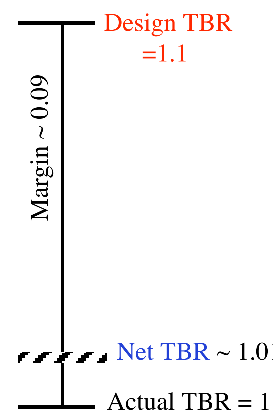
Should we Continue Considering Design TBR of 1.1?

- 5-hr discussion at 1992 ARIES project meeting @ UCLA concluded that **ARIES calculated Design TBR should be ≥ 1.1** to assure T self-sufficiency. **Key participants**: Laila, M. Abdou, M. Youssef, E. Cheng, Farrokh, Ken, Dai Kai, C. Wong.

- **1999 Snowmass** Session on Chamber Science and Technology:
  Q #6: Potential for Achieving Tritium Self-Sufficiency
  Key participants: M. Sawan, Laila, M. Youssef, S. Willms, Dai Kai, C. Wong.
  Recommendations:
  - Calculated Design TBR > Net TBR
  - Net TBR > 1.01
  - Uncertainties in calculated Design TBR could reach 10%
  - Aggressive effort is required to reduce uncertainty to < 3%



- **3/2001 ARIES "Tritium Town Meeting"**:
  Laila presented ARIES position: Calculated Design TBR **should be ≥ 1.1**.

Calculated Design TBR ≥ 1.1 for all Previous ARIES Designs

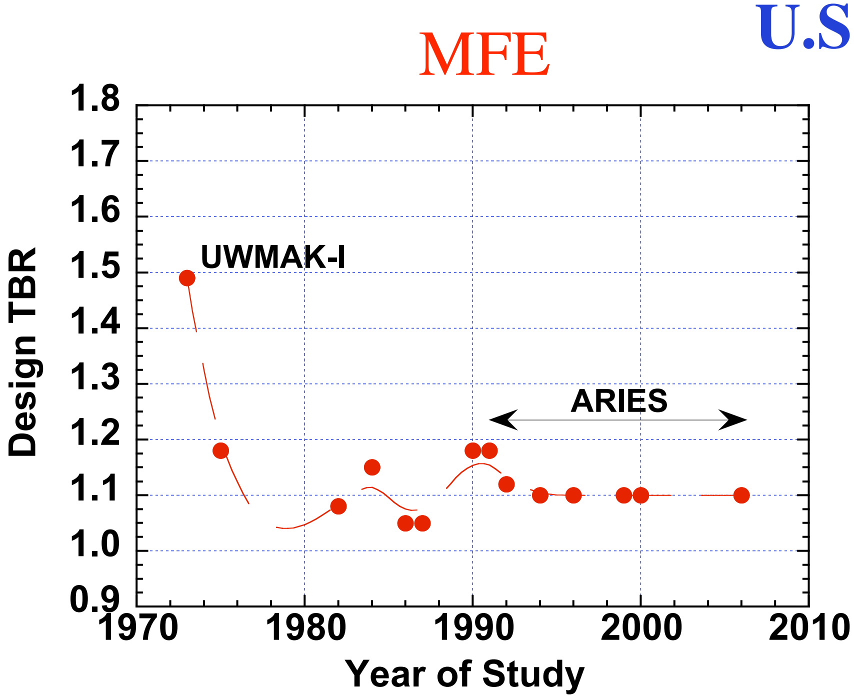
ARIES Designs	Blanket Concept	Design TBR	Enrichment
1992 **ARIES-II**	Li/V	**1.12**	Nat. Li
1992 **ARIES-IV**	Li_2O/Be/He/SiC	**1.12**	Nat. Li
1994 **SPPS**	Li/V	**1.1**	Nat. Li
1996 **ARIES-RS**	Li/V	**1.1**	Nat. Li
1999 **ARIES-ST**	LiPb/He/FS	**1.1**	**70%** *
2000 **ARIES-AT**	LiPb/SiC	**1.1**	90%
2006 **ARIES-CS**	LiPb/He/FS	**1.1**	**70%** – offering flexibility to increase TBR, if needed.

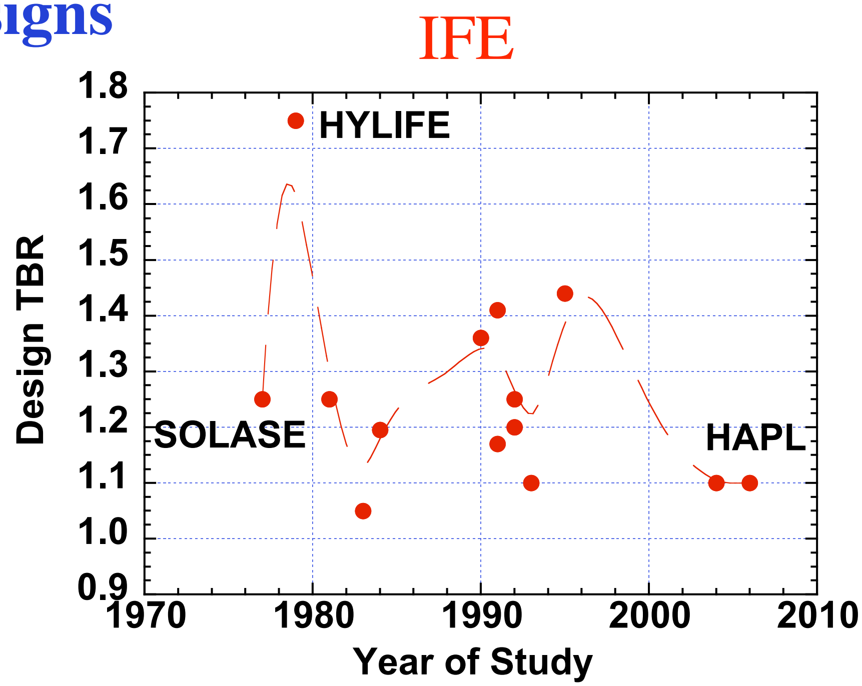
- There is no general consensus within fusion community on what the Design TBR should be.
- U.S. **HAPL** design along with many **Japanese and European designs** adopted ARIES 1.1 Design TBR.
- Other neutronics experts call for higher Design TBR, ranging from 1.15 to 1.3, with higher Net TBR of 1.05.

* Enrichment dropped from 90% to 70% in response to FW design modification that came very late in the design process calling for less FW structure.

Evolution of Calculated Design TBR Over Past 40 years

U.S. Designs





- Majority of ARIES designs employed liquid breeders (Li or LiPb).
- ARIES TBR design margin did not change over past 10-15 years (no US/J/EU R&D program to evaluate nuclear data of liquid breeders).
- 2007/2008 European R&D program for DCLL blanket concept, along with UW newly developed CAD/MCNP approach, will help define more accurately breeding margin for LiPb.

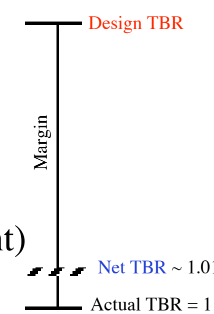
Design Margins Add Credibility to ARIES Designs

- Suggested 9% TBR margin for LiPb system assures T self-sufficiency, accounting for deficiencies in nuclear data and 3-D modeling.

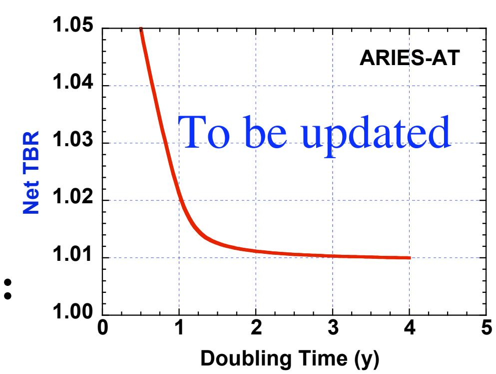
- Design margin is not unique to TBR as:
  - FS structure should operate 50 degree below temperature limit with lower η_{th}
  - FS stresses should be at 2/3 of allowable to assure structural integrity
  - Plasma should operate few % below beta limit to avoid disruption
  - BS current should be kept ~5% below limit to avoid disruption.

1.1 Design TBR Could Drop to ~1.01 due to Known Deficiency in Data & Modeling

- Net TBR of ~1.01 needed to[#]:
  - Supply startup T for future power plant (~2.3 kg for ARIES-AT type)
  - Maintain equilibrium holdup inventory (~1.9 kg for LiPb system)
  - Provide ~1 day of T reserve storage for malfunction in T processing system (~0.4 kg)
  - Provide T holdups for replaceable components (~1 kg every 4-5 y)
  - Compensate for radioactive T decay (5.47%/y) between production and use (inventory dependent)
  - Account for losses to environment (< 4 g/y) (negligible).



- Main elements influencing Net TBR:
  - T burn-up fraction in plasma (36% from ASC output. Any supporting data?)
  - T inventory and holdups in sub-systems (~1.9 kg +1 kg)
  - Reserve storage (~0.4 kg)
  - Doubling time* (2.3 kg every ~ 5 y)



- **1% of TBR** is equivalent to **~1.1 kg of T/FPY for 2 GW fusion power:**
  - There is no external source of T ⇒ Net TBR should be ≥ 1.01
  - No excess T should be generated
  - Net TBR may vary slightly during operation due to uncertainties in design elements
  - Online adjustment of enrichment is mandatory for LiPb system. How? Instantaneous adjustment or over days or years? How precise could enrichment and TBR be controlled?

Memo by S. Malang on 5/22/07: Contribution to the Discussion on the Required TBR. Numbers will be updated.
M. Sawan and M. Abdou, "Physics and Technology Conditions for Attaining Tritium Self-Sufficiency for the DT Fuel Cycle," Fusion Engineering and Design 81 (2006) 1131-1144.

* Time needed to supply new machine with 2.3 kg of T (= holdups in in-vessel components + 1 day reserve).

1.1 Design TBR Could Drop to ~1.01 due to Known Deficiency in Data & Modeling (Cont.)

- To keep Net TBR around 1.01, advanced fusion designs with advanced physics and technologies *must*:
  - Increase T burn-up fraction in plasma to > 5%
  - Recycle T and α particles at high rates
  - Achieve low T inventory in all subsystems
  - Require high reliability and short repair time (< 1 day) for T processing systems
  - Have two or more T processing system
  - Ensure extremely low T losses to environment (< 4 g/y).

Breeding Margin

- Breeding margin (= Design TBR - Net TBR) accounts for **known** deficiencies in:
  - **FENDL-2.1** nuclear data of breeders, multipliers, coolant, and structure (up to 20%)
  - 3-D neutronics model (up to 7%)*:
    - Imperfect 3-D model
    - Homogenization of both FW and blanket.

- These known deficiencies negatively affect Design TBR, mandating:

Calculated Design TBR $\geq$ 1.1

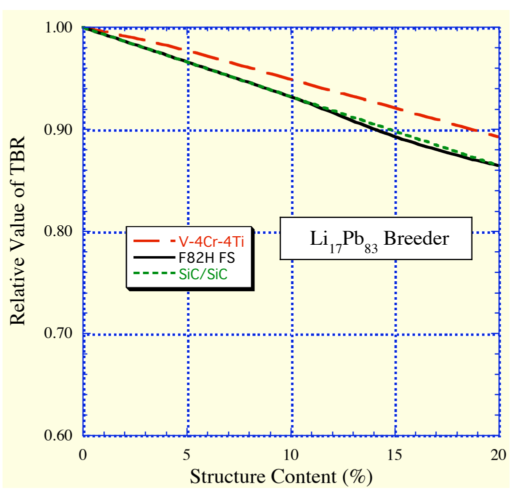
- **Improved** nuclear data and **perfect** 3-D modeling help reduce breeding margin.

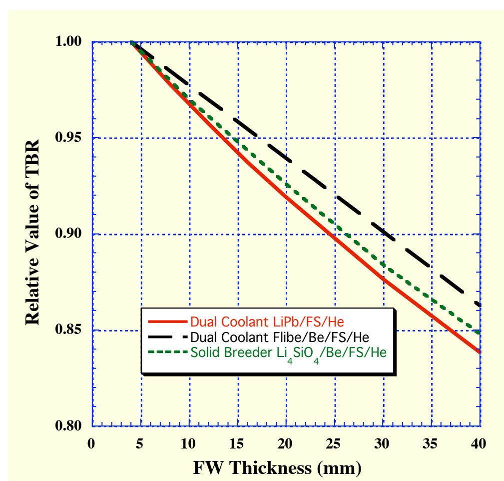
* **Reference**: M. Sawan and M. Youssef, "Three-Dimensional Neutronics Assessment of Dual Coolant Molten Salt Blankets with Comparison to One-Dimensional Results," Fusion Engineering and Design 81 (2006) 505-511.

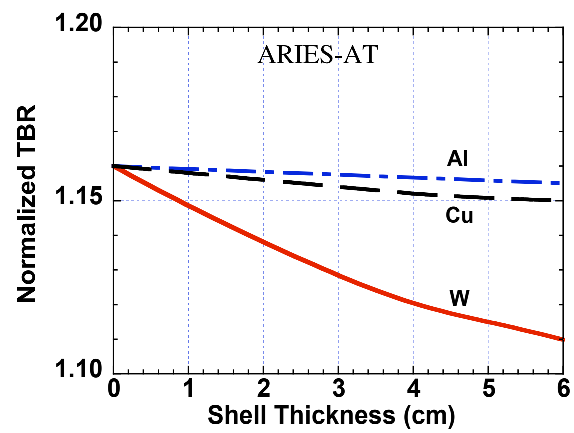
Breeding Margin (Cont.)

- **Design changes** will influence breeding, calling for larger breeding margin, <u>if design allows</u>. For example, adding 2 mm W on FW to improve plasma performance, more structure in blanket, FW armor, thicker FW, thicker SiC insulator, thicker stabilizing shells, larger penetrations, details of geometry, etc.

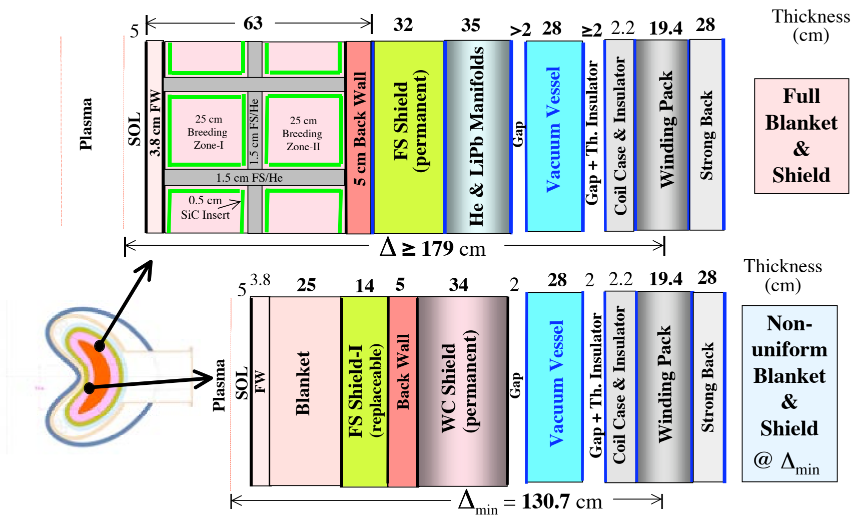
- In ARIES, no provision was made in calculated Design TBR to account for possible design changes. This means <u>any **design change** will require different enrichment and/or redesigning blanket</u> to assure Net TBR of 1.01.

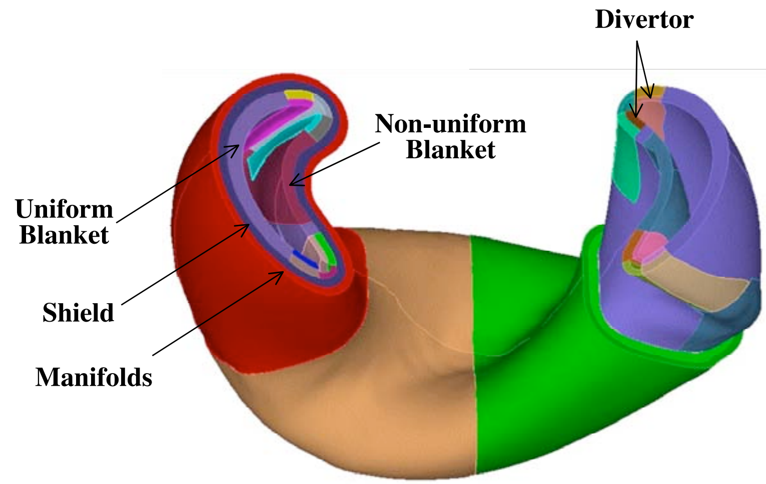






Example of 3-D Nuclear Model Lacking Engineering Details





- UCSD CAD model for ARIES-CS delivered to UW **homogenized**:
  - FW, blanket, back wall of full blanket
  - FW, blanket, shield, back wall of non-uniform blanket.

- Such crude model calls for more than 3% deficiency in TBR due to modeling.

What Technologies should be Developed to Narrow Gap between Design TBR and Net TBR?

- DOE should allocate neutronics funding to:
  - Improve nuclear data with extensive R&D program
  - Continue developing CAD/MCNP approach to facilitate 3-D modeling.
- In 2003, UW started improving 3-D modeling capability using newly developed CAD/MCNP approach. Future CAD model (by UCSD) should include all details to increase fidelity in calculated Design TBR.
- Nuclear data is not just cross-section measurements. It includes secondary neutron energy and angular distributions that are more difficult to measure.
- Fixing nuclear data will take years of extensive experimental program (currently in Japan and Europe) combined with data re-evaluation (by LANL and IAEA), then data validation.
- At present, there is no U.S. experimental program to validate nuclear data.
- U.S. could collaborate with Japanese FNS or Italian FNG programs to better define C/E for LiPb using latest FENDL-2.1 nuclear data.
- Or, rely entirely on Europeans to conduct these activities in 2008.
- However, such integral experiments have their own limitations (such as neutron source strength and lower n flux within mockups). Uncertainties remain until testing is performed in real fusion environment (e.g., in ITER).

Background Info

Breeders and structural materials are made of many elements and natural isotopes:

- **Li**: Li-6, Li-7.
- **Li_2TiO_3**: **Li** (Li-6, Li-7),
  Ti (Ti-46, Ti-47, Ti-48, Ti-49, Ti-50),
  O (O-16, O17, O-18).
- **Li_2O**: **Li** (Li-6, Li-7),
  O (O-16, O17, O-18).
- **$LiAlO_2$**: **Li** (Li-6, Li-7),
  Al (Al-27)
  O (O-16, O17, O-18).
- **Li_4SiO_4**: **Li** (Li-6, Li-7),
  Si (Si-28, Si-29, Si-30)
  O (O-16, O17, O-18).
- **Be**: Be-9.
- **LiPb**: **Li** (Li-6, Li-7), ~52%
  Pb (Pb-204, Pb-206, Pb-207, Pb-208).
- **SiC**: **Li** (Li-6, Li-7),
  Si (Si-28, Si-29, Si-30),
  C (C-12, C-13).
- **F82H structure**: **Fe** (Fe-54, Fe-56, Fe-57, Fe-58),
  Cr (Cr-50, Cr-52, Cr-53, Cr-54),
  W (W-180, W-182, W-183, W-184, W-186),
  V (V-50, V-51),
  Ta (Ta-181),
  C (C-12, C-13),
  Ni (Ni-58, Ni-60, Ni-61, Ni-62, Ni-64).

ARIES-AT (32 Isotopes)

Background Info (Cont.)

- Nuclear data evaluation includes many Xns and data processing systems:
  - Scattering Xns:
    - Elastic scattering Xn (n,n)
    - Inelastic scattering Xn (n,n`)
  - Absorption Xns:
    - Radiative capture (n, γ)
    - n multiplication Xns: (n,2n; n,3n)
    - Gas production Xns: (n, p; n, d; n, t; n, He^3; n, α; n, 2α; etc.)
  - Multi-step reactions
  - Measurements of energy and angular distributions of secondary neutrons
  - Processing of Xns in continuous energy and multi-group data libraries.

- T production within blanket is highly sensitive to neutron spectrum that's controlled by nuclear data evaluation that involves several data processing systems and numerous Xns (32 isotopes in ARIES-AT blanket).

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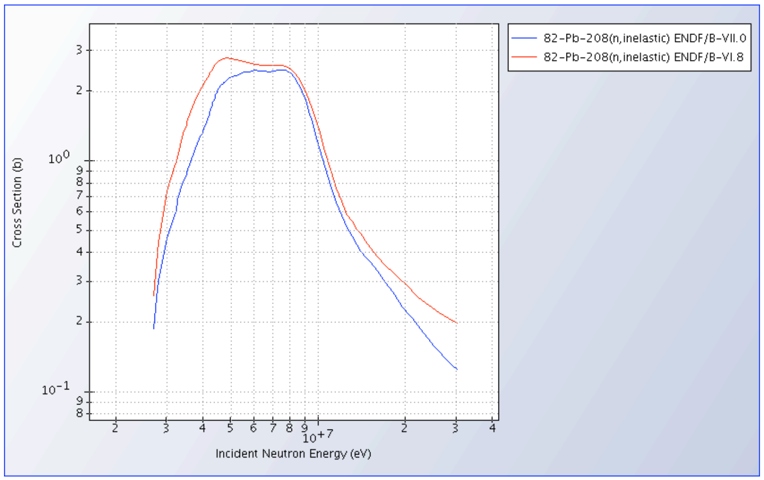
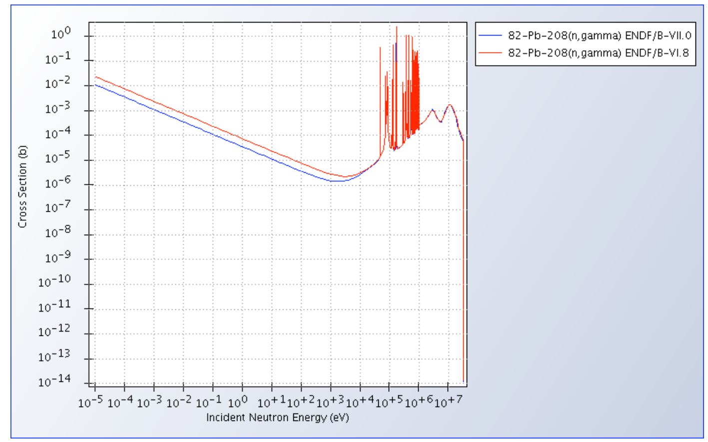
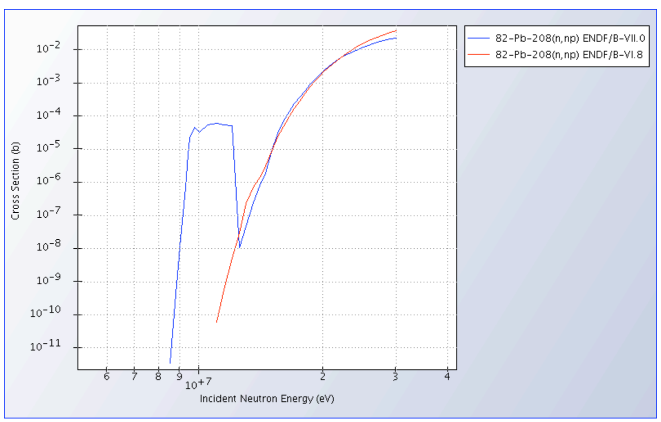
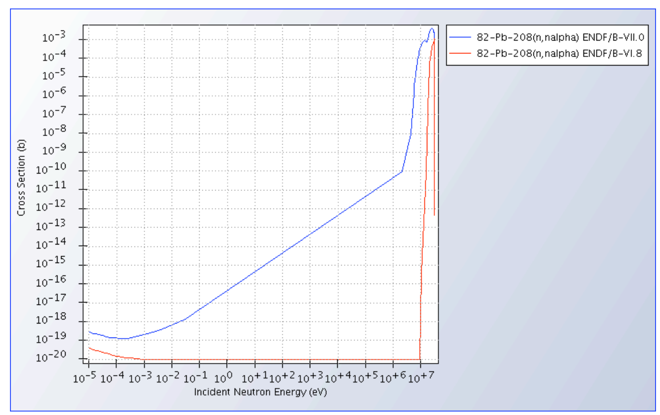
Background Info (Cont.)

- Most recent ENDF/B-VII evaluation indicates notable changes to ^{208}Pb cross sections that will surely affect calculated TBR of future designs.









Breeding-Related Japanese R&D Program

- Series of Japanese integral experiments have been performed over past 20 years with 14 MeV n source to validate nuclear data and compare calculated to measured tritium production rates.

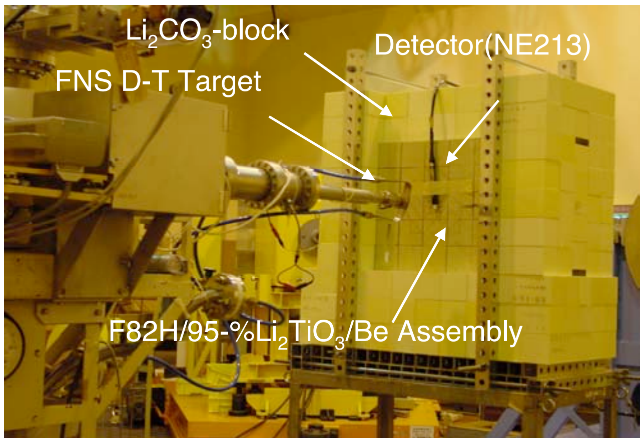
- Japanese experimental program examined blanket mockups to determine magnitude and direction (+ve or -ve) of change in tritium production rate due to uncertainties in IAEA FENDL nuclear data for several **ceramic breeders**, multipliers, coolants, and structural materials.

- No plan to examine LiPb breeder in near future, but willing to collaborate with U.S.

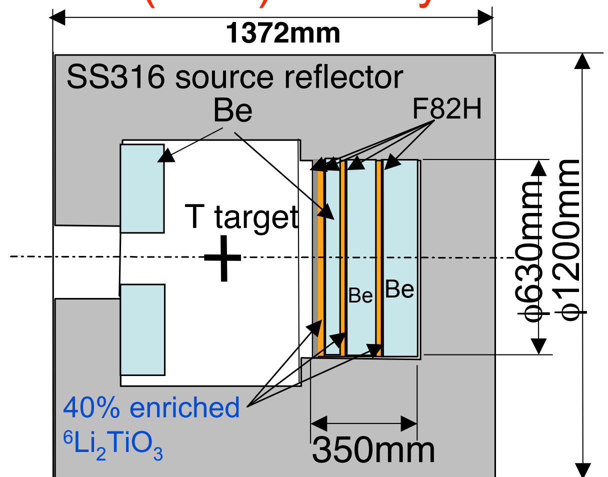
Breeding-Related Japanese R&D Program

(Most Recent Results for Li_2TiO_3/Be/F82H System)

Tritium Production Measurement and Predictive Validation
JAEA Fusion Neutron Source (FNS) Facility

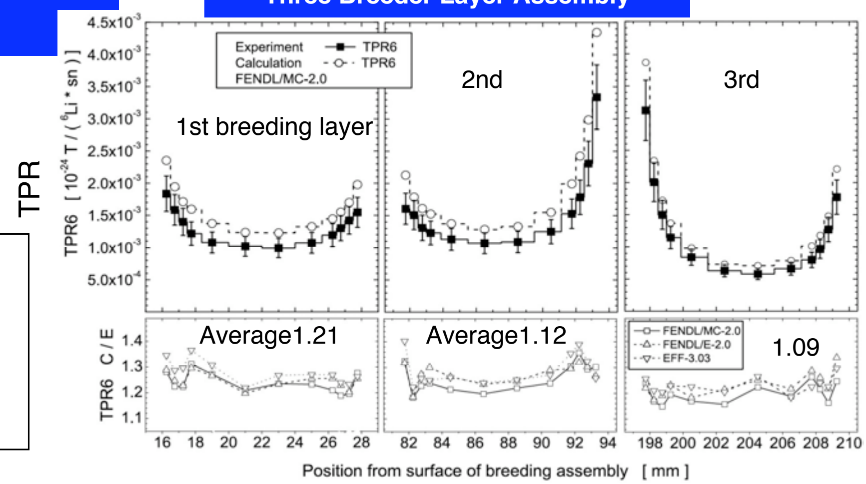


Single Breeder Layer Assembly (50 x 50 x 30 cm)
-F82H/Li_2TiO_3(^{6}Li:95%)/Be assembly surrounded by Li_2CO_3 and B_4C blocks



Three Breeder Layer Assembly

D-T neutron conditions
Neutron flux: 1.5 x 10^{11} n/sec/mA
Irradiated time: 10 ~ 20 h



Main Finding:
Calculations overestimate Li_2TiO_3 tritium production rate by up to 20%.

LiPb Breeding-Related Experiments

- As part of ITER R&D activities, new experiments are underway for helium-cooled **LiPb** blanket concept (used in ARIES-ST and -CS).
- Two independent measurements of tritium production rate planned at ENEA (Italy) and TUD (Germany).
- EUROFER structural material will be used (not F82H*)
- Results will be available in June 2008.

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* Modified F82H is used in ARIES designs.

Observations

- Using FENDL-2.1 data evaluation, Japanese R&D program indicates calculations overestimate tritium production rate by up to **20% for ceramic breeders**.
- Neither Japanese nor Europeans examined liquid breeders.
- UCLA uncertainty/sensitivity analyses predict 7-8% change in calculated TBR of LiPb/FS system, per M. Youssef (UCLA - 1992; 2007).
- ENEA (Italy) and TUD (Germany) plan to examine He-cooled LiPb blanket in 2007/2008. Results will be available by June 2008.
- Recommendations of R&D program would normally be to re-evaluate nuclear data **and** data processing systems for breeders, structure and multipliers through numerous experiments for individual isotopes.
- Iteration continues between data evaluation and experimental validation.
- Only ITER TBM **and** CTF will accurately measure T production for prototypical fusion environment (n spectrum, surrounding components, etc.)
- Best approach for ARIES is to continue including adequate margin (~6% due to nuclear data deficiency) in calculated Design TBR (based on theoretical uncertainty/sensitivity analyses) until ENEA/TUD conduct LiPb experiments in 2008.

UW Task

Assess impact of Li-6 enrichment on Design TBR of ARIES-AT

Reference ARIES-AT parameters:

LiPb/He/FS system

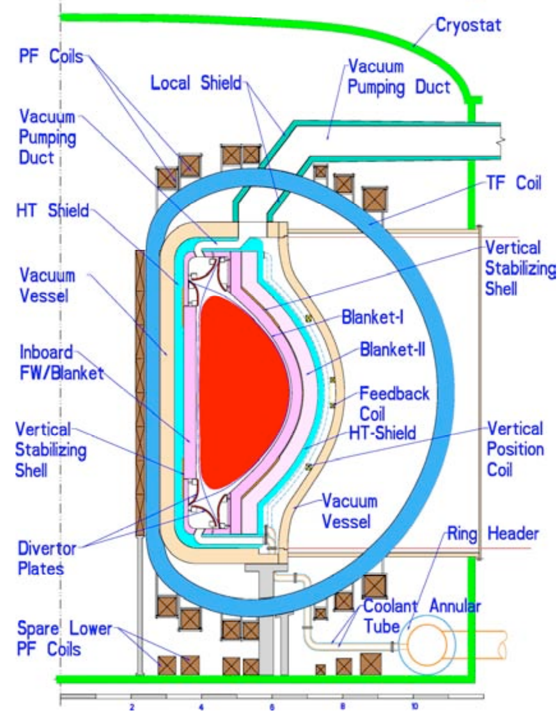
Design TBR is 1.1 with 90% Li-6 enrichment

Net TBR expected to reach 1.01 with 90% Li-6 enrichment.

Reference ARIES-AT Blanket Parameters

- 35 cm IB blanket
- 75 cm OB blanket: 30 cm B-I
  45 cm B-II

Cross Section of ARIES-AT Power Core Configuration

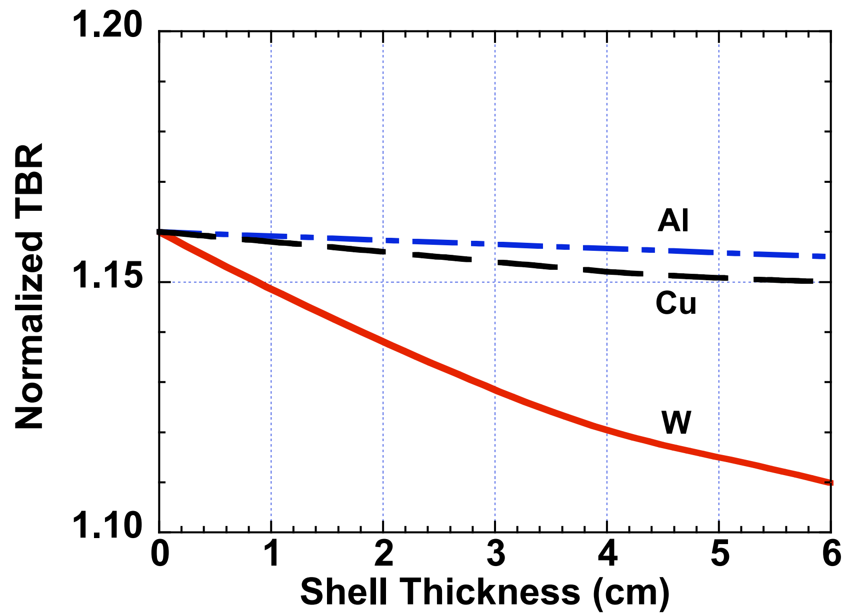


- Two W shells embedded in B-II:
  - 1 cm RWM shell at middle
  - 4 cm Vertical Stabilizing shell at top/bottom

- TBR based on 1-D estimate combined with blanket coverage fractions.
- 3-D model confirmed one data point during design process.

- FENDL-2 nuclear data Library.

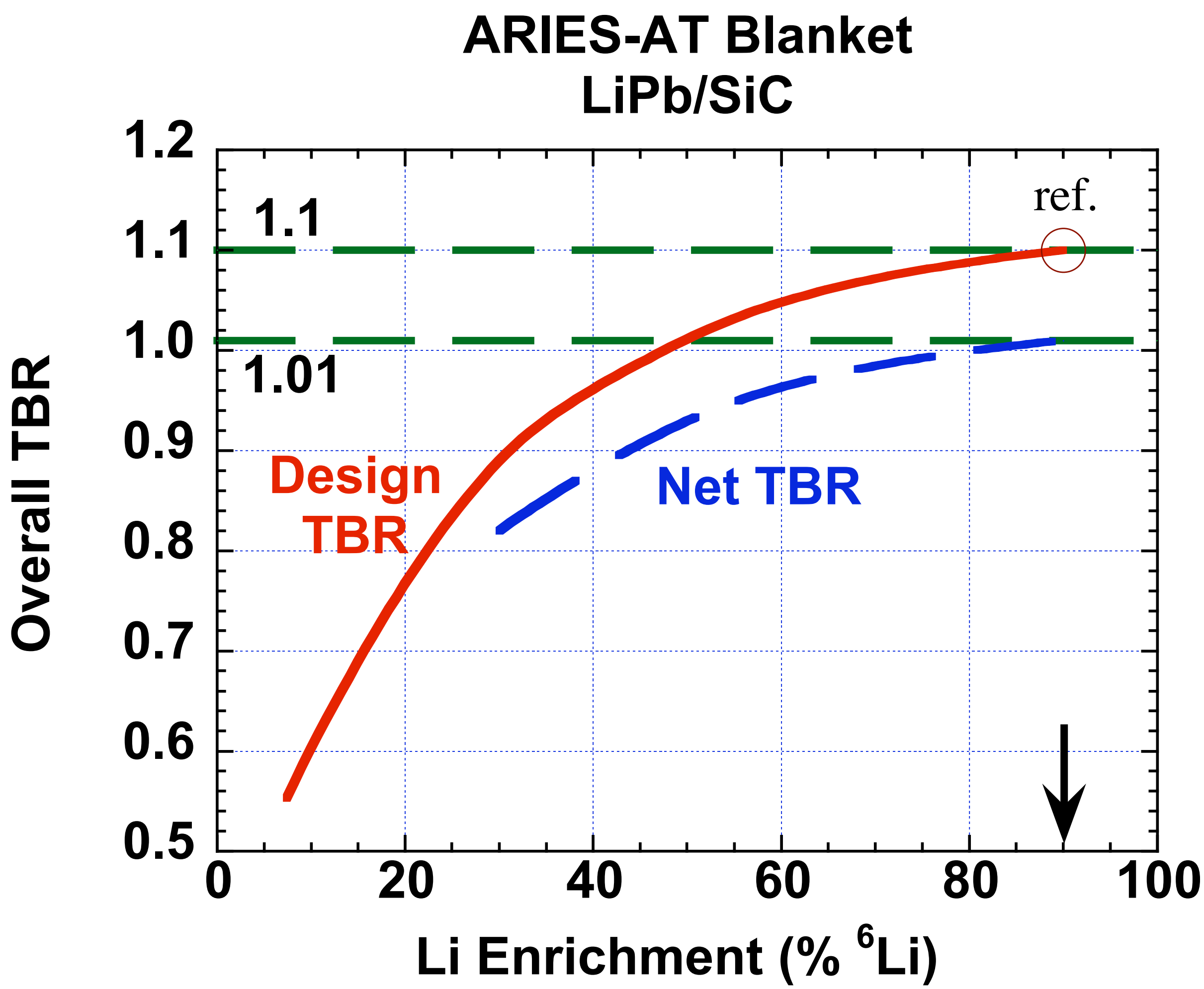
Impact of Shells on ARIES-AT Overall TBR

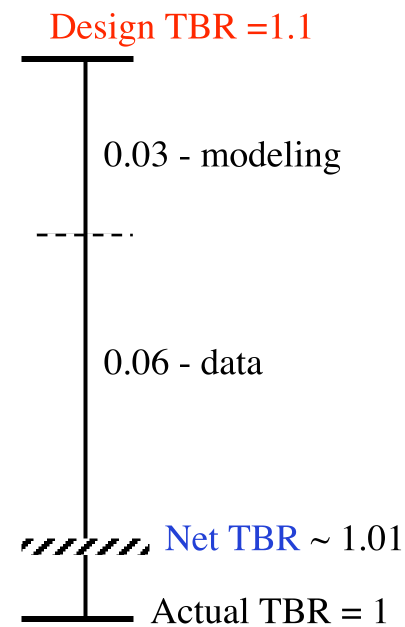


- **Preferred option**: W shells without active cooling.

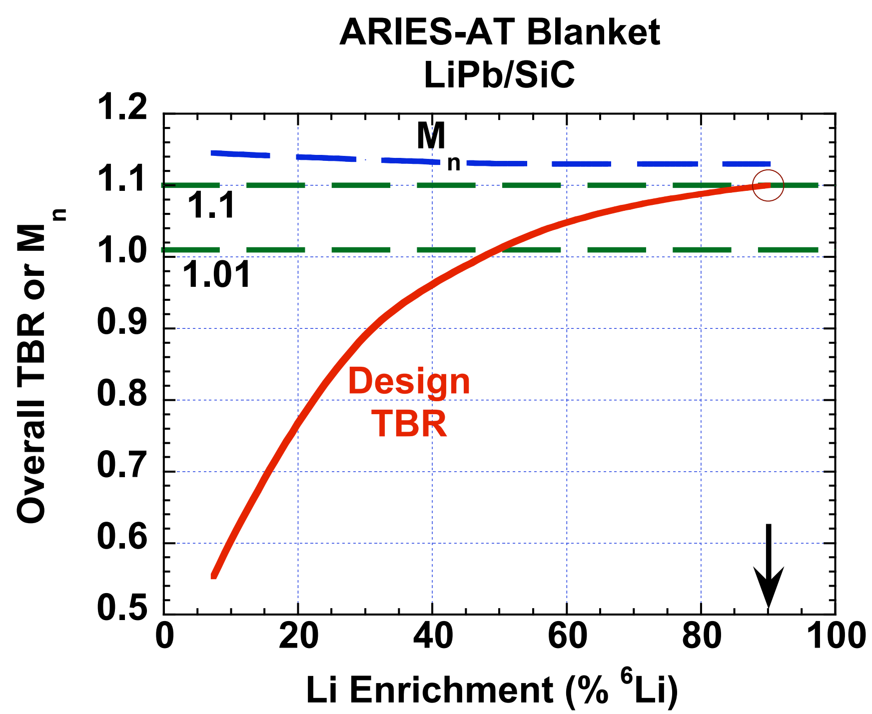
- Two W shells degrade Design TBR by ~7%.

Impact of Li-6 Enrichment on ARIES-AT TBR





50-90% Enrichment has Minor Impact on Energy Multiplication



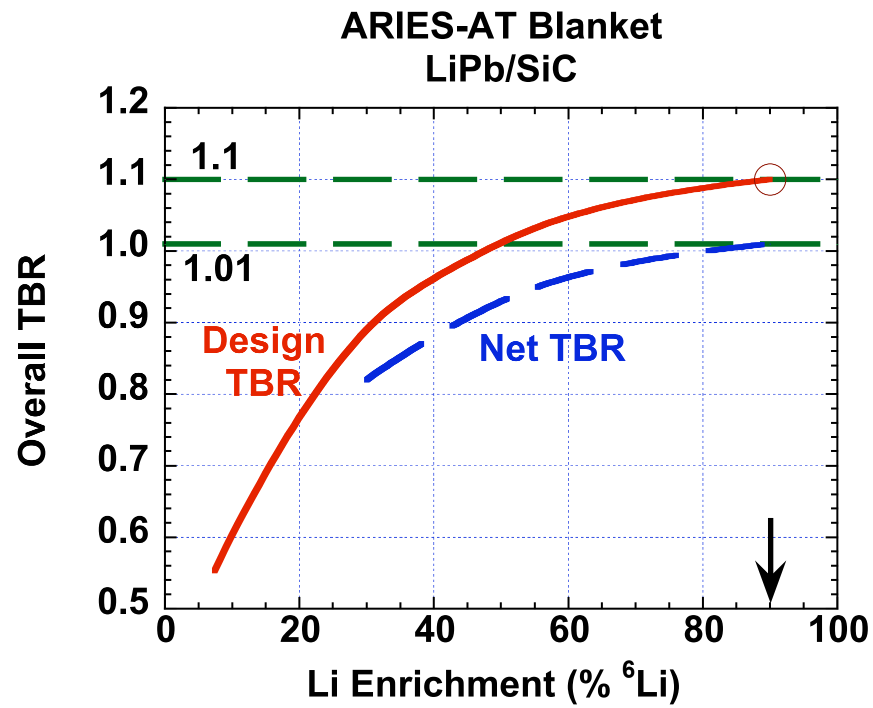
This means adjusting Li enrichment online will have insignificant impact on power balance (same trend observed in ARIES-CS LiPb/He/FS design)

Potential Means to Adjust Breeding
(LiPb System)

We will know what to design for before building first fusion power plant in 50 y. Blanket will be redesigned accordingly.

- **In case of over-breeding (Net TBR > 1.01):**
  - Lower enrichment online.
- **In case of under-breeding (Net TBR < 1.01),** major design changes are needed for first replaced blanket to adjust breeding. These include:
  - **Thickening IB and OB blankets**
  - Replacing W stabilizing shells by Al or Cu shells with active cooling
  - Lowering SiC structure in blanket, and/or
  - Adding beryllium to blanket.

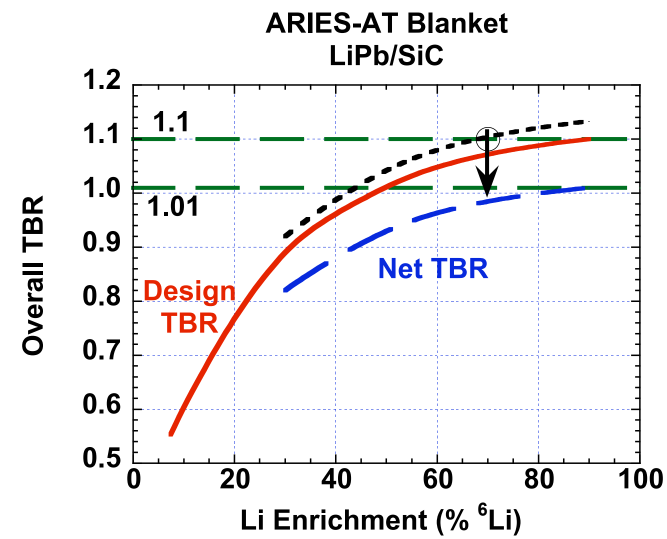
Solutions for under-breeding blanket are not feasible during operation.



It is less risky to design over-breeding blanket

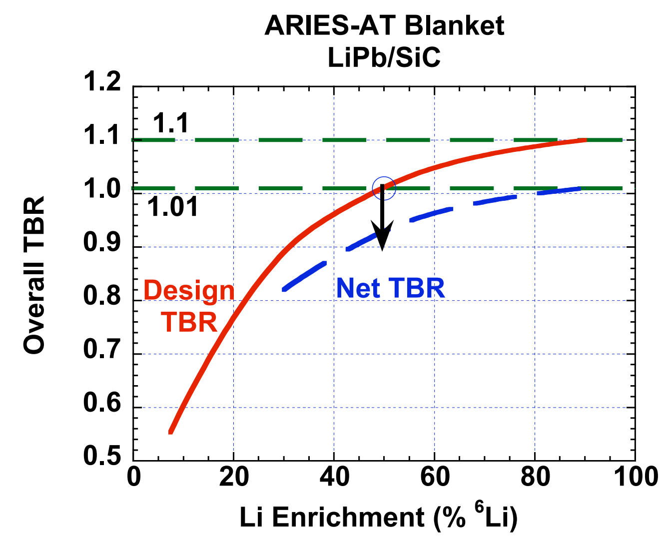
Three Pressing Questions

- Should future ARIES-AT-like designs allow larger breeding margin (a la ARIES-ST and CS) to account for uncertainties in design elements?
  - **1.1 Design TBR with Li-6 enrichment < 90%** (e.g., 50-70%)
    - ⇒ Breed few percent more T and adjust enrichment online, if needed
    - ⇒ Assure Net TBR of 1.01 during operation
    - ⇒ Assure T self-sufficiency.



- Change direction? For example, consider:
  - **1.01 Design TBR with Li-6 enrichment ~ 50%?**
    - ⇒ **Increase** enrichment online if Net TBR drops below 1.01
    - ⇒ No margin for uncertainties in design elements
    - ⇒ **Even with 90% enrichment, <u>Net TBR</u> <u>may not reach 1.01</u> during operation, meaning insufficient T for plasma operation**
    - ⇒ **Design at risk**

      (no external source to provide 1.1 kg of T/FPY / 1% of TBR / 2 GW P_f).



- What would be the impact of both options on overall design?

Both Options Seem to have Small Impact on ARIES-AT Overall Size and Cost

- **More breeding with lower enrichment than 90%:**
  - ⇒ **Design TBR = 1.1 with 50-70% enrichment**
  - ⇒ **Slightly more expensive design with Net TBR ≥ 1.01.**

  To provide more breeding, one or more options can be adopted for ARIES-AT:
  - Redefine boundary between blanket and shield:
    - Thicker blanket and thinner shield
    - Extra few cm shield needed to protect magnet
  - Replace W-shells by actively-cooled Al or Cu shells
  - Install blanket behind divertor.

- **Less breeding with lower starting enrichment:**
  - ⇒ **Design TBR = 1.01 with 50% *starting* enrichment**

    (enrichment to be increased during operation)
  - ⇒ **No change to ARIES-AT blanket design, but Net TBR may not reach 1.01 even with 90% enrichment**

Breeding-Related R&D

- **Improving TBR prediction**:
  - With better evaluation, resolve deficiencies in nuclear data that impact uncertainties in calculated TBR
  - Broaden the scope of nuclear data and code validation through integral experiments covering all relevant blanket concepts (e.g., LiPb/FS/SiC blanket)
  - Reduce uncertainty in calculated TBR attributed to approximations in modeling. The capability of using detailed engineering CAD drawings coupled directly to neutronics codes needs to be developed.
- **Improving the prediction of the minimum required TBR**:
  - Continue developing fuel cycle dynamics model that accurately predicts the minimum required TBR based on tritium behavior, transport, and inventories in all subsystems (plasma facing components, blankets, plasma exhaust, and tritium processing)
  - R&D to accurately determine the T inventory holdup in all in-vessel components
  - R&D to increase the efficiency and improve the performance of T processing and extraction systems
  - Explore plasma operating scenarios with high plasma-edge recycling mode and high T fractional burn-up.
- **Developing elements that help maximize TBR**:
  - Thin SiC electrical/thermal insulator for LiPb/FS blanket concept
  - Low-neutron absorbing materials for:
    - Plasma fueling, heating, and current drive systems
    - Passive coils and shells that stabilize advanced plasma modes
    - Impurity control system (e.g., divertor).

Conclusions & Recommendations

- Design TBR should be > Net TBR (~1.01) to assure T self-sufficiency.
- If deficiencies in design elements is 9%, calculated Design TBR should 1.1.
- Online controlling of enrichment is mandatory to adjust Net TBR to ~1.01. How?
- **Recommendations**: Future ARIES designs should allow slightly larger breeding margin to account for uncertainties in design elements. For instance, for LiPb system, 1.1 Design TBR with 50-70% Li-6 enrichment and Net TBR of ~1.01 (a la ARIES-ST and -CS).
- **9% TBR margin will be re-evaluated next year** based on:
  - 2008 results of European LiPb experiments (@ ENEA and TUD)
  - Progress made to CAD/MCNP modeling approach
  - Engineering details included in CAD model.
- Should we call for "TBR Town Meeting" and invite **neutronics** experts from U.S., J, and EU?
- ARIES team decision?