U.S. DEPARTMENT OF ENERGY

PNNL-22084

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Production TPBAR Inputs for Core Designers

TTQP-1-116, Revision 15

BA Collins
EF Love
CK Thornhill

November 2012

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

This document was printed on recycled paper.
(9/2003)

TRITIUM TECHNOLOGY PROGRAM

PRODUCTION TPBAR INPUTS FOR CORE DESIGNERS

TTQP-1-116

Revision 15

Effective Date: 11/14/12

TTQP-1-116

TRITIUM TECHNOLOGY PROGRAM

PRODUCTION TPBAR INPUTS FOR CORE DESIGNERS

Revision 15

Prepared By:	BA Collins, Engineer	3/5/2012 Date
Reviewed By:	Technical Reviewer	3/5/12 Date
Reviewed By:	Quality Assurance	3-5-12 Date
Reviewed By:	Authorized Derivative Classifier	3/5/2012 Date
Approved By:	EF Love, Design Task Manager	3/26/12 Date
Approved By:	for CK Thornhill, TTP Project Manager	10/31/12 Date

The purpose of this controlled document is to provide a convenient reference for tritium-producing burnable absorber rod (TPBAR) parameters used by reactor core designers.

1.0 TPBAR HOMOGENIZATION

Homogenized TPBAR number densities contained herein have been derived and verified for unclassified core physics calculations (Love 2007). These number densities are also verified for use for unclassified photon heating calculations.[1] The use of this information for other purposes (activation calculations, etc.) may not provide accurate, conservative or representative results and must be evaluated for applicability to the specific problem.

The homogenization represents a horizontal slice through a neutronically active region of a TPBAR. For neutronic accuracy, the TPBAR absorber pellet is modeled explicitly. All other internals structures have been homogenized into the "cladding" region. For the homogenized model, the cladding extends from the surface of the pellet to the physically correct outside diameter (OD) of the cladding. Table 1 provides material number densities at beginning-of-life (BOL) cold conditions and are applicable over a range of fuel enrichments from 5.0 to 3.5 weight percent U-235 for Watts Bar and 0.04 to 0.028 grams Li-6/in.[2] Use of this model within this range of fuel and TPBAR loadings will ensure a reactivity difference between -100 to 50 percent millirho[3] (pcm) at BOL (with a one standard deviation confidence) when compared with an explicit representation of 24 TPBARs in a fuel assembly. For further details pertaining to the development of the unclassified model, consult Love (2007) and Gates et al. (2012).

When modeling TPBAR regions outside the active absorber region, the homogenized cladding model may be used with no pellet material.

[1] It may be desired to treat the end plug masses separately for photon heating calculations. End plug masses are given in Section 6.0. The composition of stainless steel 316 used in the end plugs may be found in Gilbert (2011).

[2] With the ^{6}Li loading tolerance included, the upper and lower limits of ^{6}Li loading are 0.04125 and 0.02675 g/inch, respectively (Burns 2012).

[3] One pcm is 10^{-5} of $\Delta k/k$, calculated as $10^{5}(k_2-k_1)/(k_1{*}k_2)$.

Table 1. Homogenized Production TPBAR Dimensions and Number Densities [H-3-307846, H-3-310751 (Gates et al. 2012); Love, 2007]

Homogenized Cladding Material Dimensions	
	Mark 9.2 and Mark 10 Design
Homogenized Cladding OD (in)	0.381
Homogenized Cladding Inner Diameter (ID) (in)	0.302
Pellet OD (in)	0.302
Pellet ID (in)	0.223
Homogenized Cladding Material Number Densities	
	Mark 9.2 and Mark 10 Design
Cr (Atoms/b-cm)	8.2004E-03
Fe (Atoms/b-cm)	2.8330E-02
Ni (Atoms/b-cm)	2.7095E-02
Mo (Atoms/b-cm)	6.3490E-04
Mn (Atoms/b-cm)	6.6525E-04
Zr (Atoms/b-cm)	9.7431E-03

2.0 [REMOVED]

3.0 ASSUMPTIONS AND METHODS FOR PROPER POSITIONING OF THE TPBAR ACTIVE ABSORBER

The following discussion describes the methods Pacific Northwest National Laboratory (PNNL) proposes to use when interfacing with the core designers to properly position the TPBAR active absorber relative to the core centerline. The basic material properties of the TPBAR components are contained in TTQP-7-008, *Material Properties Handbook for the Tritium Technology Program* (Gilbert 2011).

Assumptions and Methods:

1. The core designers have the flexibility to determine the active absorber height and position relative to core centerline. The ^{6}Li loading, in grams/inch, is to be held constant within a TPBAR but may vary for different TPBARs within a core. Flexibility is currently being provided to permit specification of different absorber heights and core offsets for TPBARs used in the transition cores compared to those in the equilibrium core designs. The active absorber height is 132 inches. Selection of an absorber height greater than 132 inches will require significant TPBAR design effort to accommodate. The chosen values shall be provided to PNNL to establish required TPBAR internal component dimensions.

2. The specified active absorber height is a cold dimension (i.e., 132 inches). This height is assumed to extend from the bottom of the bottom pellet to the top of the top pellet.
3. When thermally expanding the axial dimension of the active absorber column to hot BOL conditions the thermal expansion properties of the pellet material shall be used. When thermally expanding the active absorber column radially to hot BOL conditions the thermal expansion properties of the pellet material (LI-3 of Gilbert 2011) shall be used for all designs.
4. The temperature used for thermal expansion of the absorber column shall be assumed to be the cladding temperature.
5. The position of the active absorber column relative to the core centerline at hot BOL is determined by the thermal expansion properties of the cladding (SS-3 of Gilbert 2011) and the expansion of the absorber column. The active absorber column rests on the lower cruciform spacer/long getter coining which rests on a getter disk, which in turn rests on the bottom end plug. Therefore, the active absorber column position relative to core centerline will move during heatup due to the differential expansion between the TPBAR cladding and the fuel assembly.
6. The effects of irradiation-induced dimensional changes of the TPBAR components may be of interest to the core designers. Irradiation-induced property changes are contained in the Materials Properties Handbook (Gilbert 2011) under SS-12, ZR-20, and LI-11.
7. The core designer must utilize the reactor interface drawing H-3-310734 Rev. 2 (Gates et al. 2012) to verify critical interfaces with the fuel assembly (e.g., TPBAR length will not result in contacting the lower nozzle or thimble screw at any time during the cycle).
8. The position of the BOL TPBAR active absorber centerline relative to the bottom of the hold down baseplate shall be provided to PNNL to establish a common index point for TPBAR axial dimensions. The desired BOL offset of the TPBAR active absorber column relative to the core centerline is also requested. These dimensions may be provided for either hot or cold conditions. If hot dimensions are provided, PNNL will use this information to determine the cold dimensions of TPBAR internal components that result in the desired positioning of the active absorber column at hot BOL conditions. If cold dimensions are provided, PNNL will report to the core designers the hot dimension from the bottom of the hold down baseplate to the active absorber column centerline.

Figures 1-6 are provided for information only. The actual loading patterns are determined by the fuel vendor and are not limited to these six loading patterns.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1																	
2																	
3						TP			TP			TP					
4				TP										TP			
5																	
6			TP			TP			TP			TP			TP		
7																	
8																	
9			TP			TP			IT			TP			TP		
10																	
11																	
12			TP			TP			TP			TP			TP		
13																	
14				TP										TP			
15						TP			TP			TP					
16																	
17																	

#	**Naming convention**
IT	Instrument Tube (Assembly center)
TP	TPBARs

Figure 1. 24 TPBAR Loading Pattern (For Information Only)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1																	
2																	
3						TP			TP			TP					
4				TP										TP			
5																	
6			TP			GT			TP			GT			TP		
7																	
8																	
9			TP			TP			IT			TP			TP		
10																	
11																	
12			TP			GT			TP			GT			TP		
13																	
14				TP										TP			
15						TP			TP			TP					
16																	
17																	

#	**Naming convention**
IT	Instrument Tube (Assembly center)
GT	Empty Guide Tube
TP	TPBARs

Figure 2. 20 TPBAR Loading Pattern (For Information Only)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1																	
2																	
3						TP			GT			TP					
4				TP										TP			
5																	
6			TP			GT			TP			GT			TP		
7																	
8																	
9			GT			TP			IT			TP			GT		
10																	
11																	
12			TP			GT			TP			GT			TP		
13																	
14				TP										TP			
15						TP			GT			TP					
16																	
17																	

#	**Naming convention**
IT	Instrument Tube (Assembly center)
GT	Empty Guide Tube
TP	TPBARs

Figure 3. 16 TPBAR Loading Pattern (For Information Only)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1																	
2																	
3						TP			GT			TP					
4				GT										GT			
5																	
6			TP			GT			TP			GT			TP		
7																	
8																	
9			GT			TP			IT			TP			GT		
10																	
11																	
12			TP			GT			TP			GT			TP		
13																	
14				GT										GT			
15						TP			GT			TP					
16																	
17																	

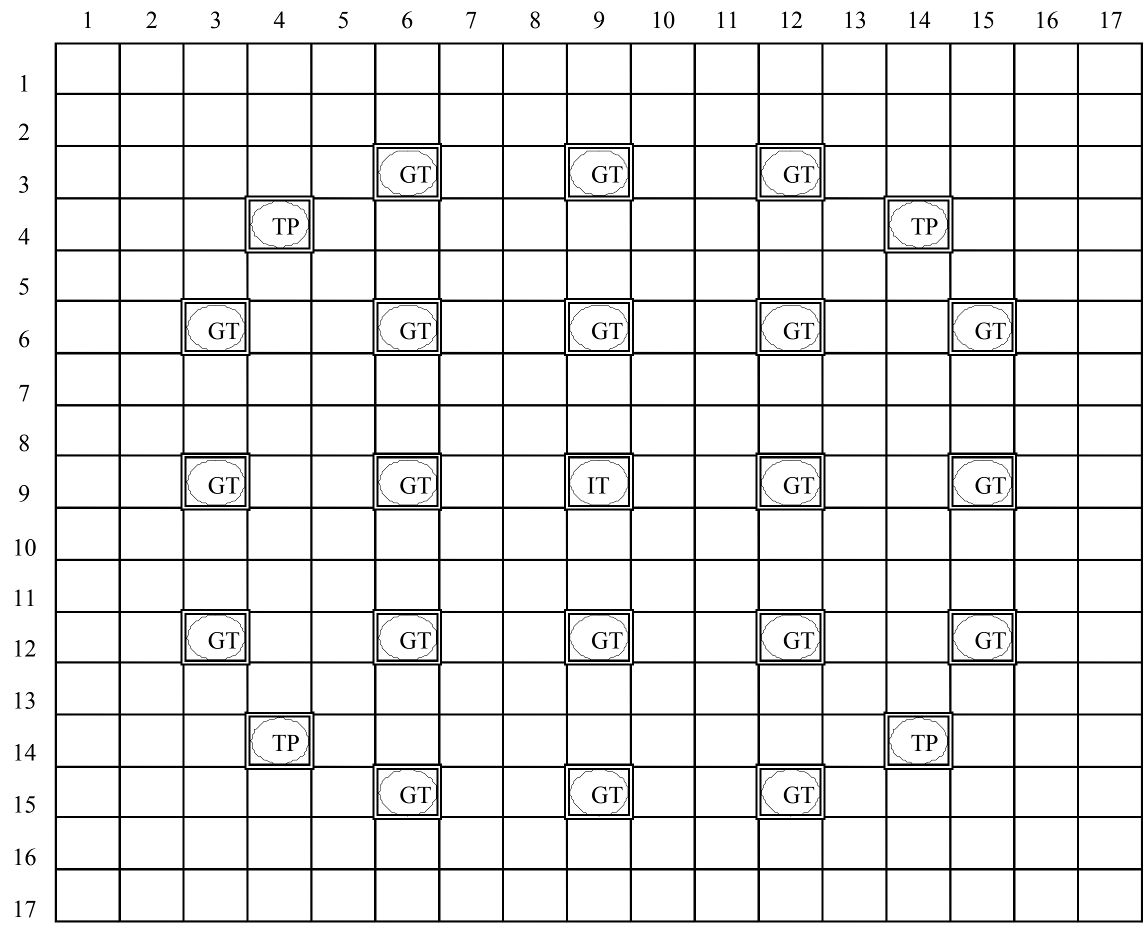
#	**Naming convention**
IT	Instrument Tube (Assembly center)
GT	Empty Guide Tube
TP	TPBARs

Figure 4. 12 TPBAR Loading Pattern (For Information Only)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1																	
2																	
3						GT			GT			GT					
4				TP										TP			
5																	
6			GT			GT			TP			GT			GT		
7																	
8																	
9			GT			TP			IT			TP			GT		
10																	
11																	
12			GT			GT			TP			GT			GT		
13																	
14				TP										TP			
15						GT			GT			GT					
16																	
17																	

#	**Naming convention**
IT	Instrument Tube (Assembly center)
GT	Empty Guide Tube
TP	TPBARs

Figure 5. 8 TPBAR Loading Pattern (For Information Only)



#	**Naming convention**
IT	Instrument Tube (Assembly center)
GT	Empty Guide Tube
TP	TPBARs

Figure 6. 4 TPBAR Loading Pattern (For Information Only)

4.0 TOLERANCES AND IMPURITIES

4.1 Lithium Loading Tolerance

The tolerance on the ^{6}Li loading is ±0.00125 g/inch (Burns 2012). This tolerance is based on the true ^{6}Li loading in the pellet material. Also, note that the tolerances on the pellet dimensions are included in this uncertainty.

4.2 Lithium Aluminate Impurities

The equivalent boron concentration of the pellet impurities is less than 1000 μg/g (Shaver 2008).

4.3 Dimensional Tolerances

The dimensional tolerance of the TPBAR cladding tube OD is ±0.0005 inches (H-3-307846, Rev. 9, Gates et al. 2012).

5.0 DISTRIBUTION OF HELIUM-3 IN TPBARS

The presence of TPBARs in a reactor core will result in an inventory of not only tritium but also ^{3}He in the core. The ^{3}He is produced as a result of tritium decay and has a relatively large neutron absorption cross section. Due to this large neutron absorption cross section, the reactor core designer and reactor operator must take the ^{3}He into consideration. During normal operation, the inventory of ^{3}He approaches a quasi-equilibrium level as the rate of production through tritium decay is largely offset by the rate of destruction through neutron absorption. The inventory of ^{3}He becomes more significant in the event the plant undergoes a lengthy outage, whereby the ^{3}He inventory continues to increase from tritium decay without any compensating destruction.

The impact on core reactivity and core power shape due to the inventory of ^{3}He can be determined provided that the axial distribution of ^{3}He in the TPBAR is known. There is potential for the ^{3}He to be present in the free gas volume or bound up in the solid components in the TPBAR. If the ^{3}He is present only in the free gas volume, then a substantial fraction of the ^{3}He is in the gas plenums at the top and bottom of the TPBAR. Since the gas plenums are near the core periphery, the neutron worth of ^{3}He in the gas plenums may be less than if the ^{3}He were locked up in the solid TPBAR components located in the middle of the core.

The precise nature of ^{3}He diffusion in the TPBAR is not known exactly and would need experimental verification. However, for the purposes of reactor physics calculations and core design activities, the following assumptions are recommended regarding the distribution of ^{3}He in TPBARs:

- In the absence of a neutron flux (i.e., when the reactor is subcritical), the ^{3}He generated by tritium decay remains locked in the solid components that contained the parent tritium.
- Under neutron irradiation, the release rate of ^{3}He from the solid components is enhanced. However, at operating temperatures, the full release of ^{3}He to the free gas is expected to require days to weeks to complete. Even if the release were instantaneous, the time required to achieve full mixing with ^{4}He would be several hours (Meriwether 2006).

- For the purposes of calculating ^{3}He production, it is necessary to determine the distribution of tritium within the TPBAR. For core physics calculations only, it can be assumed that tritium remains in the pellet where it was generated.

It may be desired to estimate the number of ^{3}He atoms in the free volume of the three major TPBAR regions: upper plenum, active length, and lower plenum. The TPBAR regions have been defined as follows:

Upper Plenum: Extends from the top of the top pellet to the top of the top end plug bore hole. (UP)

Active Length: Extends from the bottom of the bottom pellet to the top of the top pellet. (AL)

Lower Plenum: Extends from the top of bottom end plug for Mark 9.2 and Mark 10 designs to the bottom of the bottom pellet. (LP)

The total number of ^{3}He atoms in the TPBAR free volume is determined from reactor physics calculations. The ratios of the void volume per unit length between the three major sections of the TPBAR (upper plenum, active length, lower plenum) have been estimated for all TPBAR designs (Schmitt 2007). Note that these are ratios of void volume *per unit length*, not ratios of void volumes (See Figure 7):

- Ratio of void volume per unit length, UP to active region: 1.9 (R_{UP})
- Ratio of void volume per unit length, LP to active region: 1.4 (R_{LP})

If the total number of ^{3}He atoms in the free volume of a TPBAR is He3TOT, the amount of ^{3}He atoms in the free volume each of the three regions is:

$$He3UP = \frac{1.9UP}{1.9UP + AL + 1.4LP} He3TOT$$

$$He3AL = \frac{AL}{1.9UP + AL + 1.4LP} He3TOT$$

$$He3LP = \frac{1.4LP}{1.9UP + AL + 1.4LP} He3TOT$$

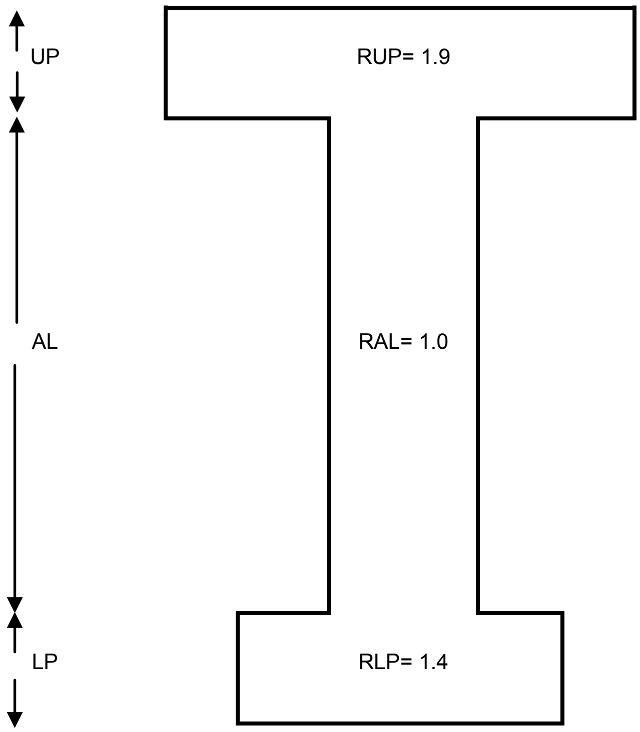


Figure 7. TPBAR Void Volume per Unit Length

The value of AL is set by the core designer. The values for UP and LP may be estimated from unclassified sources (Burns 2012), as discussed below. Define additional parameters as follows:

- L1 = TPBAR length, bottom of baseplate to tip of bottom end plug
- L2 = TPBAR bottom end plug body length (nominal below cladding)
- L3 = TPBAR top end plug body length (nominal above cladding, excluding shank)
- CEN = Distance of TPBAR absorber axial centerline relative to bottom of hold down assembly baseplate

The desired lengths may then be estimated as:

- UP = CEN – L3 – 0.5*AL
- LP = L1 – L2 – L3 – UP – AL

For neutronics analyses, the number of ^{3}He atoms in each region may be smeared into the respective unclassified void volume for each region (within the pellet ID in the active region and within the homogenized cladding ID in the plenum regions).

6.0 MASS DISTRIBUTION FOR VIBRATION ANALYSIS

The TPBAR has a bounding unclassified mass of 2.3 lb (Gates 2008). The mass of the end plugs are ~21 grams, giving an approximate mass for the end plugs of 0.05 lb (Gates 2008). The mass of the TPBAR (minus the end plugs masses) may be assumed to be uniformly distributed along the 150-inch cladding tube length as 2.25lb/150 inches = 0.015 lb/inch.

7.0 [REMOVED]

8.0 TPBAR FAILURE DURING LARGE BREAK LOSS OF COOLANT ACCIDENTS

TPBARs may fail during large break loss of coolant accidents (LBLOCAs). TPBAR failure is dependent upon both the TPBAR cladding temperature and the tritium production in the TPBAR. Figure 8 shows the bounding predicted failure curve for TPBARs of all designs during an LBLOCA (Gates 2007) for Watts Bar. The TPBAR will rupture at the core axial height coincident with the peak fuel cladding temperature.

9.0 PELLET LEACHING FOR BREACHED TPBARS

9.1 TPBAR Breach During Normal Operation

In the event of a breached TPBAR during normal reactor operation, it may conservatively be assumed that 100% of the lithium will instantaneously leach from the pellets. The composition of leached pellets is assumed to be hydrated alumina (Gibbsite), $Al_2O_3 \cdot 3H_2O$, with a density of ~2.5 g/cm^3 (Lanning and Baldwin 2001). For neutronics modeling of a breached TPBAR, the center void region shall be filled with water.

9.2 TPBAR Breach During LBLOCA

Following a LBLOCA, the maximum leach rate is conservatively assumed to be 3% per day of the initial lithium inventory at the time of breach, (e.g., amount remaining 97%, 94%, 91%,…) such that after 16 days the leaching will have reached 48% of the initial lithium inventory (52% of lithium remaining) (Lanning and Baldwin 2001, Schmitt 2010) . The maximum amount of lithium that will leach from the pellets is estimated to be 50% of the lithium inventory at the time of breach. It may be conservatively assumed that the leaching occurs uniformly throughout the TPBAR.

Due to the potentially energetic nature of the TPBAR burst during LBLOCA, some pellet material may be expelled from the TPBAR. It may be conservatively assumed that a gap in the absorber column at the breach location would be no more than 12 inches in length.

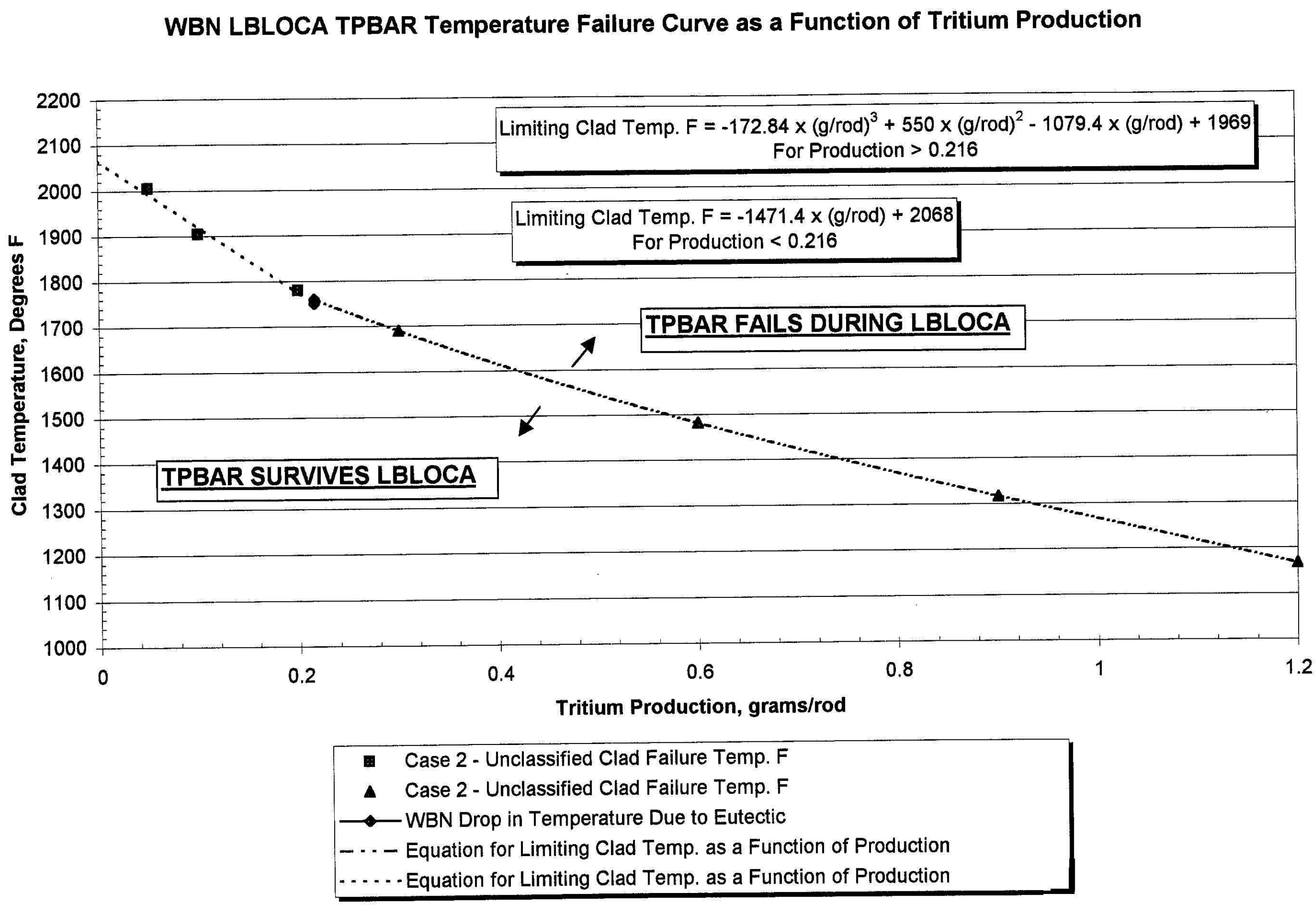


Figure 8. WBN LBLOCA TPBAR Temperature Failure Curve as a Function of Tritium Production

10.0 REFERENCES

Burns KA. 2012. *Watts Bar Unit 1, Cycle 12 TPBAR Design Inputs*. TTP-1-187-12, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Gates RO, KA Burns, and BA Collins. 2012. *TPBAR Design Drawings (U)*. PNNL-TTP-1-976, Rev. 18, Pacific Northwest National Laboratory, Richland Washington (CRD).

Gates RO. 2008. *Mark 9.2 TPBAR Dimensional Analyses (U).* PNNL-TTP-1-1109, Rev. 2, Pacific Northwest National Laboratory, Richland Washington (CRD).

Gates RO. 2007. *Mark 9.2 TPBAR Cladding Mechanical Design Analyses (U).* PNNL-TTP-1-1111, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington (CRD).

Gilbert ER. 2011. *Materials Property Handbook for the Tritium Target Qualification Project*. TTQP-7-008, Rev. 7, Pacific Northwest National Laboratory, Richland, Washington.

Lanning DD and DL Baldwin. 2001. *Lithium Leaching Rate from Breached TPBARs (U)*. PNNL-TTQP-1-768, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington (CRD).

Love EF. 2007. *Homogenization of Cycle 9 TPBARs (U)*. PNNL-TTP-1-1101, Rev. 0, Pacific Northwest National Laboratory, Richland Washington (CRD).

Meriwether GH. 2006. *Estimates of He-3 Redistribution Effect on Core Power Profiles for Watts Bar Mark-9.2 Design (U)*. PNNL-TTP-1-1107, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington (CRD).

Schmitt BE. 2010. *Impact of Production TPBAR on Water Chemistry for Watts Bar and Sequoyah (U).* PNNL-TTQP-1-713, Rev. 4, Pacific Northwest National Laboratory, Richland, Washington (CRD).

Schmitt BE. 2007. *Mark 9.2 TPBAR Void Volume Ratios (U).* PNNL-TTP-1-1112, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington (CRD).

Shaver MW. 2008. *Production Specification for Enriched, Annular LiAlO2 Pellet*s. TTQP-1-076, Rev. 5, Pacific Northwest National Laboratory, Richland, Washington.