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Review of Challenges to Achieving Tritium Self-sufficiency

Workshop for Applied Nuclear Data Activities (WANDA 2024)

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On behalf of the LLNL IFE team

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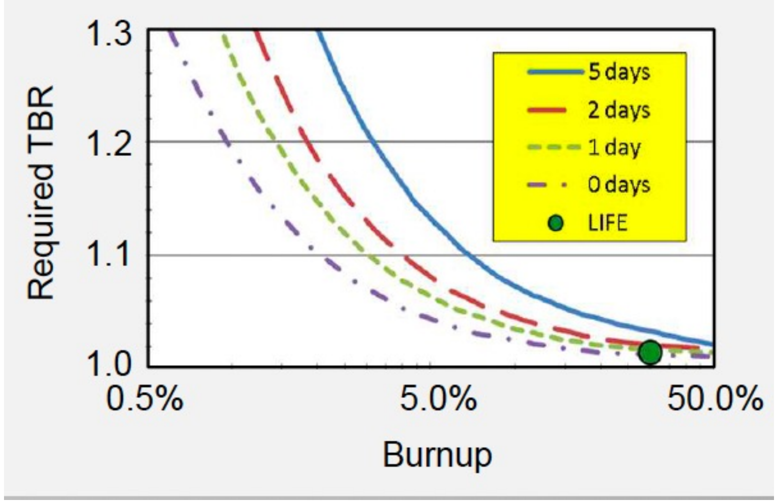
Tritium self-sufficiency

- Tritium self-sufficiency is required for a self-sustaining D-T fusion plant
- Tritium self-sufficiency is impacted by material choice and nuclear consideration
- Achievable TBR must be $\geq$ required TBR
- Required TBR must compensate for tritium losses (e.g.; retention in structures) and radioactive decay during operation and provides excess inventory to compensate for tritium loss due to failure of the tritium processing system
- Achievable TBR depends on plant design (machine type and structural materials) and uncertainty in the nuclear data

Parameters affecting required TBR

- Tritium burn-up fraction (lower fraction leads to higher TBR)
- Trapped inventories in structural components (first wall and blanket)
- Fueling efficiency and amount of tritium lost in tritium processing
- Amount of tritium supply kept in reserve storage for use during problems with the tritium processing system (higher reserve time leads to higher TBR)
- Doubling time for supply to other fusion power plants (shorter doubling time leads to higher TBR)

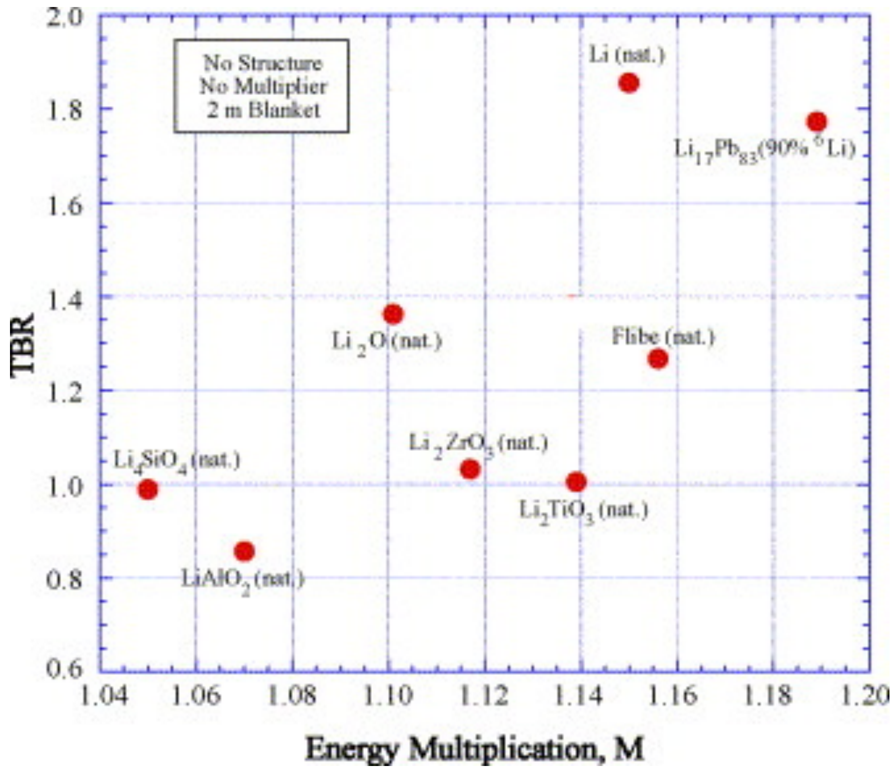


Parameters affecting achievable TBR

- Selection of breeding material
- Selection of materials used in the first wall and blanket, conducting coils, etc.
- Confinement scheme (e.g.; IFE allows for higher blanket coverage and targets with ~20-30% burn-up significantly relax requirements for fuel self-sufficiency)
- Size of penetrations in the breeding blanket (laser, heating, diagnostics, etc.)
- Uncertainties in predicting the achievable TBR due to neutronics modeling and nuclear data

TBR for selected breeders

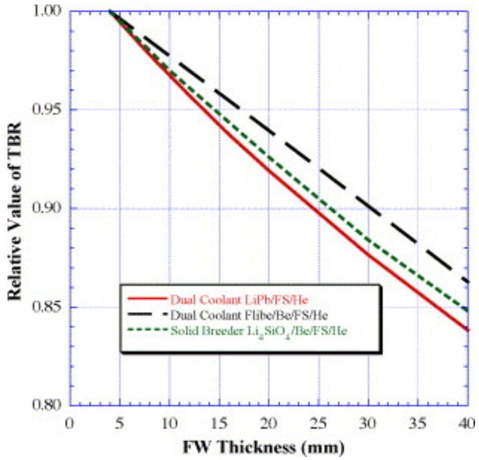
- Natural Li and LiPb have the highest TBR
- Flibe and Li_2O may require the use of neutron multipliers
- Low TBR are associated with ceramic breeders, requiring the use of neutron multipliers
- The choice of structural material and coolant will have a significant impact on the TBR

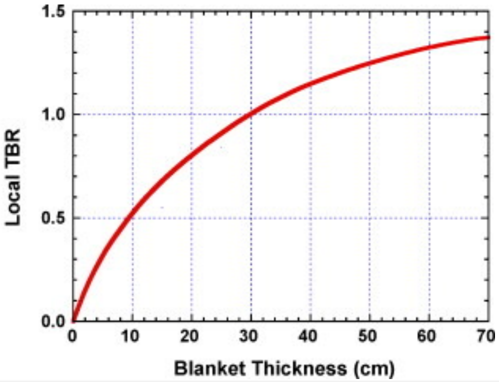


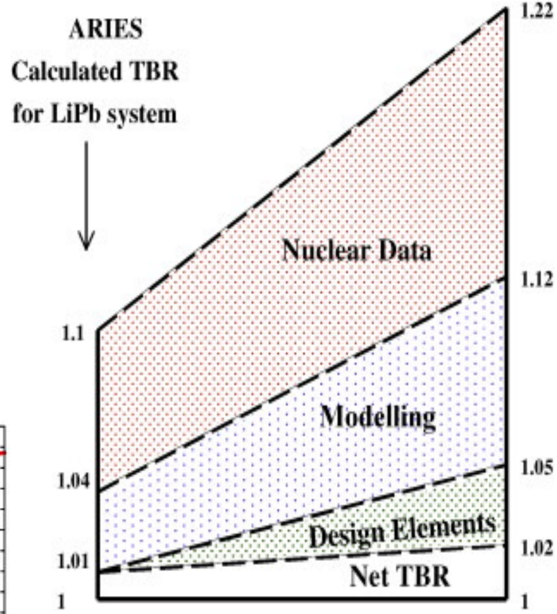
M. Sawan and M. Abdou, Fusion Engineering & Design, 81(8–14), 2006

Factors impacting calculated TBR

- First wall structure has a significant impact on the achievable TBR
- Tritium lost by retention in structures, decay, etc.
- Selection of neutron multiplier (Be or Pb)
- Accuracy and details of the neutronics modeling
- Accuracy of measured cross sections







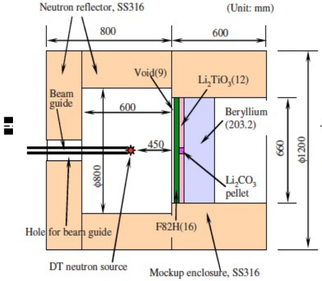
L. El-Guebaly and S. Malang, Fusion Engineering & Design, 84 (12), 2009

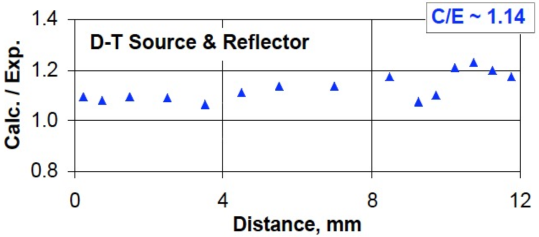
Nuclear data impact on calculated TBR

- Uncertainties in the achievable TBR associated with nuclear data are mostly caused by the uncertainties in the measured neutron cross sections
- Uncertainties are also associated with measurements of energy and angular distribution of secondary neutrons production
- A UCLA study in 1980s indicated that uncertainties in nuclear data evaluation on calculated TBR could be as high as 6%
- These uncertainties include those introduced in generating various cross-section libraries (e.g., processing system, weighting spectra, multigroup boundaries, etc.)

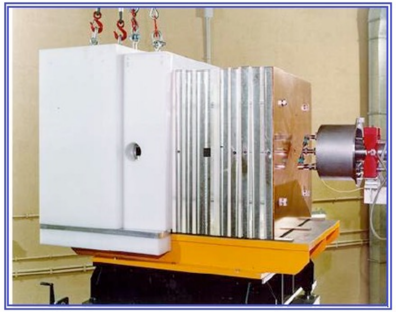
Integral experiments are used to check nuclear data accuracy

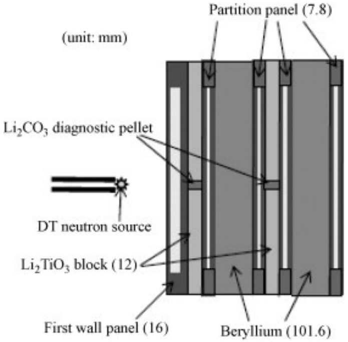
- Integral experiments performed at in the early 2000s showed overestimation in the calculated tritium production rate for solid breeders
- FNS experiment for Li_2TiO_3 breeder with ferritic steel FW and Be multiplier showed an overestimation of ~ 10-20%
- FNG experiment predicted tritium production rate within 5-10% uncertainty





FNS Experimental Assembly





FNG Experimental Assembly

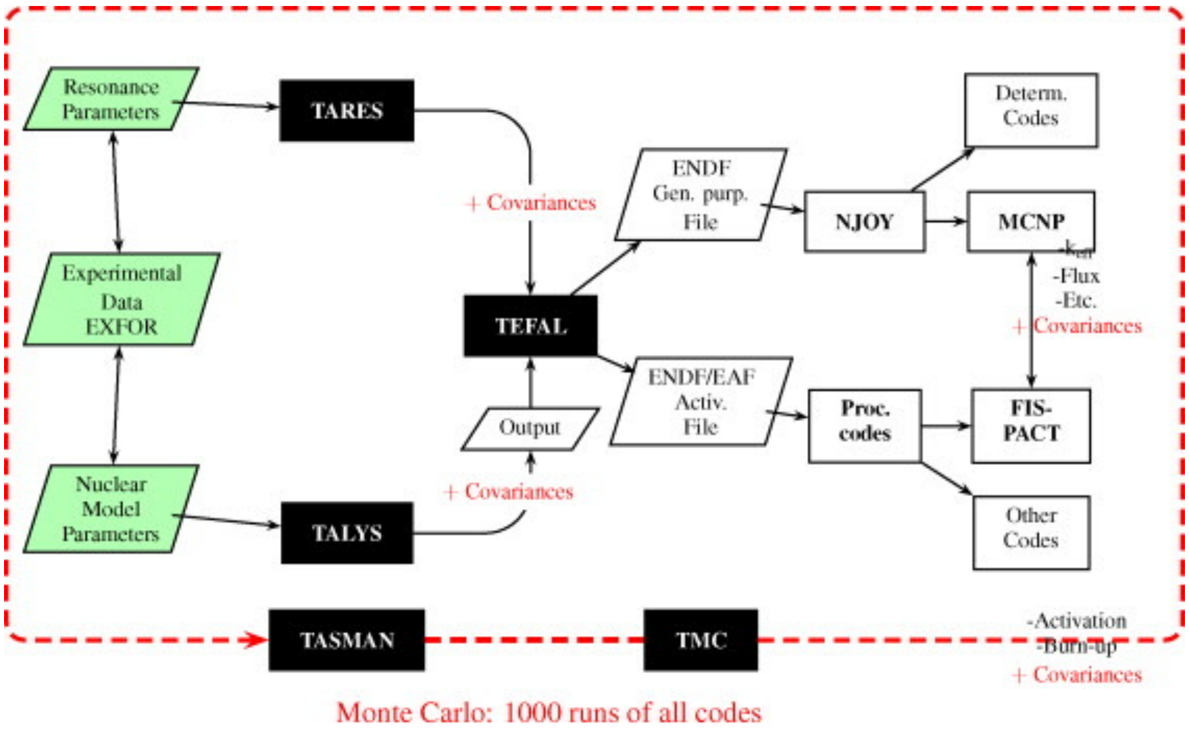
Propagation of nuclear data uncertainty

- Propagation of ND uncertainty is important for accurate estimation of the achievable TBR
- The two most common methods to propagate the ND uncertainties are based on using perturbation theory and probabilistic random sampling (TMC) methods
- The XSUN-2022/SUSD3D package provides a complete set of tools for S/U analysis using multigroup cross-section and covariance matrix libraries based on ENDF/B-VIII.0, JEFF-3.3, and FENDL-3.2a
- Reliable covariance data are needed for the perturbation theory method
- ENDF/B-VIII.0 has covariance data for only 182 out of 557 isotopes and FENDL-3.2 covariance data is incomplete
- TENDL and JEFF-3.3 provide covariance data for all nuclides

TMC method

- The TMC method requires the use of large number of random nuclear data files for all nuclides used in the MC simulation
- No randomized ND files from ENDF/B, FENDL or JEFF
- TENDL provides limited sets of randomized data files (~300 files per nuclide)
- Thousands of iterations with random data files are needed to find general trend for the TMC results
- Available covariance data can be used to generate large number of random data files by random variations of nuclear model parameters in the TALYS code within predefined deviations
- Codes such as BEKED and SANDY have been used to generate the random data files

Flow chart of TMC



D. Rochman et al., Fusion Engineering and Design, 85 (5), 2010

Examples for perturbation and TMC analyses

- Using perturbation method with the MCSEN patch and covariance data from different libraries, a sensitivity and uncertainty analysis of TBR for the EU-DEMO Helium Cooled Pebble Bed (HCPB) design using ^{6}Li enriched Li_4SiO_4 ceramic breeder estimated an uncertainty of 3.2% to 8.6%

- Limited set of isotopes considered from Li, Be, O, Si, Fe, Cr, and W with the TBR uncertainty dominated by ^{6}Li and ^{16}O

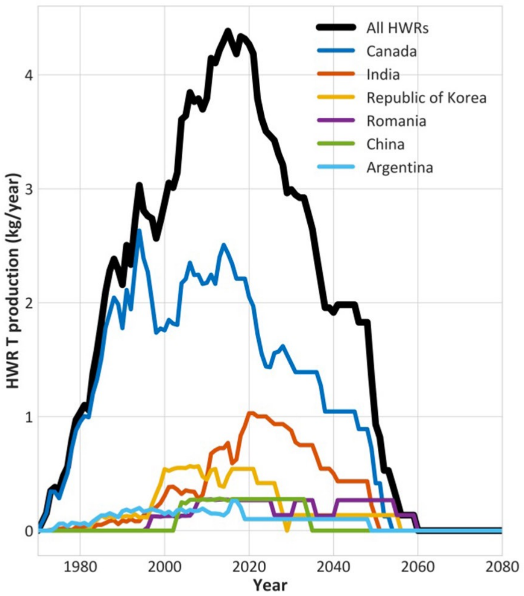
- Using the TMC method with the BEKED code, the TBR uncertainties for the EU-DEMO HCPB and WCLL designs are estimated at 3% for the HCPB and 4% for the WCLL

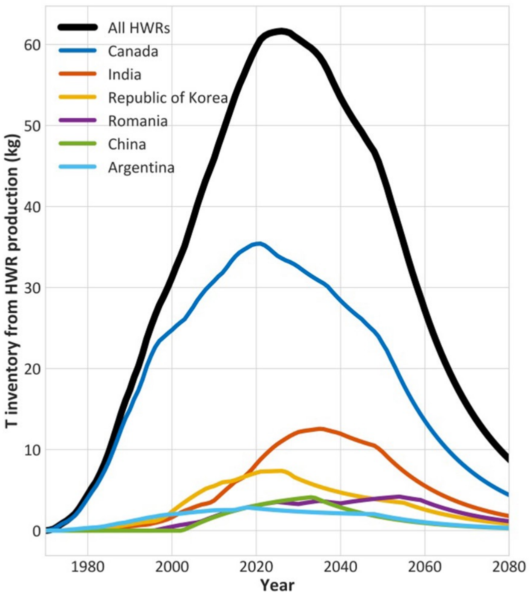
J. Park et al., Applied Sciences 2021 (11), 5234

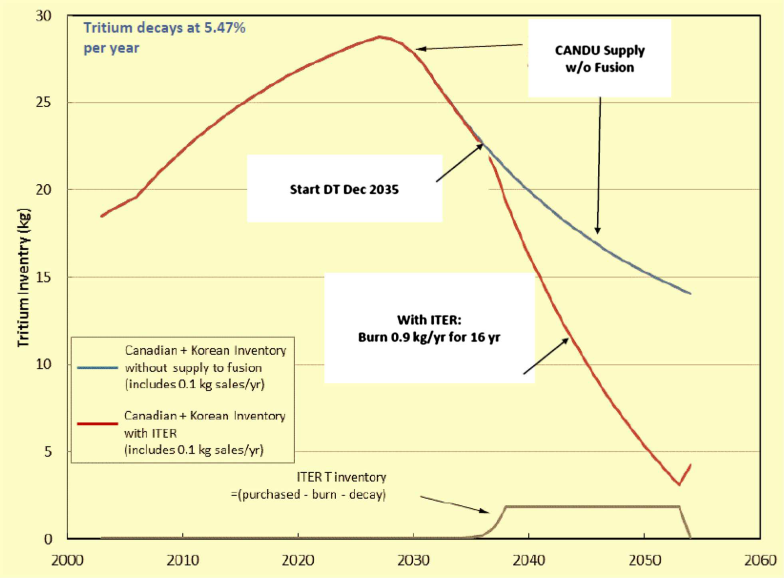
Tritium resources

- A 1 GW D-T power plant will require ~ 56 kg of tritium per year
- CANDU heavy water reactors are currently holding an inventory of ~ 25 kg of tritium with inventory dropping to < 5-10 kg by 2060
- Using tritium producing burnable absorber rods at a light water reactor (e.g., Watts bar) can produce ~ 1 kg of tritium per year
- In the late 1990, the Accelerator Production of Tritium (APT) plant design was based on a 1700 MeV proton linear accelerator operating at a current of 100 mA.
- The APT design envisioned reaching a production rate of 2-3 kg of tritium per year

Global tritium production in heavy water reactors





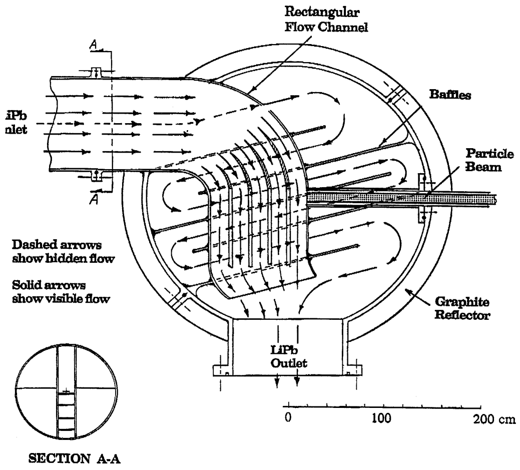


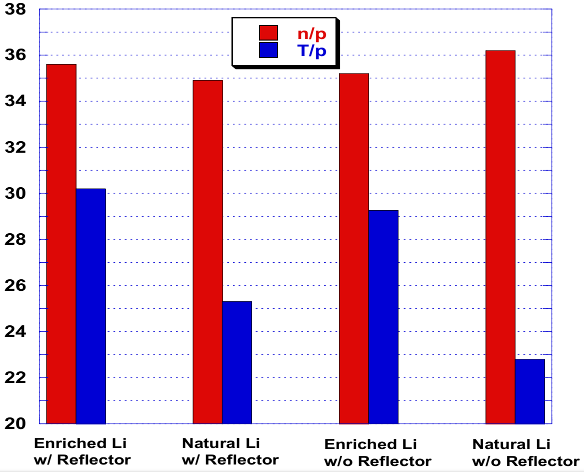
M. Kovari et al., Nuclear Fusion, 2018

M. Abdou et al., Nuclear Fusion, 61, 2021

APT conceptual design

- 200 mA - 1 GeV proton beam
- 2 m chamber radius with 2 cm thick steel wall and 20 cm thick graphite reflector
- Rectangular parallel beam (10 cm x 10 cm) impinging on the target at 20 cm from center of a spherical chamber
- $Pb_{83}Li_{17}$ alloy is used as a spallation target, neutron multiplier, and a tritium breeder
- The $Pb_{83}Li_{17}$ alloy with 90% enriched ^{6}Li





Summary

- Achievable TBR is sensitive to confinement system parameters and blanket design considerations
- Material selection should minimize tritium retention and reduce tritium inventory
- Blanket design must optimize the size and number of penetrations to minimize the impact on TBR
- Limited external sources of tritium are available
- Uncertainties in material selection, neutronics models and nuclear data adds up to about 10% of the achievable TBR

Summary (Cont.)

- Continuing improvement in nuclear data validation and integral experiments is needed
- Limited availability and quality of covariance data
- The Total Monte Carlo Method (TMC) is an attractive (but computationally expensive) technique for propagation of ND uncertainties
- Some nuclear data libraries provide randomized nuclear data files for the TMC method
- Interested researchers could generate more random files
- A 1% uncertainty in TBR translates into a shortage or surplus of 560 g of tritium per year for a one GW of fusion power

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