Pacific Northwest NATIONAL LABORATORY

Tritium Production in a Commercial PWR: Overview and Target Design Considerations

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Tritium Production Enterprise: Background

- Tritium is required for US nuclear weapons stockpile
- Tritium has a 12.3 year half-life and must be replenished
- 1988: DOE ceased production of tritium at SRS
- 1988-1992: The US considered the use of dedicated reactors for tritium production
  - Heavy water reactors (HWRs)
  - High temperature gas-cooled reactors (HTGRs)
  - Light water reactors (LWRs)
- 1995-1998: The US considered dual-use facilities
  - Commercial LWRs
  - Accelerators
- 1995: PNNL selected by DOE to be Design Authority for Commercial Light Water Reactor irradiation demonstration

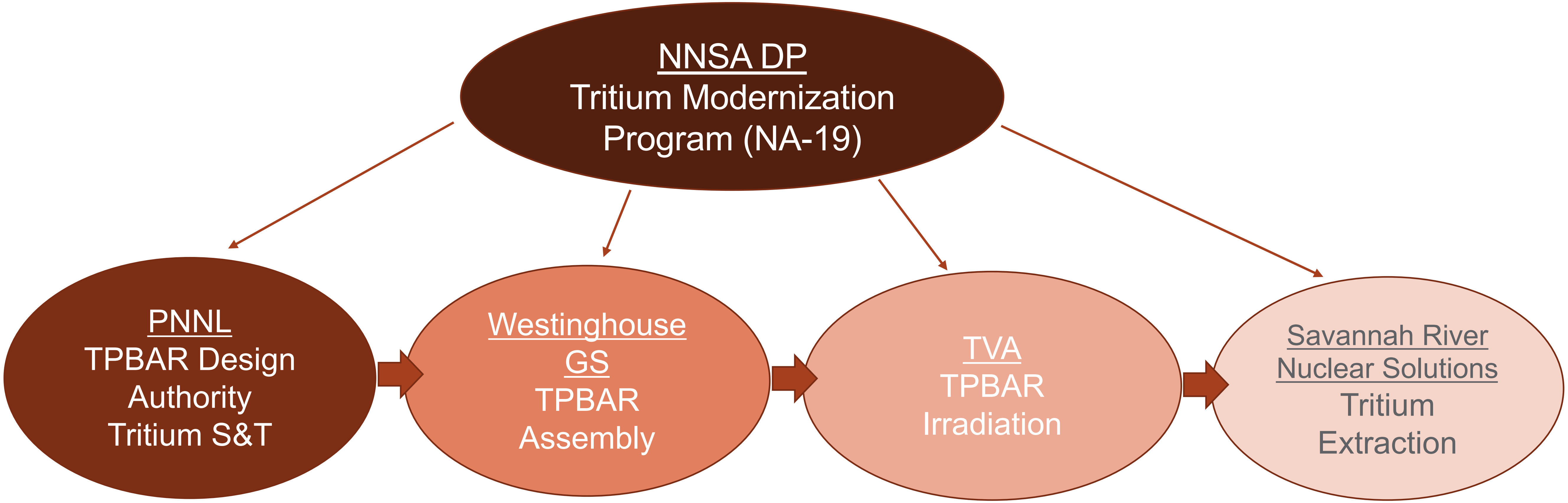
L Reactor at SRS

Tritium Production Enterprise: Background

- 1995 – 1997: Lead Test Assembly (32 Tritium-Producing Burnable Absorber Rods, TPBARs) designed and built at PNNL for irradiation in TVA Watts Bar Nuclear Unit 1
- 1999: Post-irradiation examination of LTA
- 2000: The Commercial Light Water Reactor tritium program was selected by DOE over accelerators for production
- 2001 – 2003: Design and manufacturing scale-up for production TPBARs
- 2003: First production core (240 TPBARs) irradiated at WBN1
- 2005 – present: Irradiation of 2nd through 14th production cores at WBN1
- 2019: License amendment for 1792 TPBARs in WBN2 approved
- 2020: First irradiation of TPBARs in WBN2
- 2023: TVA submitted a license amendment request to increase TPBAR limit to 2496

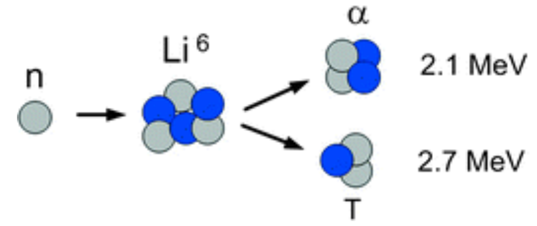
Watts Bar Nuclear Plant
Spring City, TN

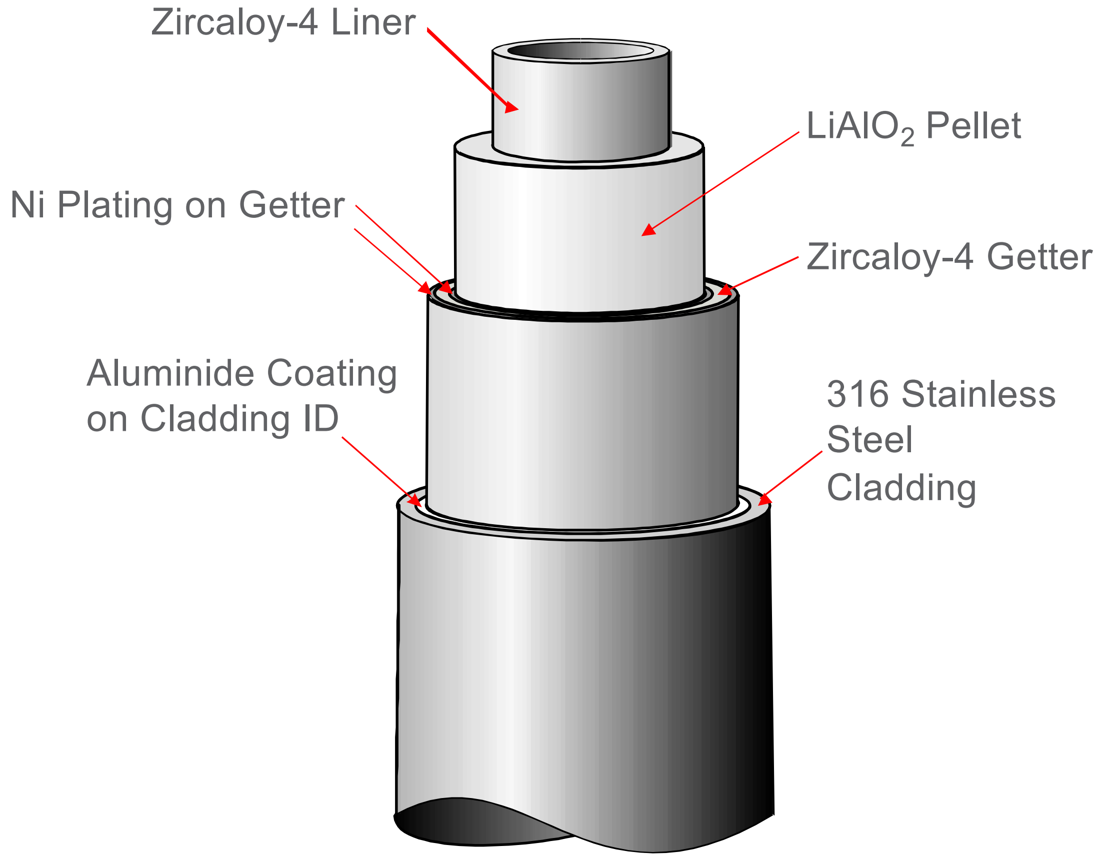
NNSA Tritium Modernization Program



TPBAR Design Fundamentals

- TPBARs replace burnable absorber rods normally used in Westinghouse PWRs (WABAs)
  - WABA reaction:
    - $^{10}B + {}^{1}n_{th} \rightarrow {}^{4}He + {}^{7}Li$
  - TPBAR reaction:
    - $^{6}Li + {}^{1}n_{th} \rightarrow {}^{3}H + {}^{4}He$
  - TPBARs introduce more negative reactivity than WABAs
- TPBARs are safety-related basic components licensed per 10 CFR 50 requirements
  - All TPBAR-related design, procurement and manufacturing conforms to 10 CFR 50, Appendix B quality assurance requirements
- TPBARs produce, on average, 0.95 g of tritium per cycle
- Current production goal is 1400 g tritium per unit per cycle, but NNSA is working to increase production

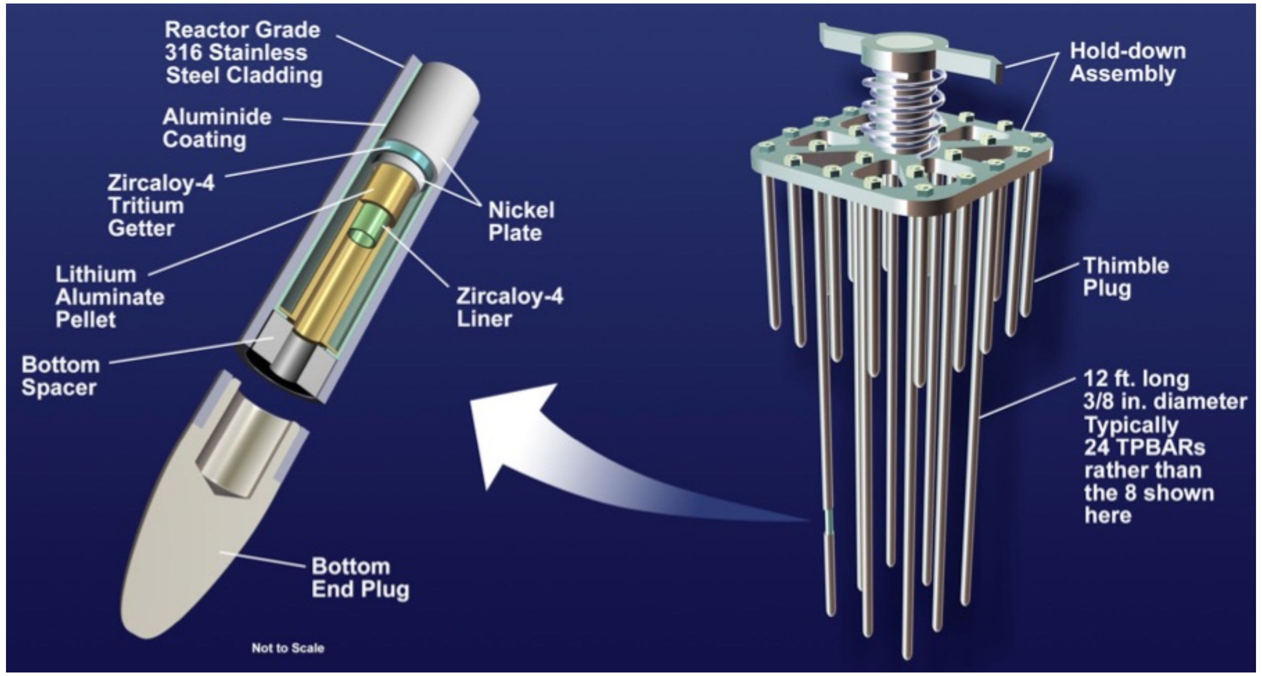


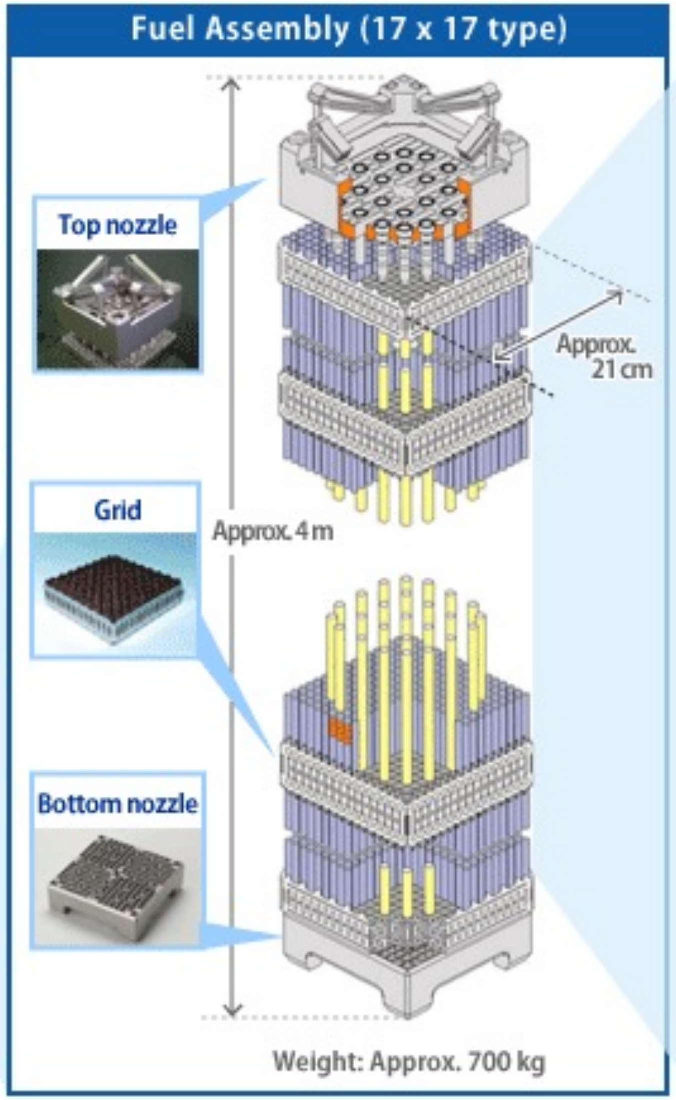


Not to scale

TPBAR Design Fundamentals

- Up to 24 TPBARs are attached to a hold-down assembly (multiples of four in symmetric locations) and inserted into a fresh fuel assembly
  - Hold-down assembly is loaded into fresh fuel assembly at the fuel fabrication plant and shipped to the reactor in the fuel assemblies
  - TPBARs reside in the fuel assembly guide tubes
  - Empty guide tubes have a thimble plug to regulate coolant flow
- After irradiation for one cycle, the hold-down assembly is removed from the fuel assembly, the TPBARs are removed from the hold-down assembly, and the TPBARs are shipped in a spent fuel cask to the Savannah River Site for tritium extraction





Watts Bar Nuclear

- Westinghouse PWR Design
  - 3459 MWt, ~1100 MWe
  - Four-loop
  - Ice condenser containment
  - 193 Westinghouse 17x17 fuel assemblies
- Two units at the plant
  - Unit 1 used for tritium production since Cycle 6
    - Construction began in 1973
    - Operation began in 1996
    - Currently in Cycle 19
    - 40-year license expires in 2035
  - Unit 2 used for tritium production since Cycle 4
    - Construction began in 1973
    - Construction halted in 1988
    - Construction resumed in 2007
    - Operation began in August 2016
    - Currently in Cycle 5
    - 40-year license expires in 2055
- Operate on an ~18 month fuel cycle
  - Outages offset by six months between the two units

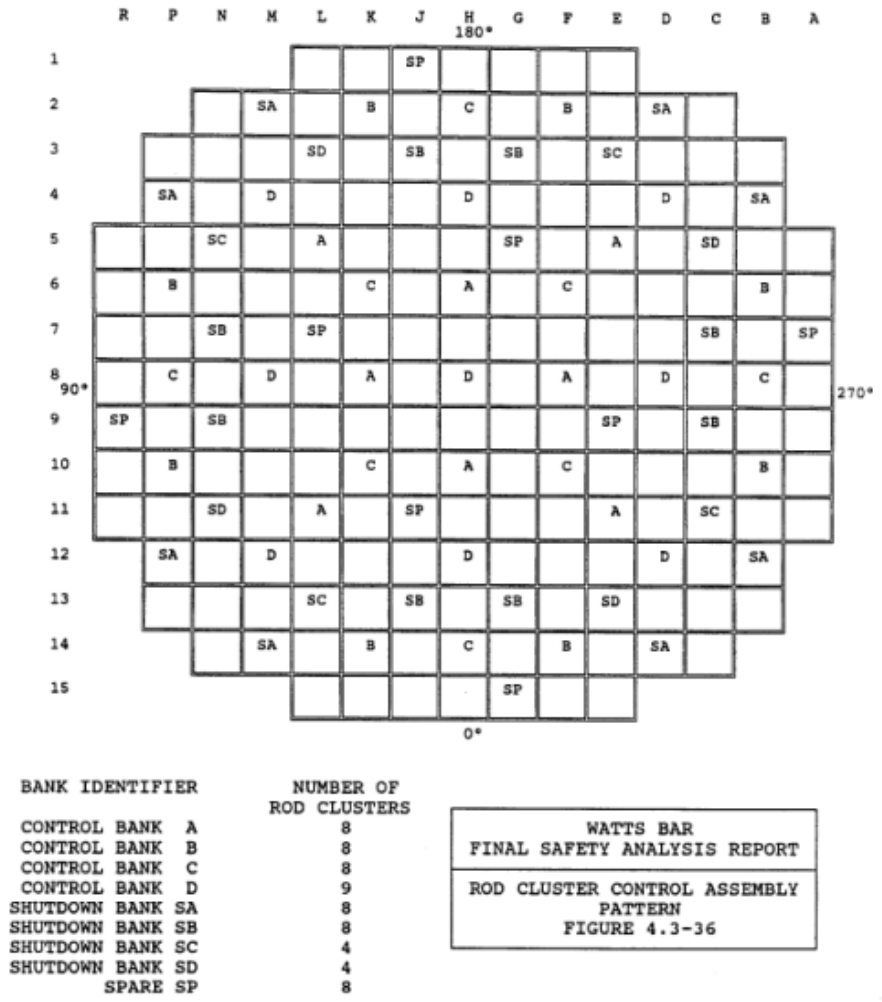
TPBAR Irradiation History

WBN1 Cycle	WBN2 Cycle	TPBAR Quantity	TPBAR Design	Cycle Start	Cycle End
2		32	LTA	Fall 1997	Spring 1999
6		240	Production	Fall 2003	Spring 2005
7		240	Production	Spring 2005	Fall 2006
8		240	Production	Fall 2006	Spring 2008
9		368	Mark 9.2	Spring 2008	Fall 2009
10		240	Mark 9.2	Fall 2009	Spring 2011
11		544	Mark 9.2	Spring 2011	Fall 2012
12		544	Mark 9.2	Fall 2012	Spring 2014
13		704	Mark 9.2	Spring 2014	Fall 2015
14		704	Mark 9.2	Fall 2015	Spring 2017
15		1104	Mark 9.2	Spring 2017	Fall 2018
16		1584	Mark 9.2	Fall 2018	Spring 2020
17		1792*	Mark 9.2	Spring 2020	Fall 2021
	4	544	Mark 9.2	Fall 2020	Spring 2022
18		1792*	Mark 9.2	Fall 2021	Spring 2023
	5	1104	Mark 9.2	Spring 2022	Fall 2023
19		1792*	Mark 9.2	Spring 2023	Fall 2024
	6	1672	Mark 9.2	Fall 2023	Spring 2025
20		>1792	Mark 9.2	Fall 2024	Spring 2026

*Current WBN1 and WBN2 license limit is 1792 TPBARs

TPBAR and Core Design Considerations

- Tritium production is optimized while maintaining the reactor's energy goals for the cycle
  - Fuel enrichment is higher than a core design without TPBARs
  - More fresh fuel assemblies are required each cycle than a core design without TPBARs
  - NNSA covers the cost of the additional ^{235}U and fresh fuel assemblies
- Placement of TPBARs is constrained by several factors
  - TPBARs are only inserted in fresh fuel assemblies
  - TPBARs cannot be inserted in fuel assemblies with control rods or secondary sources
  - Core design must be symmetric by quadrant
- Other design considerations
  - Fuel enrichment is limited to 4.95% ^{235}U
  - Core design must accommodate a cycle length of 550 EFPD at 3459 MW_t
  - Deleterious effects of fast neutron flux on pressure vessel lifetime must be avoided
  - Core design must meet all steady-state and design-basis accident criteria
  - Individual TPBAR maximum tritium production limited to 1.2 g, including all uncertainty



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TPBAR Design Basis

Material Compatibility (MC)

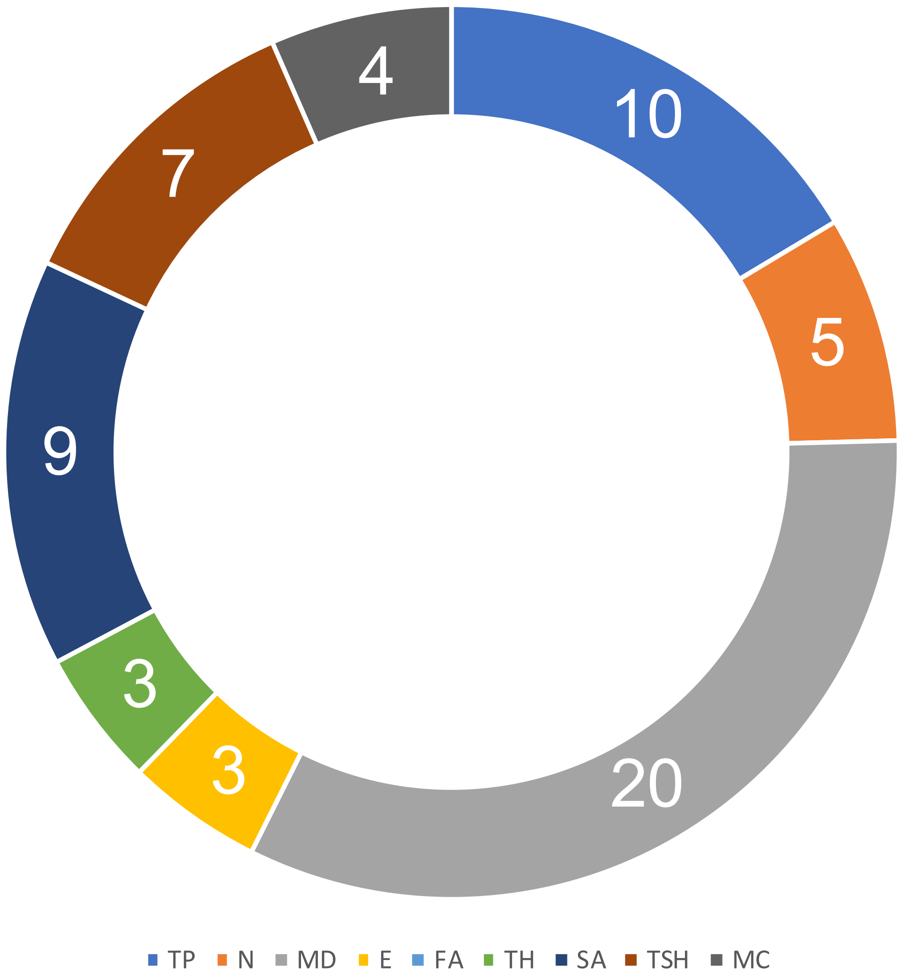
Transportation Shipping and Handling (TSH)

Safety Analysis (SA)

Thermal Hydraulic Performance (TH)

Extraction (E)

Number of analyses addressing each functional requirement (as of U1C19)



Tritium Production and Permeation (TP)

Neutronics (N)

Mechanical Design (MD)

Fabricability (FA)

TPBAR Mechanical Design Requirements

Mechanical Design (MD)

MD.1: The TPBAR components shall be mechanically compatible with each other and the host fuel assembly.

- Components must fit inside the TPBAR.
- The TPBAR must be removable from the host fuel assembly.
- Failure by fatigue or wear of the TPBAR or guide thimble must be precluded.

Dimensional analyses

Cyclic loading and fatigue analyses

MD.2: The structural integrity of the TPBAR cladding and end plugs shall be sufficient to perform their functions throughout the irradiation cycle.

- Cladding, end plugs, and welds must not fail.
- The cladding must not buckle.

Cladding stress analyses

End plug and weld stress analyses

Creep buckling analysis

LOCA stress analysis*

MD.3: The mechanical integrity of all internal components shall be sufficient to perform their functions throughout the irradiation cycle.

- Pre-irradiation handing shall not compromise the TPBAR including buckling and retention by the spring clip.
- Pellets and getter shall not lose structural integrity or crumble.
- Formation of a eutectic during Condition III shall be precluded.

Internal component stress analysis

Spring clip analysis & testing

Pellet & getter integrity analyses

MD.4: The TPBAR cladding shall remain intact during pool storage and post-irradiation handling prior to arrival at the TEF.

- Cladding stress must remain below yield during post-irradiation handling.
- Cladding shall not burst during transportation.

Cladding stress analyses

Shipping and handling analyses

Cladding & internal component thermal analyses

MD.5: The TPBAR shall be compatible with the host reactor's fuel assembly design, be a removable component within the assembly, and be located as a stationary element in a guide thimble location.

- TPBAR must be compatible with the hardware of the host reactor.
- The TPBAR must be removable from the baseplate after irradiation.

Dimensional analyses

Top end plug modeling & testing

Operational Impacts

- The tritium concentration in the WBN primary coolant is sampled multiple times per week
  - PNNL uses these data, in conjunction with water movement data, to attribute tritium permeation to TPBARs (i.e., measured tritium minus non-TPBAR sources) during and after each cycle
- NNSA funded construction of a 500,000 gallon tank at WBN to help manage tritiated water
- The negative reactivity provided by TPBARs results in an atypical soluble boron injection profile over the course of the cycle compared to other PWRs
- The Watts Bar Nuclear plant has one spent fuel pool serving both units, so TPBAR consolidation and shipping operations must be carefully coordinated with other plant activities
  - Motivation for design, construction and licensing of higher-capacity casks to minimize the number of required shipments