WCAP-16996-P/WCAP-16996-NP Volumes I, II, and III, Revision 0, “Realistic Loss-of-coolant accident [LOCA] Evaluation Methodology Applied to the Full Spectrum of Break sizes (FULL SPECTRUM^{TM} LOCA (FSLOCA) Methodology)”

REQUEST FOR ADDITIONAL INFORMATION (RAI)

FIFTH SET OF RAI QUESTIONS

RAI Questions 46 through 77

Table 1: List of RAI Questions

Question No.	Subject	Date Issued (Draft/ Formal)	Date Responded (Draft/ Formal)	Disposition (O/C)$^{(\dagger)}$	Note
Set 1	**Questions 1 - 19**				
1.	WCOBRA/TRAC MOD7A Revision 7	1/09/12; 6/26/12			
2.	TRAC-PF1/MOD2 Code	1/09/12; 6/26/12			
3.	Large-break LOCA (LBLOCA) and small-break LOCA (SBLOCA) phenomena identification and ranking tables (PIRTs)	1/09/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
4.	End of blowdown	1/09/12; 6/26/12			
5.	Gap conductance	1/09/12; 6/26/12			
6.	Pressurizer response	1/09/12; 6/26/12	6/26/12 (draft form)	Partially resolved	
7.	Long-term cooling and PIRT	1/09/12; 6/26/12			
8.	SBLOCA boundary and Region-I to Region-II boundary	1/09/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
9.	Worst SBLOCA	1/09/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
10.	Loss-of-offsite power (LOOP) versus RCPs operating	1/09/12; 6/26/12	10/02/12 (draft form)	Partially resolved	
11.	Loop seal behavior	1/09/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
12.	Worst break sampling	1/09/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
13.	Decay heat multiplier/sampling	1/09/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
14.	Number of SBLOCA cases sampled: 93 versus 124	1/09/12; 6/26/12	1/24/13 (draft form)	Partially resolved	
15.	SBLOCA upper limit break size	1/09/12; 6/26/12	10/31/12 (draft form)	Partially resolved	

Table 1: List of RAI Questions (Continued)

Question No.	Subject	Date Issued (Draft/ Formal)	Date Responded (Draft/ Formal)	Disposition (O/C)$^{(\dagger)}$	Note
16.	Long-term cooling restriction	1/09/12; 6/26/12		Partially resolved	
17.	Swelled or two-phase mixture level versus collapsed level	1/09/12; 6/26/12		Partially resolved	
18.	High pressure safety injection (HPSI) curve basis and uncertainty	1/09/12; 6/26/12	9/07/12 (draft form)	Partially resolved	
19.	SBLOCA axial power shape	1/09/12; 6/26/12	10/31/12;	Partially resolved	
Set 2	**Questions 20 - 29**				
20.	^{235}U, ^{238}U, and ^{239}Pu decay heat uncertainty fits to ANS 5.1-1979	1/12/12; 6/26/12	8/8/12; 5/31/13	Partially resolved	
21.	^{235}U, ^{238}U, and ^{239}Pu decay heat and uncertainty comparison to ANS 5.1-1979	1/12/12; 6/26/12	10/25/12; 5/31/13	Partially resolved	
22.	^{235}U, ^{238}U, and ^{239}Pu decay heat uncertainty comparison to ANS 5.1-1979	1/12/12; 6/26/12	10/25/12; 5/31/13	Partially resolved	
23.	Burnup limit in assessing kinetics parameters	1/12/12; 6/26/12	8/8/12; 5/31/13	Partially resolved	
24.	editorial	1/12/12; 6/26/12	9/7/12; 5/31/13	Partially resolved	
25.	Utilized codes	1/12/12; 6/26/12	5/31/13 (formal form)	Partially resolved	
26.	Actinides decay heat power	1/12/12; 6/26/12	8/8/12; 5/31/13	Partially resolved	
27.	Decay heat in demonstration plant analyses	1/12/12; 6/26/12	10/31/12; 5/31/13	Partially resolved	
28.	Decay heat uncertainty distribution	1/12/12; 6/26/12	8/8/12; 5/31/13	Partially resolved	
29.	Decay heat sampling approach	1/12/12; 6/26/12	10/31/12; 5/31/13	Partially resolved	
Set 3	**Questions 30 - 35**				
30.	Scaling of the Westinghouse vertical COSI test facility and tests	2/22/12; 6/26/12	11/09/12; 5/31/13	Partially resolved	
31.	Westinghouse vertical COSI downcomer condensation	2/22/12; 6/26/12	11/09/12; 5/31/13	Partially resolved	
32.	Westinghouse vertical COSI heat loss	2/22/12; 6/26/12	11/09/12; 5/31/13	Partially resolved	

Table 1: List of RAI Questions (Continued)

Question No.	Subject	Date Issued (Draft/ Formal)	Date Responded (Draft/ Formal)	Disposition (O/C)$^{(\dagger)}$	Note
33.	Westinghouse vertical COSI data and condensation outside the jet region	2/22/12; 6/26/12	11/09/12; 5/31/13	Partially resolved	
34.	Westinghouse vertical COSI data qualification	2/22/12; 6/26/12	11/09/12; 5/31/13	Partially resolved	
35.	Scale impact on cold leg condensation	2/22/12; 6/26/12	11/09/12; 5/31/13	Partially resolved	
Set 4	**Questions 36 - 45**				
36.	Fuel Thermal Conductivity Model	3/19/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
37.	Burnup Impact on Fuel Thermal Conductivity and Initial Stored Energy	3/19/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
38.	Treatment of Fuel Burnup Dependant Parameters	3/19/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
39.	Fuel Burnup Sampling	3/19/12; 6/26/12	10/31/12 (draft form)	Partially resolved	
40.	Fuel Burnup Limit in FSLOCA Methodology	3/19/12; 6/26/12	10/31/12; 5/31/13	Partially resolved	
41.	Nuclear Fuel Rod Special Model Changes	3/19/12; 6/26/12	10/31/12; 5/31/13	Partially resolved	
42.	Nuclear Fuel Rod Special Models Validation	3/19/12; 6/26/12	10/31/12 (draft form); 5/31/13	Partially resolved	
43.	Dummy Rod Component Models	3/19/12; 6/26/12	10/31/12 (draft form); 5/31/13	Partially resolved	
44.	Fuel Rod Material Properties	6/26/12 (formal form)	10/31/12 (draft form); 5/31/13	Partially resolved	
45.	Validity of Wilks theorem	6/26/12 (formal form)	6/14/13 (formal form)		
Set 5	**Questions 46 - 77**				
46.	COCO Component	5/01/12; 6/2013	3/28/13 (draft form)	Partially resolved	
47.	TRAC-PF1 One-Dimensional Component Models	5/01/12; 6/2013			
48.	Steam Generator Modeling	5/01/12; 6/2013			

Table 1: List of RAI Questions (Continued)

Question No.	Subject	Date Issued (Draft/ Formal)	Date Responded (Draft/ Formal)	Disposition (O/C)$^{(\dagger)}$	Note
49.	TEE Component	5/01/12; 6/2013			
50.	Component Multipliers	5/01/12; 6/2013	4/15/13 (draft form)	Partially resolved	
51.	Fluid Properties for Nusselt Number in Dispersed Droplet Flow	5/01/12; 6/2013	4/14/13 (draft form)	Partially resolved	
52.	Nusselt Number Correlation Applicability for Dispersed Droplet Flow	5/01/12; 6/2013	4/14/13 (draft form)	Partially resolved	
53.	Interfacial Heat Transfer in Inverted Annular and Liquid Slug Flows	5/01/12; 6/2013			
54.	Interfacial Heat Transfer to Droplet/Bubble	5/01/12; 6/2013			
55.	Droplet Diameter for Interfacial Heat Transfer in Dispersed Droplet Flow	5/01/12; 6/2013			
56.	Droplet-Wall Direct Contact Heat Transfer in Dispersed Flow Film Boiling	5/01/12; 6/2013			
57.	LBLOCA Heat Transfer Package in WCOBRA/TRAC-TF2	5/01/12; 6/2013			
58.	Flow Regime Map Selection Criterion for Vessel Component	5/01/12; 6/2013			
59.	WCOBRA/TRAC-TF2 Flow Maps for Vessel and One-Dimensional Components	5/01/12; 6/2013			
60.	PWR Core Two-Phase Mixture Level and Sensitivity to Axial Nodalization	5/01/12; 6/2013			
61.	Oak Ridge National Laboratory (ORNL) Thermal Hydraulic Test Facility (THTF) Mixture Level Predictions and Axial Nodalization Sensitivity	5/01/12; 6/2013			
62.	ORNL THTF Mixture Level Predictions Detailed Results	5/01/12; 6/2013			
63.	Interfacial Drag Correlations in WCOBRA/TRAC-TF2	5/01/12; 6/2013			

Table 1: List of RAI Questions (Continued)

Question No.	Subject	Date Issued (Draft/ Formal)	Date Responded (Draft/ Formal)	Disposition (O/C)[(†)]	Note
64.	Interfacial Area in Inverted Slug Flow	5/01/12; 6/2013			
65.	Interfacial Drag for Inverted Slug Flow	5/01/12; 6/2013			
66.	Annular Film Flow Interfacial Drag	5/01/12; 6/2013			
67.	Bubbly Flow Interfacial Drag "Ramping" to "Hot Wall" Inverted Annular Drag	5/01/12; 6/2013			
68.	Approach to Interfacial Drag "Ramping" Between "Cold Wall" and "Hot Wall" Regimes	5/01/12; 6/2013			
69.	Calculation Results for Bubbly Flow Interfacial Drag	5/01/12			
70.	Film Flow Drag Assessment Using THTF Test Data	5/01/12			
71.	Film Drag Impact on Bubbly Flow Void Predictions for THTF Tests	5/01/12			
72.	Bubbly Flow Drag Assessment Using THTF Test Data	5/01/12	6/14/13	Partially resolved	
73.	Bubbly Flow Drag Assessment Using G-1 and G-2 Test Data	5/01/12	6/14/13	Partially resolved	
74.	Interfacial Drag Sampling Approach	5/01/12	6/14/13	Partially resolved	
75.	Interfacial Drag Sampling Impact on ROSA-IV LSTF Test Predictions	5/01/12			
76.	WCOBRA/TRAC-TF2 Interfacial Drag Assessment	5/01/12	6/14/13	Partially resolved	
77.	Follow-up to RAI #45	5/01/12			

(†) O=Open; C=Closed.

Table 2: List of Abbreviations

Abbreviation	Meaning	Note
1D	One Dimensional	
ASTRUM	Automated Statistical Treatment of Uncertainty Method	
CFD	Computational Fluid Dynamics	
CHF	Critical Heat Flux	
COBRA	Coolant Boiling in Rod Arrays	
COCO	Containment Pressure Analysis Code	
COSI	Condensation on Safety Injection	
CQD	Code Qualification Document	
CSAU	Code Scaling, Applicability, and Uncertainty	
CSE	Containment Systems Experiment	
CT	Churn-Turbulent	
DEG	Double Ended Guillotine	
EM	Evaluation Model	
ECCS	Emergency Core Cooling System	
EOP	Emergency Operating Procedures	
EPRI	Electric Power Research Institute	
FD	Film/Drop	
FLECHT	Full Length Emergency Cooling Heat Transfer	
FSLOCA	Full Spectrum Loss-of-Coolant Accident	
GE	General Electric	
HPTF	High Pressure Test Facility	
HTSTR	Heat Structure	
IAEA	International Atomic Energy Agency	
ISP	International Standard Problem	
JAERI	Japan Atomic Energy Research Institute	
LB	Large Bubble	
IBLOCA	Intermediate Break Loss-of-Coolant Accident	
IET	Integral Effects Test	
LBLOCA	Large Break Loss-of-Coolant Accident	
LHGR	Linear Heat Generation Rate	
LOCA	Loss-of-Coolant Accident	
LSTF	Large Scale Test Facility	
MLO	Maximum Local Oxidation	
NRC	U. S. Nuclear Regulatory Commission	
ORNL	Oak Ridge National Laboratory	
PCT	Peak Cladding Temperature	
PDF	Probability Density Function	
PIRT	Phenomena Identification and Ranking Table	
PKL	Primärkreislauf (German for Primary Coolant Circuit)	
BNWL	Battelle Northwest Laboratories	
PWR	Pressurized Water Reactor	

Table 2: List of Abbreviations (Continued)

Abbreviation	Meaning	Note
RBHT	Rod Bundle Heat Transfer Test	
RCP	Reactor Coolant Pump	
RCS	Reactor Coolant System	
RELAP	Reactor Excursion Leak Analysis Program	
RG	Regulatory Guide	
ROSA	Rig-of-Safety Assessment	
SB	Small Bubble	
SBLOCA	Small Break Loss-of-Coolant Accident	
SEASET	Separate Effects and System Effects Test	
SG	Steam Generator	
SLB	Small-to-Large Bubble	
SI		
TC	Thermocouple	
TEE	T-Junction	
TF	Three-Field	
TF	Two-Fluid	
TF2	Three-Field and Two-Fluid	
THTF	Thermal Hydraulic Test Facility	
TPTF	Two-Phase Flow Test Facility	
TRAC	Transient Reactor Analysis Code	
TRAC-M	Transient Reactor Analysis Code - Modernized	

Question #46: Containment Pressure Analysis Code COCO Component

The Full Spectrum^{TM} LOCA methodology uses the COCO containment code (Bordelon, F. M., Murphy, E. T., “Containment Pressure Analysis Code (COCO),” WCAP-8327 (Proprietary), WCAP-8306 (Non-Proprietary), 1974) to compute the containment backpressure **[** **]** The COCO code was integrated into WCOBRA/TRAC-TF2. WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 10.11, “COCO Component,” explains that “the COCO computer program (Bordelon and Murphy, 1974) is used to predict the containment pressure response to a LOCA for dry containment buildings, with modeling assumptions to conservatively minimize the back pressure as described in (Bordelon et al., 1974).” WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Section 25.6, “Containment Response,” further clarifies that COCO is used to calculate the containment pressure **[**

] Section 25.6 states that input values are shared consistently between WCOBRA/TRAC-TF2 and COCO (i.e., safety injection temperature) with the exception of the single failure assumption. Whereas a failure of a single-train of ECCS is assumed for the LOCA transient calculations, all trains of containment spray, fan coolers, etc. are assumed to be in operation for the containment pressure calculation. Also, Section 25.6 states that “the values for inputs pertinent only to the containment model were typically selected to provide a minimum containment pressure (e.g. maximum heat transfer areas and volumes are modeled for containment heat sinks).” **[**

]

Please clarify the following items related to the COCO containment component in WCOBRA/TRAC-TF2.

(1) Please identify the frozen code version of the stand-alone COCO containment code that was used to develop the integrated in WCOBRA/TRAC-TF2 and provide a complete set of references that document this code version. Explain if this code version has been approved by the U. S. Nuclear Regulatory Commission (NRC) and provide appropriate references. If any changes were made to the stand-alone code as part of its integration in to WCOBRA/TRAC-TF2, please describe these changes and explain if they have been previously reviewed and approved by the NRC.

(2) Please describe briefly the balance equations used in the lumped parameter modeling approach and identify the subsystems included in the containment model. In addition, describe the implemented modeling assumptions and explain any possible non-conservatism in the modeling approach. Describe the modeling of engineered features, components, and safety systems that can have an impact on the containment pressure response predictions and identify any modeling limitations in this regard.

(3) Please describe and present results from validation cases that demonstrate the applicability and appropriateness of the COCO component for the purposes of the FULL SPECTRUM^{TM} LOCA methodology. Identify any modeling biases and their possible impact on LBLOCA prediction results.

(4) COCO is used to calculate the temperature and pressure inside a pressurized water reactor (PWR) dry containment following a LOCA for containment design (i.e., peak pressure) as well as for containment backpressure prediction for LOCA analyses. Please identify and provide a list of all parameters for which Section 25.6 states that "the values for inputs pertinent only to the containment model were typically selected to provide a minimum containment pressure" applies. In addition, please provide these selected values and explain the basis for their determination. Clarify if any of these input values are plant-specific and if so explain how it is ensured that appropriate inputs will be used for intended FULL SPECTRUM^{TM} LOCA methodology applications.

(5) Please describe the modeling options for determining the heat transfer to containment walls and structures (e.g., input tables). Please describe any implemented heat transfer coefficient correlations along with their range of applicability and activation logic. Explain how **[**

] was determined and implemented in the COCO component.

(6) Please identify any parameters related to the COCO component that are subject to sampling in FULL SPECTRUM^{TM} LOCA methodology applications. For each such parameter, define the sampling range and distribution and explain their determination for best-estimate plant LOCA applications.

(7) WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 10.11, "COCO Component," refers at its end to the topical report Section 25.5, "Operator Actions." It is believed that the reference in Section 10.11 should be Section 25.6, "Containment Response," instead of Section 25.5, "Operator Actions."

Question #47: TRAC-PF1 One-Dimensional Component Models

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 10, "WCOBRA/TRAC-TF2 One-Dimensional Component Models," explains that the one-dimensional components in WCOBRA/TRAC-TF2 used to model the reactor primary system are derived from TRAC-PF1. As stated in Subsection 10.1, "Introduction"

> "…many of the base modules, such as PIPE, TEE, HTSTR, VALVE and PUMP are virtually unchanged from their original TRAC-PF1 versions, so their descriptions are very similar to those given by TRAC-PF1 user manual."

Please clarify the following items related to the one-dimensional component modules in WCOBRA/TRAC-TF2.

(1) Please identify the frozen code version of TRAC-PF1, from which the one-dimensional component modules implemented in WCOBRA/TRAC-TF2 were taken and provide a reference to the cited TRAC-PF1 user manual. In addition,

explain how it was determined that the existing TRAC-PF1 modules were adequate for the purposes of the WCOBRA/TRAC-TF2 code. If any changes were made to these modules as part of their integration in WCOBRA/TRAC-TF2, please document the changes and explain if they have been previously reviewed by NRC.

(2) In describing the HTSTR component, WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 10.10, “HTSTR Components,” refers on several occasions to the TRAC-M code. TRAC-M was the predecessor of the TRACE code developed by the NRC. Please identify the code from which the HTSTR component was taken and explain how TRAC-M was used for the purpose of implementing this HTSTR component in WCOBRA/TRAC-TF2.

Question #48: Steam Generator Modeling

WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Subsection 10.5, “Steam Generator,” explains that PWR Steam Generator (SG) is modeled in WCOBRA/TRAC-TF2 with a combination of PIPE, TEE, and HTSTR components. The example noding diagram for a U-tube SG shown in Figure 10-8, “Steam Generator Noding Diagram,” includes a single PIPE component representing the entire U-tube bundle. The SG models in the plant examples discussed in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 26, “WCOBRA/TRAC-TF2 Model of Pilot Plants,” follow the same modeling approach. As seen from Figure 26.2-9, “Virgil C. Summer Steam Generator Component Noding Diagram,” and Figure 26.3-15, “Beaver Valley Unit 1 Steam Generator Component Noding Diagram,” the U-tube bundle is modeled with a single PIPE component as well.

Although WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 10.5, “Steam Generator,” mentions that in the implemented approach the SG U-tube bundle is represented by “a single effective tube that has the heat transfer characteristics of the entire tube bank,” the following related items need further clarification.

Using a single PIPE in combination with a HTSTR component allows preserving the heat transfer surface area of the entire SG U-tube bundle. At the same time, individual U-tubes in the bundle are characterized by various elevation heights of the apex points in their bending sections that range between the height of the apex of the shortest tube raw and that of the longest tube raw. It is recognized that the height of individual U-tubes in the bundle is an important factor under conditions involving natural circulation through the primary coolant loops. Such conditions are of importance when modeling small break LOCAs. Accordingly, several U-tube rows of different heights are used in integral PWR test facilities to represent the SGs. For example, the PKL III (abbreviation from Primärkreislauf, German for primary coolant circuit) 1:1 vertical scale replica of a 1,300 MegaWatt PWR employs seven different U-tube clusters of variable height to represent the SG U-tube bundle. The elevation difference between the apex of the longest tube cluster and that of the shortest one amounts to 2.020 m or 6.63 ft (see Figure 2.3, “Axial Locations of Thermocouples in SG Tubes,” in NUREG/IA-0170, “RELAP5/MOD3.2 Post Test Calculation of the PKL-Experiment PKLIII-B4.3”, December 1999). As reported by K. Umminger, T. Mull, and B. Brand, “Integral Effect Tests in the PKL Facility with International Participation,” Nuclear Engineering and Technology, Vol. 41, No. 6, pp. 765-774, August 2009, representing the SG tubes by three lengths can be insufficient for adequate modeling of processes in the SG tubes that are of importance for specific accident conditions.

Please explain and provide the technical basis in support of using a single PIPE representation of the SG U-tube bundle in WCOBRA/TRAC-TF2 models of plants with such SGs. Discuss possible limitations of this approach with regard to modeling thermal-hydraulic phenomena that can take place during small break LOCA transients using the FULL SPECTRUM^{TM} LOCA methodology. Explain how it is ensured that the SG U-tube bundle representation and SG modeling are adequate in resolving specific processes of safety importance that can occur during the course of a SBLOCA.

Question #49: T-Junction Component

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 10.3, “TEE Component,” explains that WCOBRA/TRAC-TF2 basically treats a TEE component as two PIPE components as shown in Figure 10-2, “TEE Component Noding.” If the primary-side PIPE component, PIPE 1, has NCELL1 cells and the secondary-side PIPE component, PIPE 2, has NCELL2 cells, please explain the meaning of the parameter NCELLS, defined in Figure 10-2 by the expression NCELLS = NCELL1 + 1 + NCELL2.

Question #50: Component Multipliers

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 10, “WCOBRA/TRAC-TF2 One-Dimensional Component Models,” states that additional user-defined multipliers were added that enable the code user to affect specific models and correlations in WCOBRA/TRAC-TF2.

The HS_SLUG multiplier, identified in Subsection 10.2, “PIPE Component,” can be used to affect the horizontal flow calculation for all WCOBRA/TRAC-TF2 one-dimensional hydraulic components, except the PUMP. According to Subsection 10.2, this multiplier ranges between 0.1 and 9.99. WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Subsection 4.4.5, “Horizontal Stratified Flow,” provides a range from 0.1 to 9.9 for the same parameter. Its default input value is equal to 1.0 and, according to WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Subsection 17.3.4, “WCOBRA/TRAC-TF2 Results: Sensitivity Studies,” its uncertainty range is **[**
]

User specified allowances for horizontal stratification within a PIPE component can be provided through the MSTRTX and STRTX input. Similarly, the user has the option to specify allowance for horizontal stratification in the TEE main and side pipes through the STRTX1 and STRTX2 multipliers. The option to provide user specified allowance for horizontal flow is not available in the VALVE component model.

Interfacial drag multipliers YDRGX can be defined by the user at any cell faces of the PIPE, TEE and VALVE components. Similarly, interfacial condensation heat transfer at user selected cells can be modified by using the CNDNX multipliers for the PIPE and TEE components and the XCNDX multiplier for the VALVE component.

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.6, “Cold Leg Condensation (KCOSI),” identifies a cold leg condensation multiplier, KCOSI, that was added in the code to allow varying the cold leg condensation heat transfer rate for the purpose of the uncertainty analysis.

Please clarify the following items related to the use of user-defined multipliers in conjunction with the one-dimensional component models discussed in Section 10 of WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0:

(1) Please provide a table that lists all user-defined multipliers that can be applied to the one-dimensional component models in WCOBRA/TRAC-TF2 presented in Section 10. For each multiplier, include its identifier, relevant one-dimensional component, applicable cells/interfaces, default value, and allowable range of input values as appropriate.

(2) Please identify the multipliers that are subject to sampling in the uncertainty analyses and provide a table that lists all such multipliers. For each such parameter, provide its identifier, sampling range and corresponding distribution. Explain the technical basis for establishing the provided sampling ranges and sampling distributions. Please explain each individual case for which the range of allowable input values for a multiplier is broader than the defined sampling range (e.g., HS_SLUG).

(3) For the multipliers that are not subject to sampling, if any, please explain the basis for introducing such multipliers. In addition, please clarify how the ranges of allowed input values were established and explain the process of determining the input values in performing plant analyses using the FULL SPECTRUM^{TM} LOCA methodology. Explain if an input value in a plant model can fall outside of the documented range of allowable input values.

(4) Please address items (1) through (3) above for user-defined multipliers that can be applied to VESSEL component models in WCOBRA/TRAC-TF2, as applicable.

Question #51: Fluid Properties for Nusselt Number in Dispersed Droplet Flow

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 6.2.7, "Dispersed Droplet Flow Regime," provides the interfacial heat transfer coefficient between superheated vapor and dispersed droplets in Equation (6-70), which can be presented in terms of the Nusselt number as follows:

[ ]

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 6.2.7 identifies **[**

]

Please clarify the following items related to the application of the above correlation for predicting the interfacial heat transfer from superheated steam to liquid droplets for dispersed droplet flow in WCOBRA/TRAC-TF2.

(1) Define the quantities used in Equation (6-71) to determine **[**
] Explain if B reduces to zero when the steam superheat becomes negligible. Explain how WCOBRA/TRAC-TF2 determines the thermodynamic properties that are used to calculate **[** **]** in Equation (6-71).

(2) Under high-temperature superheated steam conditions, the Reynolds, Prandtl, and Nusselt numbers become significantly dependent on the fluid properties that are used to calculate the values. The values for these dimensionless numbers evaluated at the free stream (ambient) temperature can differ significantly from those evaluated at the film temperature. Usually, the temperature of the film formed around the droplet from vaporization is defined as the mean of the droplet surface temperature and the ambient gas temperature. Please explain which thermodynamic properties are used in WCOBRA/TRAC-TF2 to calculate the Reynolds, Prandtl, and Nusselt numbers in Equation (6-70).

(3) Equation (6-70) is basically **[**

]

Question #52: Nusselt Number Correlation Applicability for Dispersed Droplet Flow

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 6.2.5, “Inverted Annular Regime,” explains that the coefficient **[**

] The same coefficient appears in Equation (6-70) in WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Subsection 6.2.7, “Dispersed Droplet Flow Regime,” which provides the interfacial heat transfer coefficient between superheated vapor and dispersed droplets. Equation (6-70) can be presented as:

[**]**

As mass transfer away from the drop has been found to decrease the heat transfer, the effect of evaporation on the interfacial heat transfer needs to be accounted for if the free stream gas phase is superheated. The shielding function **[** **]** in Equation (6-70) accounts for steam superheating. Importantly, during the re-flood phase of a PWR LOCA, the core seam flow conditions range from negligible to considerable steam superheating. For example, at a typical re-flood pressure of 0.3 MPa and an assumed superheated steam temperature of 1,000 K (723 ºC or 1,340 ºF), the heat to increase the temperature of the evaporated steam to 1,000 K exceeds half of the latent heat of evaporation.

Yuen and Chen (1978) (M. C. Yuen and L. W. Chen, 1978, “Heat-Transfer Measurements of Evaporating Liquid Droplets,” Int. J. Heat and Mass Transfer, Volume 21, Issue 5, pp. 537-542, May 1978) studied heat transfer to water and methanol droplets in an atmospheric vertical hot air tunnel and showed that the experimental data can best be correlated by:

$Nu_f = (2+0.6Re_M^{1/2} Pr_f^{1/3})/(1+B)$.

Their experiments were limited to the following range of flow conditions:

Reynolds number:	200 - 2,000
Pressure:	atmospheric
Free stream air temperature:	150 - 960 °C (302 - 1,760 ºF)
Velocity:	2.1 - 11.4 m/s (6.9 - 37.4 fps)

Renksizbulut and Yuen (1983) (M. Renksizbulut and M. C. Yuen, "Experimental Study of Droplet Evaporation in a High-Temperature Air Stream," J. Heat Transfer, Volume 105, Issue 2, pp. 384-388, May 1983) measured heat transfer rates to liquid droplets of water, methanol and heptane in an atmospheric hot air tunnel in a Reynolds number range of 25 to 2,000 and a Spalding number range of 0.07 to 2.79. It was shown that the obtained experimental data along with data by others can best be correlated by:

$Nu_f = (2+0.57Re_M^{1/2} Pr_f^{1/3})/(1+B)^{0.7}$.

Ban and Kim (2000) (Ch. Hw. Ban and Y. Kim, "Evaporation of a Water Droplet in High-Temperature Steam," J. Korean Nuclear Society, Volume 32, Number 5, pp. 521-529, October, 2000) proposed a modification to the Lee and Ryley (1968) correlation (K. Lee and D. J. Ryley, "The Evaporation of Water Droplets in Superheated Steam," J. Heat Transfer, Volume 90, Issue 4, pp. 445-451, November 1968):

$Nu_f = (2+0.74Re_M^{1/2} Pr_f^{1/3})/(1+B)$.

The proposed expression correlated well with data for a water droplet in gas flow for both negligible and considerable degree of superheating. Ban and Kim (2000) also explained that the necessity of the exponent 0.7 in the correlation by Renksizbulut and Yuen (1983) comes from the data of heptane and stated that water and methanol data can be well correlated with an exponent of 1.0. In this case, the correlation is identical with that by Yuen and Chen (1978) if radiation heat transfer is neglected in the calculation of the Spalding number as proposed by Renksizbulut and Yuen (1983).

A sensitivity study performed with the TRACE code by B. Belhouachi, S. P. Walker, and G. F. Hewitt, "Analysis and Computational Predictions of CHF Position and Post-CHF Heat Transfer," NUREG/IA-0236, May 2010, illustrated the central role of the droplet Nusselt number in the PCT and CHF predictions. Please clarify the following items related to the use of the correlation for predicting the interfacial heat transfer from superheated steam to liquid droplets for dispersed droplet flow in WCOBRA/TRAC-TF2.

(1) Identify the experimental data and provide the technical basis in support of the application of Equation (6-70) to calculate the interfacial heat transfer coefficient between superheated vapor and dispersed droplets in WCOBRA/TRAC-TF2. Describe the ranges of test conditions for which the applicable data sets were obtained and provide the applicability ranges for this equation.

(2) Present the technical basis for using a shielding function of **[ ]** Equation (6-70). Applying different shielding functions to the same zero mass transfer Nusselt number can have a pronounced effect on the resulting heat transfer coefficient as the degree of superheating increases. For example, under typical reflood conditions at 0.3 MPa pressure and 1,000 K (1,340 ºF) steam temperature, using a shielding function of **[ ]** with the same zero mass transfer Nusselt number will increase the predicted heat transfer coefficient by more than 20 percent. Accordingly, this can have a pronounced impact on the calculated PCT.

(3) Demonstrate the applicability of Equation (6-70) for prediction of interfacial heat transfer between water droplets and superheated steam under the range of conditions occurring in a PWR core following a LBLOCA. Provide the expected ranges for the controlling flow parameters of interest for PWR LBLOCA re-flood analyses and compare these ranges against the test data conditions used to establish Equation (6-70) and its range of applicability. Discuss effects related to the correlation's applicability to PWR core flow re-flood conditions considering each governing parameter.

Question #53: Interfacial Heat Transfer in Inverted Annular and Liquid Slug Flows

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 6.2.5, "Inverted Annular Regime," provides expressions for calculation of the interfacial heat transfer coefficient from both continuous liquid and droplets to superheated vapor for inverted annular flow in Equations (6-56) and (6-57). Subsection 6.2.6, "Inverted Liquid Slug Regime," defines the correlations for prediction of the interfacial heat transfer coefficient from the continuous liquid and droplets interface to superheated vapor for inverted liquid slug flow in Equations (6-65) and (6-66). The interfacial heat transfer coefficients given by the above identified equations can be presented in terms of the Nusselt number with a single expression:

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Please clarify the following items related to the use of the above correlation for predicting the interfacial heat transfer coefficient for inverted annular and inverted liquid slug flows in WCOBRA/TRAC-TF2.

(1) Describe the way of determining the fluid properties in calculating the Reynolds, Prandtl, **[ ]** and Nusselt numbers in Equations (6-56), (6-57), (6-65), and (6-66) as applied in WCOBRA/TRAC-TF2 in the case of inverted annular and inverted liquid slug flows.

(2) Please present the technical bases and justify the applicability of Equations (6-56), (6-57), (6-65), and (6-66) for computing the interfacial heat transfer coefficient for inverted annular and inverted liquid slug flows in WCOBRA/TRAC-TF2.

Question #54: Interfacial Heat Transfer to Droplet/Bubble

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 6.2.3, "Churn-Turbulent Regime," provides an expression for the interfacial heat transfer coefficient from superheated vapor to liquid droplets that can appear in the flow from entrainment and from adjoining channels. It states that “the interfacial heat transfer coefficient is given by the Lee-Ryley (1968) correlation,” which is given in Equation (6-26). The relationship can be presented in terms of the Nusselt number as:

$Nu_d=2+0.74Re_d^{1/2}\,Pr_v^{1/3}$.

The correlation by K. Lee and D. J. Ryley, “The Evaporation of Water Droplets in Superheated Steam,” J. Heat Transfer, Volume 90, Issue 4, pp. 445-451, November 1968, is given a special recognition in LOCA analyses as it was based on data for droplet evaporation in superheated steam in contrast to other experiments that studied liquid droplet evaporation in air. The droplet diameter and flow parameters were varied as follows:

Droplet diameter:	230 µm - 1,130 µm (9 mils - 44.5 mils)
Reynolds number:	64 - 250
Pressure:	101.4 - 200 kPa (14.7 - 29 psia)
Superheat:	2.8 - 33.9 K (5 - 61 ºF)
Velocity:	2.7 - 11.9 m/s (9 - 39 fps)

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 6.2.7, “Dispersed Droplet Flow Regime,” refers to **[**

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WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 6.2.2, “Small to Large Bubble Regime,” explains that the heat transfer coefficient for large bubbles of superheated vapor for the discussed flow regime is determined using the correlation by Lee and Ryley (1968) as given in Equation (6-14).

Please clarify the following items related to the prediction of the interfacial heat transfer from superheated steam to liquid droplets and from large superheated bubbles to the continuous liquid phase for different flow regimes in WCOBRA/TRAC-TF2.

(1) Explain why two different existing correlations are provided in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 6, “WCOBRA/TRAC-TF2 Interfacial Heat and Mass Transfer Models,” when describing the technical basis for predicting interfacial heat transfer from superheated steam to liquid droplets.

(2) Equation (6-49) with small variations in the coefficient of the second term (0.552, 0.55, 0.60) is often cited in the technical literature. In the case of a liquid droplet falling through a moving airstream, Frössling (1938) developed an empirical relation of the same form for the mass transfer number (Frössling, “Über die Verdunstung fallender Tropfen," Gerlands Beitrage Zur Geophysik, Volume 52, pp. 170-216, 1938). Ranz and Marshall (1952) used the heat transfer analogy to show that the heat transfer data can be correlated through the droplet Nusselt number using a relationship of the same form (see W. E. Ranz and W. R. Marshall, Jr.: “Evaporation from Drops: I,” Journal of Chemical Engineering Progress, Volume 48, No. 3, pp. 141-146, March 1952. Also W. E. Ranz and W. R. Marshall, Jr.: “Evaporation from

Drops: II," Journal of Chemical Engineering Progress, Volume 48, No. 4, pp. 173-180, April 1952). Please provide the reasons for its identification as "a correlation by Forslund and Rohsenow (1968)."

(3) According to Abou Al-Sood (2010), the Frössling (1938) and Ranz and Marshall (1952) correlations are applicable to describe droplet evaporation in a laminar convective flow (see M. M. Abou Al-Sood, "Simple Model for Turbulence Effects on the Vaporization of Liquid Single Droplets in Forced Convective Conditions," 23rd Annual Conference on Liquid Atomization and Spray Systems, ILASS – Europe 2010, Brno, Czech Republic, September 2010). Please explain the applicability of the Lee-Ryley (1968) correlation under flow conditions expected in a PWR core following a LBLOCA.

(4) The Lee and Ryley (1968) correlation was developed from data describing heat transfer from evaporating droplets. Although Subsection 6.2.2, "Small to Large Bubble Regime," recognizes that such bubbles are unlikely to occur extensively in a LOCA transient, please justify the technical basis for the use of the Lee and Ryley (1968) correlation for the description of heat transfer mechanisms in the case of large bubbles of superheated steam.

Question #55: Droplet Diameter for Interfacial Heat Transfer in Dispersed Droplet Flow

The liquid droplet diameter is an important parameter when computing the interfacial heat transfer for dispersed droplet flow. Considering single isolated droplet, the heat transfer coefficient decreases with increasing droplet diameter. However, the product of the heat transfer coefficient and the surface area will increase by virtue of surface area's higher order dependence on diameter. For a dispersed droplet flow at a certain flow quality, the product of the heat transfer coefficient and the integral droplet surface area will decrease when increasing the assumed droplet diameter as both the heat transfer coefficient and the integral surface area of all droplets will decrease.

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 6.2.7, "Dispersed Droplet Flow Regime," does not explain how the droplet size is determined for the purpose of predicting the interfacial heat transfer coefficient and associated heat transfer rate between the dispersed droplets and the continuous gas phase.

Please explain and justify the implemented modeling approach for calculating the droplet size in predicting the interfacial heat transfer between superheated steam and liquid droplets in addition to the information provided in Subsection 6.2.7, "Dispersed Droplet Flow Regime."

Question #56: Droplet-Wall Direct Contact Heat Transfer in Dispersed Flow Film Boiling

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 7.2.7, "Dispersed Flow Film Boiling," explains that the VESSEL component wall heat transfer logic in WCOBRA/TRAC-TF2 invokes the Dispersed Flow Film Boiling (DFFB) heat transfer regime when the void fraction is greater than **[ ]** and the wall temperature is greater than the minimum stable film boiling temperature, T_{MIN}, as given in Equation (7-91). The subsection states that heat transfer in this post-dryout or post-CHF flow regime “is calculated as a “two-step” method where the dominant heat transfer mode is forced convection to superheated steam.” The code computes the dispersed flow film boiling heat flux as a sum of four components: (1) convective heat flux to vapor, (2) radiative heat flux to vapor, (3) radiative heat flux to droplets, and (4) drop-wall direct contact heat transfer. What is also important, Subsection 7.2.7 explains that “the steam superheat is then determined by the interfacial heat transfer rate to the entrained droplets as part of the hydrodynamic solution.”

Subsection 7.2.7 states that the drop-wall direct contact heat transfer that accounts for droplet impingement on the heated surface is calculated using the model by R. P. Forslund and W. M. Rohsenow, “Dispersed Flow Film Boiling,” J. Heat Transfer, Vol. 90, Issue 4, pp. 399-407, November 1968, as given in Equation (7-130).

WCOBRA/TRAC-TF2 implements **[**

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Following the initial surge into the core, the PWR core re-flood after a LBLOCA takes place at low flow and low pressure conditions. Flooding rates are very low and typically stay below 1 in/s. Under such conditions, post-dryout heat transfer with dispersed flow film boiling in the upper core region controls the PCT. For example, a typical re-flood flow rate of 0.8 in/s (0.02 m/s) of safety injection water at 150 ºF (65.6 ºC of 338.7 K) and 20 psia (1.4 bar or 0.14 MPa) corresponds to a mass flux of:

ρ_W (338.7 K, 0.14 MPa) $\times$ $V_{Reflood}$ = 980.3 kg/m^3 $\times$ 0.02 m/s = 19.9 kg/m^2-s = 14,687 lbm/ft^2-hr.

For a fuel rod with a standard diameter of 0.422 inches (10.7×10^{-3} m) and an assumed peak LHGR of 15 kW/ft (49.2 kW/m), the linear heat rate and rod surface heat flux conditions for decay heat power ratios of 5 percent, 3 percent, and 2 percent (about 10 sec, 100 sec, and 1,000 sec after scram) are given in the Table 1 below.

Table 1: Fuel Rod LHGR and Surface Heat Flux Conditions

Parameter	Units	Value			
Decay Ratio	-	1.0	0.05	0.03	0.02
Decay Time	s	0.0	~10	~100	~1,000
LHGR	kW/ft	15	0.75	0.45	0.30
	kW/m	49.2	2.46	1.48	0.98
Heat Flux	Btu/(ft^2-hr)	463,298	23,165	13,899	9,266
	kW/m^2	1,461	73.1	43.8	29.2

Typical dispersed flow film boiling conditions at low reflood rate can be identified as:

Pressure: 1 to ~3 bar (0.1 to ~0.3 MPa or 14.5 to ~44 psia),
Mass rate: ~1 in/s (0.0254 m/s) or ~25 kg/m^2-s (18,700 lbm/ft^2-hr),
Void fraction: higher than 80 percent.

A work by M. Andreani and G. Yadigaroglu, “Prediction Methods for Dispersed Flow Film Boiling,” Int. J. of Multiphase Flow,” Vol. 20, p. 1-51, 1994, and more recently a report by the International Atomic Energy Agency (IAEA), “Thermohydraulic Relationships for Advanced Water Cooled Reactors,” IAEA-TECDOC-1203, April 2001, represent a comprehensive review of post-dryout heat transfer methods for water cooled reactors. NUREG/CR-6975, “Rod Bundle Heat Transfer Test Facility Test Plan and Design,” July 2010, summarizes the available single-tube and rod bundle data and existing modeling approaches.

As discussed by M. Andreani and G. Yadigaroglu, “Difficulties in Modeling Dispersed-Flow Film Boiling,” Wärme und Stoffübertragung, Volume 27, Number 1, pp. 37-49, 1992, the difficulties in the post-dryout heat transfer modeling are related to phenomenological characteristics of participating processes can be grouped into four major areas: (1) thermal non-equilibrium effects, (2) mechanical non-equilibrium effects, (3) flow history dependant heat transfer, and (4) sub-channel and spacer grid effects in fuel rod bundles. In addition, a major limitation is related to the area averaging aspect of any one-dimensional (1D) modeling approach that is used in LOCA analyses.

Thermal non-equilibrium effects are related to significant steam superheats have been measured in reflood experiments performed both with single-tube and rod bundle test sections. For example, Ghazanfari, A., Hicken, E.F., and Ziegler, A., “Unsteady Dispersed Flow Heat Transfer Under Loss-of-Coolant Accident Related Conditions,” Nuclear Technology, Vol. 51, pp. 21-26, November 1980, measured vapor superheat of 260 K (468 ºF) on average at the top of the test tube. More recent experiments by S.-Ki Moon et al., “An Experimental Study on Post-CHF Heat Transfer for Low Flow of Water in a 3x3 Rod Bundle,” Nuclear Engineering and Technology, Vol.37, No. 5, October 2005, also showed a significant degree of thermal non-equilibrium near the end of the heated length of a 3×3 test section. Mechanical non-equilibrium effects are related to the behavior of clusters of droplets in the continuous steam flow. M. Andreani and G. Yadigaroglu, “Effect of the Cross-Sectional Droplet Distribution in Dispersed Flow Film Boiling at Low Mass Flux,” Proceedings of the 5th International Topical Meeting on Reactor Thermal-Hydraulics (NURETH-5), Volume III, pp. 823-831, September 21-24, 1992, Salt Lake City, Utah, USA, discuss related effects on prediction results obtained with 1D models. A recent work by F. B. Cheung and S. M. Bajorek, “Dynamics of Droplet Breakup Through a Grid Spacer in a Rod Bundle,” Nuclear Engineering and Design, Vol. 241, pp. 236–244, 2011, focused on the dynamics of droplet breakup associated with the flow of a dispersed two-phase mixture through a rod bundle grid spacer during a PWR re-flood transient and presented new test data from the Rod Bundle Heat Transfer Test (RBHT) Facility.

Andreani and Yadigaroglu (1992) pointed out to modeling limitations related to the assumption of a uniform droplet distribution over the channel cross section. Importantly, it was recognized that 1D models can overestimate the interfacial heat transfer between vapor and droplets if a cross-section averaged temperature difference between vapor and droplets is used instead of a temperature difference based on a lower mean temperature of vapor in the central core region where droplets tend to reside. As a result, such models can fail to adequately predict the wall surface temperature particularly at low flow conditions of interest for DFFB modeling.

Please clarify the following items related to the method of calculating the dispersed flow film boiling heat flux in WCOBRA/TRAC-TF2.

(1) Explain what corrections and modeling features are applied in WCOBRA/TRAC-TF2 to overcome the major difficulties in modeling the dispersed flow film boiling with regard to both the interfacial and wall to fluid heat transfer processes. In addition, please explain how the limitation of the 1D approach stemming from the highly non-uniform steam temperature profile across the radial flow direction (maximum steam temperature near the wall with a cooler core region containing droplets) is rectified.

(2) The Forlsund-Rohsenow (1968) correlation is based on data for dispersed flow film boiling of nitrogen under the following conditions:

Mass flux:	70,000 to 190,000 lbm/ft^2-hr (94.9 kg/m^2-s to 257.7 kg/m^2-s)
Heat flux:	5,000 to 25,000 Btu/ft^2-hr (15.8 to 78.9 kW/m^2)
Test section inlet pressure:	25 psia (1.72 bar or 0.172 MPa)
Test section exit quality:	35 percent to 315 percent
Test section inner diameter:	0.228 in, 0.323 in, 0.462 in (5.79 mm, 8.20 mm, 11.73 mm)

Please present a table that includes typical ranges for conditions incurring during reflood dispersed flow film boiling in a PWR core and compare those against the Forlsund-Rohsenow (1968) test data conditions. Present comparison against data that are representative of prototypical reflood conditions to support the WCOBRA/TRAC-TF2 dispersed flow film boiling model for prediction of PWR reflood PCTs.

Heat transfer from a heated tube to dispersed steam-water flow under post-dryout conditions was studied experimentally by Ghazanfari, A., Hicken E., and Ziegler, A., "Unsteady Dispersed Flow Heat Transfer Under Loss-of-Coolant Accident Related Conditions," Nuclear Technology, Vol. 51, pp. 21-26, November 1980. The test conditions varied as follows:

Mass flux:	10,300 to 26,500 lbm/ft^2-hr (14 to 36 kg/m^2-s)
Heat flux:	5,400 to 13,300 Btu/ft^2-hr (17 to 42 kW/m^2)
Pressure:	17.4 to 23.2 psia (1.2 to 1.6 bar)
Inlet quality:	0.50 to 1.00.

As already mentioned, vapor superheat of 260 K (468 ºF) on average was measured at the top of the test tube in the tests. It was also concluded that the wall-droplet contribution to the total heat transfer rate was negligible at flow qualities greater than 50 percent.

The Forlsund-Rohsenow (1968) correlation is based on an equilibrium model where the bulk vapor temperature is assumed to be equal to the local saturation temperature. As such, its validity as a model basis for predicting direct contact heat transfer for the dispersed droplet field in WCOBRA/TRAC-TF2 is questionable. In addition, the use of this correlation above the quench front where the clad temperature is above the minimum stable film boiling temperature, T_{MIN}, and significant steam superheating can take place is considered inappropriate. Once the liquid droplets enter into the central flow region, there can be insufficient lateral momentum that is needed for them to penetrate the highly superheated boundary layer and reach the wall. As a result, the droplets will have little influence on cooling the fuel rod surfaces at locations above the quench front where the cladding temperature is in excess of T_{MIN}.

(3) Please explain why **[**

] Accordingly, an increased heat transfer rate could lead to under predicting the PCT. Such changes in the coding of relations in WCOBRA/TRAC-TF2 that are implemented without providing the underlying technical basis or discussing possible impact on prediction results of safety relevance are found unacceptable. Please explain this specific case and clarify if such an approach has been applied with regard to other constitutive relations coded in WCOBRA/TRAC-TF2. Present a table that documents such deviations in as coded expressions and the actions taken to rectify or substantiate each individual occurrence of such a modification.

(4) Please provide plots of WCOBRA/TRAC-TF2 prediction results for the parameters listed below for FLECHT SEASET Tests 31504, 35304, 31805, 34006, 34907, 35807, 34209, 34103, 33903, 31922, and 31108:

(a) forced convective heat transfer coefficient to vapor,
(b) grid enhancement multiplier, F_{grid},
(c) two-phase enhancement multiplier, $F_{2\phi}$,
(d) radiation heat transfer coefficient to vapor,
(e) radiation heat transfer coefficient to droplets,
(f) Forslund-Rohsenow drop-wall direct contact heat transfer coefficient,
(g) interfacial heat transfer coefficient between the drops and the vapor,
(h) droplet number and diameter,
(i) minimum stable film boiling temperature, T_{MIN}.

Plot the above parameters as function of time for the elevation of PCT occurrence and for two additional elevations located approximately two and four feet below the hot spot. In addition, please show the steam and liquid flow rates, void fraction, steam temperature, liquid temperature, and clad temperature as function of time at all three locations. Please plot also a comparison of the measured local PCT against the code predictions as a function of the vertical test bundle axis.

(5) Please provide plots of WCOBRA/TRAC-TF2 prediction results for the following FLECHT low flooding rate skewed power shape tests:

Parametric Effects:	Run Numbers:
Flooding rate (in/sec):	0.6, 0.8, 1.0, 1.5, 3, 6, 15606, 15305, 13404, 13303, 12102, 13001

Pressure (psia): 20, 40, 60	13609, 13404, 13711
Initial Cladding Temp (ºF): 500; 1,000; 1,600	12816, 12515, 13303
Subcooling (ºF): 5, 80, 140	15713, 13812, 13914
Peak Power (kW/ft): 0.45, 0.7, 1.0	11618, 13303, 16022
Initial (Variable) Flooding Rate:	15305, 15132, 15034

Include plots of the following quantities:
(a) forced convective heat transfer coefficient to vapor,
(b) grid enhancement multiplier, F_{grid},
(c) two-phase enhancement multiplier, $F_{2\phi}$,
(d) radiation heat transfer coefficient to vapor,
(e) radiation heat transfer coefficient to droplets,
(f) Forslund-Rohsenow drop-wall direct contact heat transfer coefficient,
(g) interfacial heat transfer coefficient between the drops and the vapor,
(h) droplet number and diameter,
(i) minimum stable film boiling temperature, T_{MIN}.

Plot the above parameters as function of time for the elevation of PCT occurrence and for two additional elevations located approximately two and four feet below the hot spot. In addition, please show the steam and liquid flow rates, void fraction, steam temperature, liquid temperature, and clad temperature as function of time at all three locations.

Present plots that show the parametric effects with regard to flooding rate, pressure, initial clad temperature, subcooling, peak power, and initial (variable) flooding rate on the WCOBRA/TRAC-TF2 capabilities to predict the FLECHT test data. Please plot also a comparison of the measured local PCT against the code predictions as a function of the vertical test bundle axial position.

(6) The WCOBRA/TRAC heat transfer from the fuel rod to the surrounding media does not consider rod-to-rod thermal radiation. Since the FLECHT and other heat transfer data contain thimbles, cooler neighboring rods, and wall bundle boundaries, etc. that absorb thermal radiation from the hot rod of interest, please explain how the convective heat transfer coefficient is extracted/determined from all test data where thermal radiation is a component heat transfer removal mechanism.

Question #57: Large Break LOCA Heat Transfer Package in WCOBRA/TRAC-TF2

Please provide a summary table that presents the core heat transfer package that is implemented in WCOBRA/TRAC-TF2 and as it is applied in the modeling of LBLOCA transients. Include five columns identifying LBLOCA phases, pre-CHF, CHF, transition boiling, and dispersed flow film boiling correlations. Provide the implemented relations for the three major post-LBLOCA phases blowdown, refill, and re-flood with each phase presented by a separate raw in the table. Include the corresponding expressions for each correlation as coded in WCOBRA/TRAC-TF2, the range of applicability of the correlation, and a typical range of flow and heat transfer conditions as occurring in a PWR core following an LBLOCA. Justify the applicability of each model for prototypical reactor core analyses.

Question #58: Flow Regime Map Selection Criterion for Vessel Component

The mixture level swell in the reactor core governs the fuel cladding temperature response in the late stages of a small or intermediate break LOCA when the reactor core can uncover. The WCOBRA/TRAC-TF2 vessel component relies on flow regime maps in modeling the two-phase flow behavior including the response of the reactor core region. WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 4, "WCOBRA/TRAC-TF2 Flow Regime Maps and Interfacial Area," explains that the code vessel component utilizes two different flow regime maps: (1) a "Normal Wall" or also referred to as a "Cold Wall" flow regime map and (2) a "Hot Wall" flow regime map. The former is applied when a momentum cell contains heated surfaces that are expected to be fully wetted by liquid and the latter is used to describe the hydrodynamics of highly non-homogeneous and thermally non-equilibrium two-phase flow that can take place during blowdown and reflood. Subsection 4.2, "Vessel Component Normal Wall Flow Regimes," explains that the criterion for selecting a flow regime map, defined by Equation (4-1), is based on the surface temperature of the heated structures present within a computational cell. As described in Subsection 4.2, the transitional temperature is set equal to "the surface temperature at the critical heat flux," T_{CHF}, approximated as $T_w=T_{CHF} \approx (T_{sat}+75)$ °F = $(T_{sat}+41.7)$ K and limited by the critical water temperature given as 705.3 ^{o}F (374.1 ^{o}C or 647.2 K). When the metal surface temperature exceeds the CHF criterion, it is assumed that the liquid can only partially wet the wall and the "Hot Wall" flow regime map is used. Below T_{CHF}, it is considered that the liquid fully wets the wall and the "Cold Wall" flow regime map is applied.

The "Cold Wall" flow regime map recognizes four different regimes: (1) SB with a flow regime indicator ISIJ of 1 (see Table 4.2-1, "Summary of Flow Regime Number in Vessel Components"), (2) SLB with ISIJ=2, (3) CT, and (4) FD with ISIJ=5. The "Hot Wall" flow regime map identifies five individual regimes: (1) Subcooled Inverted Annular, (2) Inverted Liquid Slug, (3) Dispersed Droplet, (4) Falling Film, and (5) Top Deluge with ISIJ=11. The selection of the vessel flow regime takes place in subroutine INTFR, which also computes the wall and interfacial drag coefficients.

(1) Please explain the appropriateness and provide the technical basis in support of the implemented criterion in Equation (4-1) for selection between the "Cold Wall" and the "Hot Wall" flow regime maps in two-phase flow modeling for the vessel component. Clarify if the WCOBRA/TRAC-TF2 applies the same modeling approach to both plant designs with top down cooling (i.e., Upper Plenum Injection (UPI) plants) and bottom up re-flood. As different validation/qualification processes apply to both designs, please describe the technical bases that demonstrate the applicability of the modeling approach for each plant design.

(2) As explained in Subsection 4.2, "It is assumed that for cells in which a metal surface temperature exceeds the criterion given by Equation (4-1), liquid can only partially wet the wall and the hot wall flow regime is used." The introduced phenomenological approach for flow regime map selection between the "Cold Wall" map and the "Hot Wall" map is based on surface wetting. At the same time, when surfaces are hot enough, liquid droplets are not expected to even partially wet the metal wall. Please clarity how the phenomenon of hot surface wetting relates to the flow map identification criterion defined by Equation (4-1).

(3) Please explain which heat transfer correlations are employed in WCOBRA/TRAC-TF2 to model partially wetted wall surfaces and describe the applicable technical basis. In particular, identify and describe the data used to validate the wetting of walls and related heat transfer when the wall surface temperature, T_w, is above the defined criterion for wall surface wetting.

(4) Please explain how the criterion defined by Equation (4-1) and the assumed approximation for the CHF surface temperature as $T_{CHF} \approx (T_{sat}+75)$ °F relate to the Leidenfrost wall temperature limit, T_{Leid}. A simple correlation for the Leidenfrost temperature used by Bricard et al. (see Bricard, P., Péturaud, P. and Delhaye, J. M., "Understanding and Modeling DNB in Forced Convective Boiling: Modelling of a Mechanism Based on Nucleation Site Dryout," Multiphase Science and Technology, No. 9, p. 329, 1997) gives $T_{Leid}=(T_{sat}+150)$ °C. Similarly, a range of Leidenfrost wall superheat of 100 to 150 °C is provided by Celata et al. (see Celata, G. P., Cumo, M., Mariani, A. and Zummo, G., "Burnout in subcooled boiling of water. A visual experimental study," Int. J. Therm. Sci., No. 39, pp. 896-908, 2000).

Question #59: WCOBRA/TRAC-TF2 Flow Maps for Vessel and One-Dimensional Components

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 4.2.2, "Small Bubble Regime," explains that the Small Bubble (SB) regime is applied when the two-phase flow void fraction is less than 20 percent. As such, it models what is generally referred to as "bubbly flow" in the two-phase flow literature. In this regime, the vapor phase is assumed to exist as uniform spherical bubbles dispersed in a continuous liquid phase. The bubble radius is determined by Equation (4-15) using a critical Weber number of 10 and applying the vector sum of the maximum lateral relative velocity and the axial relative velocity for the cell. According to Equation (4-16), the bubble diameter is limited to the cell hydraulic diameter or **[ ]** whichever is smaller.

According to WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 4.2.3, "Small to Large Bubble Regime," this regime is applied for void fractions greater than or equal to 20 percent and less than or equal to 50 percent. In the SLB regime, the vapor phase is modeled by a SB field accounting for 20 percent void fraction with the remaining vapor content being attributed to one or more large bubbles. The large bubble radius is determined by Equation (4-24) and it cannot be larger than the cell hydraulic diameter or **[ ]** according to Equation (4-23).

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 4.2.4, "Churn-Turbulent Flow Regime," explains that this regime is used when the void fraction is above 50 percent and remains below a certain critical void fraction at which a stable liquid film at the wall is formed. It is explained that this critical void fraction, determined by the flow channel size and the vapor velocity, is limited to a minimum void fraction of 80 percent as below this value waves are expected to bridge across the flow channel and cause a transition to CT flow. The CT regime as modeled as a combination of the Large Bubble and the FD regimes.

According to WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 4.2.5, "Film/Drop Flow Regime," this regime exists above a certain critical void fraction criterion. The liquid phase is present as a wall film and possibly droplets that can be entrained by the steam flow. The droplet diameter is determined by Equation (4-48) using the entrained liquid fraction and it is limited to **[** **]** Table 1 below presents major correlations used in the implementation of the “Cold Wall” flow regime map in WCOBRA/TRAC-TF2.

(1) Please demonstrate the applicability of the value used for the critical Webber number in Equation (4-15) to predict the diameter of the small bubble, D^*_b. Provide the units for the SB radius as defined by this equation. Define the range of applicability of this expression with regard to hydraulic diameter, pressure, phase mass flow rates, and void fraction, along with supporting test data. Explain how the vector sum of relative velocities between the vapor and continuous liquid phases, $\underline{U}_{vl}$, used in Equation (4-15), is calculated, and describe any limitations with regard to slip (velocity ratio). Please explain if Equations (4-15) and (5-60) define the same physical parameter.

(2) Equation (4-24) defines the large bubble diameter, D^*_{LB}, as being proportionate to the volume of the hydraulic computational cell, $\Delta V = A_X \Delta X$:

$$D^*_{LB} \sim (A_X \Delta X)^{1/3}.$$

Please explain the appropriateness of defining a physical parameter that is introduced to describe a phenomenon of relevance for the core two-phase level swell modeling by making this diameter dependent upon the fluid volume in a computational mesh cell. Nodalization can vary and so will the predicted value of the relevant physical parameter describing the phenomenon of interest. Such an approach can introduce uncertainties and nonphysical behavior in code predictions through artificial distortions of physical models used in the prediction of safety relevant thermal-hydraulic process. Please estimate the bounding effect on core level-swell prediction results. Define the range of applicability of this expression with regard to hydraulic diameter, pressure, phase mass flow rates, void fraction, and slip along with supporting test data.

Table 1: Major Correlations in the WCOBRA/TRAC-TF2 “Cold Wall” Flow Regime Map

Flow Regime	Void Fraction, α (%)	Bubble/Droplet Diameter or Film Thickness	Size Limitations	Flow Structure
Small Bubble	$0 < \alpha \le 20$	Small bubble diameter, Equation (4-15): $D^*_b=We_{crit}\sigma g_c/(\rho_l\underline{U}^2_{vl})+0.00002$ $\underline{U}_{vl}$ – vector sum of relative velocities between vapor and continuous liquid $We_{crit}=10$	D^*_b=Min (D_h ; 0.04 ft)	Small bubble only
Small-to-Large Bubble	$20 < \alpha \le 50$	Large bubble diameter, Equation (4-24): $D^*_{LB}=[3/(4\pi)(\alpha_v-V_{SB}/\Delta V)\Delta V]^{1/3}$ $\Delta V=A_X\,\Delta X$ – cell volume V_{SB} – volume of small bubbles	**[ ]**	Small and large bubbles
Churn-Turbulent	$50 < \alpha \le \alpha_{crit}$	Entrained droplet diameter, Equation (4-48): **[ ]**	**[ ]**	
Film/Drop	$\alpha_{crit} < \alpha \le 100$	Critical layer thickness and void, Equation (4-39): $\delta_{crit}=C_l\sigma/(\rho_v\lvert\underline{U}_{vl}\rvert^2)$ $\underline{U}_{vl}$ – relative velocity between continuous liquid and vapor $\alpha_{crit} = 1-4\delta_{crit}/D_h-\alpha_e$ $C_l=0.5$	$\alpha_{crit,\ min}$=80%	Liquid film and entrained drops, if any

(3) According to Equation (4-16), the bubble diameter in the SB regime is limited to 0.04 ft (0.48 in or 12.2×10^{-3} m) or to the hydraulic diameter. A typical fuel assembly has a hydraulic diameter of 0.045 ft (0.53 in or 13.6×10^{-3} m). Based on Equation (4-23), the large bubble diameter in the SLB or CT flow regimes cannot be larger than the cell hydraulic diameter or **[ ]** whichever is smaller. Accordingly, for a two-phase flow in a fuel bundle, the SB diameter would be limited to 0.04 ft (0.48 in or 12.2×10^{-3} m) and the large bubble diameter would be limited **[ ]**

Please explain the appropriateness and applicability of the applied limits for the diameters of the small and large bubbles. Please explain the technical basis for the **[ ]** limit for the large bubble diameter limit and its impact on two-phase level swell calculations.

(4) Equation (4-41) defines the critical film thickness used in the CT flow regime modeling. Please define the range of applicability of this expression with regard to hydraulic diameter, pressure, and phase mass flow rates along with supporting test data. Explain how the relative velocity between the continuous liquid and the vapor phase, $\underline{U}_{vl}$, used in Equation (4-41), is calculated. Explain how the entrained liquid fraction, α_e, appearing in Equation (4-41) and Equation (5-80), is calculated. Please clarify why the critical void fractions, as defined in Equation (5-93) in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.4, “Film/Drop Flow Regime,” and in Equation (5-127) in Subsection 5.6.2, “Entrainment in Film Flow,” do not take into account the entrained liquid fraction, α_e. Please address the threshold conditions for liquid entrainment and define the range of applicability of the correlations used to predict the entrained liquid fraction, α_e, with regard to hydraulic diameter, pressure, and phase mass flow rates, and void fraction along with supporting test data. In addition, please explain the way in which WCOBRA/TRAC-TF2 predicts the diameter of the entrained droplets, the number of droplets and the drop interfacial area density. Given these droplet diameters and associated interfacial areas, describe how this formulation is used in or related to the computation of interfacial heat transfer between the steam and liquid phases. Please explain if this model predicts entrained droplets leaving the two-phase surface and entering the steam region during periods of predicted core uncovery for small breaks in the order of 0.02 to 0.01 ft^2.

(5) WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.3, “Churn-Turbulent Flow Regime Interfacial Drag,” explains that “The churn-turbulent regime is assumed to be a combination of the large bubble regime and the film/drop regime.” Please explain how the CT flow is modeled in WCOBRA/TRAC-TF2 as a combination of LB and FD regimes. In particular, please explain the assumed forms of presence for each phase, e.g., small bubbles, large bubbles, droplets, slugs, continuous form.

(6) Please provide a table that describes constitutive correlations used for flow regime identification by the “Cold Wall” and “Hot Wall” flow maps for a vessel component and the flow regime map for the one-dimensional components in WCOBRA/TRAC-TF2. For each individual correlation, please provide information that describes the source reference, applicability range for defining parameters, extrapolations, and limitations outside of applicability ranges as appropriate, and the supporting technical basis including applicable test data and references to validation analyses. Include the flow regime indicator and number for each individual flow regime as Table 4.2-1 appears incomplete. In addition, please describe major differences in the modeling of corresponding flow regimes for the vessel and one-dimensional components.

Question #60: Pressurized Water Reactor Core Two-Phase Mixture Level and Sensitivity to Axial Nodalization

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.3, “WCOBRA/TRAC-TF2 Determination of the Mixture Level,” explains that “WCOBRA/TRAC-TF2 does not include a specific model or pointer to identify the exact location of the mixture level. Rather, mixture level tracking is accomplished through detailed nodalization.” It continues to say that “…the ability of WCOBRA/TRAC-TF2 to track a mixture level is dependent upon the axial noding. In the core, the typical height of a hydraulic cell is 10 to 12 inches." With regard to the WCOBRA/TRAC-TF2 axial core noding strategy, Subsection 26.1.2, "Modeling Consistency," of WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, explains that "the axial noding in a PWR core and in tests with simulated cores is established by the overall heated length and the location of spacer grids." According to noding details provided in Table 26.1-1, "Core Section Axial Cell Lengths," the PWR core models for V. C. Summer (CGE) and Beaver Valley Unit 1 (DLW), considered in Volume III, employed 14 axial cells with a minimum cell length of 7.78 in and 7.46 in, correspondingly, and a maximum cell length of 12.84 in. It is stated in Subsection 26.1.2 of WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, that "the average cell heights for all of the test models and the plant models fall within a narrow range."

NRC Regulatory Guide (R. G.) 1.157, Revision 0, "Best-Estimate Calculations of Emergency Core Cooling System Performance," requires that "sensitivity studies and evaluations of the uncertainty introduced by noding should be performed."

(1) Please describe assessment studies that have been performed to examine sensitivity effects related to core axial nodalization on the mixture level predictions by WCOBRA/TRAC-TF2 under conditions of interest for SBLOCA analyses. Results from such studies should include quantification of nodalization effects on core mixture level predictions and the resulting impact on peak clad temperature predictions in WCOBRA/TRAC-TF2 analyses of test facilities and plant SBLOCA transients.

(2) It is recognized that with cell heights of 10 – 12 inches, a very small quantity of liquid in the cell containing the two-phase level will cause the entire cell to saturate, thus greatly reducing the PCT as the mixture level is not tracked nor used to determine the axial elevation of the uncovered region in the core. Please explain the impact of cell height on PCT considering a cell containing the two-phase mixture surface when the mixture level is any small finite distance above the bottom interface of this cell. Given such possible circumstances and taking into account the fact that the two-phase mixture level is not tracked, it appears that finer axial nodalization involving many more cells is needed to properly capture the location of the two-phase mixture surface and the degree of superheat that is associated with the cell containing the mixture level once core uncovery begins.

Question #61: Oak Ridge National Laboratory Thermal Hydraulic Test Facility Mixture Level Predictions and Axial Nodalization Sensitivity

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.4.2, "ORNL-THTF Small Break Tests," presents WCOBRA/TRAC-TF2 prediction results for ORNL THTF tests. The analyzed tests include six bundle uncovery tests (3.09.10I, 3.09.10J, 3.09.10K, 3.09.10L, 3.09.10M, 3.09.10N) and six level swell tests (3.09.10AA, 3.09.10BB, 3.09.10CC, 3.09.10DD, 3.09.10EE, 3.09.10FF) described in NUREG/CR-2456 (March 1982).

Figure 13.4.2-3, “WCOBRA/TRAC-TF2 Model of the ORNL-THTF,” shows the noding of the WCOBRA/TRAC-TF2 model of ORNL THTF. **[**

]

Subsection 13.4.2.5, “WCOBRA/TRAC-TF2 Model of the ORNL-THTF,” also explains that “This section is divided into twelve axial nodes, in a manner consistent with the PWR core noding (Subsection 26.1.2, WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Volume III).” According to Table 26.1-1, “Core Section Axial Cell Lengths,” all cells have practically an identical axial length of 12 inches.

(1) Figures 13.4.2-4 through 13.4.2-15 show the results of WCOBRA/TRAC-TF2 void predictions for all 12 analyzed ORNL THTF bundle uncovery and level swell tests. Please explain how the predicted void profiles shown in these figures relate to Channel 2 and Channel 3 results in the described WCOBRA/TRAC-TF2 THTF model.

(2) Please provide results from a noding sensitivity study performed with WCOBRA/TRAC-TF2 when using “nominal” two-phase flow correlations (no bias or sampling) with the number of cells modeling the heated bundle length set to 24 and 48. The axial length of each cell in Section 2 of the ORNL THTF model shown in Figure 13.4.2-3 would amount to 6 and 3 inches, respectively. Include axial void fraction distribution, two-phase mixture level, and collapsed liquid level predictions as well as vapor and wall temperature profiles for the uncovered-bundle heat transfer tests. Compare the sensitivity results against those obtained with a cell height of 12 inches and presented in Figures 13.4.2-4 through 13.4.2-15 as well as against measured test data. In all comparisons, please use results that are representative for the entire test bundle flow area.

(3) In analyzing WCOBRA/TRAC-TF2 capabilities in predicting level swell, Section 13, “Core Void Distribution and Mixture Level Swell,” makes use of a mixture level swell parameter, S. This parameter is defined by Equation (13-1) through the two-phase mixture level, $Z_{2\Phi}$, the elevation where the liquid reaches the saturation point, Z_{SAT}, and the collapsed liquid level, Z_{CLL}, as follows:

$S=[(Z_{2\Phi}–Z_{SAT}) – (Z_{CLL}–Z_{SAT})]/(Z_{CLL}–Z_{SAT})$.

Please explain the way in which quantities $Z_{2\Phi}$ and Z_{SAT} are determined from code results and assess their uncertainties considering nodalization effects. Assess and provide the uncertainty of S that results from uncertainties associated with $Z_{2\Phi}$ and Z_{SAT}.

(4) Please provide code results for the two-phase mixture levels in the THTF test bundle that are determined with the assumption that the void fraction in the computational cell containing the two-phase mixture level is equal to the void fraction in the neighboring cell located flow upstream. Compare the computed two-phase mixture levels against the measured data. Include data uncertainty bars in the comparison figures.

Question #62: Oak Ridge National Laboratory Thermal Hydraulic Test Facility WCOBRA/TRAC-TF2 Detailed Prediction Results

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.4.2, "ORNL-THTF Small Break Tests," presents WCOBRA/TRAC-TF2 prediction results for ORNL THTF tests that included six bundle uncovery tests (3.09.10I, 3.09.10J, 3.09.10K, 3.09.10L, 3.09.10M, 3.09.10N) and six level swell tests (3.09.10AA, 3.09.10BB, 3.09.10CC, 3.09.10DD, 3.09.10EE, 3.09.10FF).

To illustrate the performance of WCOBRA/TRAC-TF2 two-phase flow models, including flow regime maps, employed by the vessel component to predict the thermal hydraulic response of the reactor core region, please provide code prediction results for two THTF bundle uncovery tests: 3.09.10J performed at 610 psia and 3.09.10M performed at 1,010 psia, and two level swell tests: 3.09.10AA at 590 psia and 3.09.10DD at 1,170 psia. For these tests, please provide code prediction results identified below and obtained with WCOBRA/TRAC-TF2 using "nominal" two-phase flow correlations (no bias or sampling) and the existing THTF model shown in Figure 13.4.2-3. Please include the following parameters: (1) predicted flow regime with flow regime indicator number, (2) pressure, (3) fluid phase temperatures, (4) wall temperature, (5) void fraction and its attributed components (e.g., SB, large bubbles, slugs, continuous field), (6) diameter and number of bubbles in each category (small, large), (7) liquid fraction and its attributed components (e.g., entrained drops, film, slugs, continuous field), (8) diameter and number of droplets, (9) phase mass flow rates for each field, and (10) phase velocities for each field and relative velocities as used in any related constitutive equation, e.g., Equation (4-15).

Please present the results in a table format for each of the twelve cells or associated interfaces, as appropriate, with the cells listed in the first column and each of the above parameters provided in a separate column. Please provide results that are representative for the entire test bundle cross sectional flow area based on results for individual channels.

Question #63: Interfacial Drag Correlations in WCOBRA/TRAC-TF2

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4, "Vessel Component Interfacial Shear Models," describes the relationships used in WCOBRA/TRAC-TF2 to quantify interfacial friction forces between flow fields in various two-phase flow regimes by means of interfacial drag coefficients. The interfacial drag forces appear in the vessel component momentum conservation equations described in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 3. The interfacial drag coefficients are calculated in subroutine INTFR to yield the average interfacial drag force per unit length when multiplied by the new time velocity difference between the fluid phases. Thus, Equation (5-42) defines the average interfacial drag force, F_D, exerted on the continuous liquid phase by vapor per unit length along the X axis, $F_D / \Delta X = \tau'_{iX,\,vl}$, as a product of the flow regime dependent interfacial drag coefficient, $K_{iX,\,vl}$, and the axial relative velocity between the vapor and the continuous liquid, $\underline{U}_{vl}$:

$$F_D / \Delta X = \tau'_{iX,\,vl} = K_{iX,\,vl}\ \underline{U}_{vl}\ .$$

Thus defined dimensional drag coefficient, $K_{iX,\,vl}$, is calculated using a dimensionless drag coefficient, C_D, commonly used in the literature. Equation (5-45) provides the relationship between $K_{iX,\,vl}$ and C_{Db} for a bubbly flow as:

$K_{iX,\,vl} = C_{Db}\ \rho_l\ \underline{U}_{vl}\ A_{P,b} / 2\Delta X$,

where $A_{P,b}$ is the total projected area of all bubbles in the volume. From the above equations, the drag force, F_D, is obtained from the dimensionless drag coefficient, C_{Db}, and relative velocity, $\underline{U}_{vl}$:

$F_D = C_{Db}\ \rho_l\ \underline{U}_{vl}\ |\underline{U}_{vl}|\ A_{P,b} / 2$.

Subsections 5.4.1 through 5.4.4 present the WCOBRA/TRAC-TF2 approach to interfacial drag calculation for vessel component "Cold Wall" two-phase flow regimes. Table 1 summarizes this modeling approach.

Table 1: WCOBRA/TRAC-TF2 Approach to Interfacial Drag for Vessel Component "Cold Wall" Two-Phase Flow Regimes

Flow Regime	Void Fraction α (%)	Major Constitutive Correlations	Note
Small Bubble	$0 < \alpha \leq 20$	$C_{Db} = 24/Re_b\ (1+0.1Re_b^{0.75})$ $C_{Db} = (2/9)^{1/2}\ N_\mu\ Re'_b\ (1-\alpha_v)^2$ $C_{Db} = (8/3)\ (1-\alpha_v)^2$ $C_{Db} = 0.45\ (1-\alpha_v)^2$	Equation (5-50) Equation (5-53) Equation (5-57) Equation (5-58)
Small-to-Large Bubble	$20 < \alpha \leq 50$	$C'_{Db} = C_{Db}\ (1-\alpha_v)^2$ Interpolation between small bubble drag at 20% void and large bubble drag at 50% void.	Equation (5-71)
Churn-Turbulent	$50 < \alpha \leq \alpha_{crit}$	Interpolation between large bubble drag at 50% void and film/drop interfacial drag.	Equation (5-78)
Film/Drop	$\alpha_{crit} < \alpha \leq 100$	$f_{i,W} = 0.005[1+75(1-\alpha_v)]$ **[ ]**	Equation (5-92)

In a SB regime, the interfacial drag between the continuous liquid and the vapor is calculated from Equations (5-67a). For a SLB regime, the interfacial drag between the continuous liquid and vapor is calculated by interpolation between the SB drag at 20 percent void and the Large Bubble (LB) drag at 50 percent void in accordance with Equations (5-74a) and (5-74b). Similarly, for a CT flow, the drag is assumed to be a linear combination between the LB drag and the FD drag according to Equation (5-78). In a FD regime with a stable liquid film, the interfacial friction factor is calculated using Equation (5-92). In the case of an unstable wall film, **[**

]

(1) WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, does not provide a complete description of individual interfacial drag correlations as implemented in the vessel component interfacial shear models. Thus, WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, does not define applicability ranges for individual interfacial drag correlations nor does it provide supporting data and analysis that demonstrate the technical bases for individual models. Important description characteristics include, among others, applicability ranges for participating parameters, possible extrapolation beyond ranges for which correlations were developed or assessed and associated limitations, availability and quality of supporting test data and validation analyses, relevant source references as appropriate. Please provide a table that describes the interfacial drag correlations implemented in the two-phase flow regimes of the vessel component "Cold Wall" flow map. For each individual constitutive correlation, please describe the following items: (1) expressions for the dimensionless drag coefficient for an individual flow element (bubble, droplet, slug, film) in a form allowable to calculate drag force using element's characteristics such as projected cross-sectional or interfacial area and an appropriate relative velocity, (2) source references as appropriate, (3) applicability ranges for defining parameters, (4) extrapolation outside of applicability ranges as applicable and associated limitations, (5) qualified available test data, and (6) references to validation analyses.

Please include description for each item (1) to (6) above in a separate column with each constitutive correlation described in a separate raw. Closure relations that are based on interpolation between distinct constitutive correlations should be provided at the end of the table following the description of all other constitutive correlations. Please define all participating quantities including participating dimensionless numbers, thermodynamic fluid properties, and experimentally determined parameters. State and explain code implementation assumptions including phenomenological considerations related to treatment of characteristic sizes (e.g., bubble diameter or film thickness), ensemble numbers (e.g., number of drops or bubbles), distributions and categories (e.g., size distribution, large versus small bubbles). Please identify any quantities that are nodalization or input dependant or have other implementation conditions and restrictions.

(2) Please provide information for the interfacial drag constitutive correlations implemented in the two-phase flow regimes of the vessel component "Hot Wall" flow map as requested in item (1) above for the "Cold Wall" flow map.

(3) Please provide information for the interfacial drag constitutive correlations implemented in the drag models considered in Subsection 5.7, "One-Dimensional Component Interfacial Drag Models," for the one-dimensional component flow map as requested in item (1) above for the vessel component "Cold Wall" flow map.

(4) Please provide the information related to items (1) to (3) above using a consistent nomenclature set with units for included dimensional parameters.

Question #64: Interfacial Area in Inverted Slug Flow

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.6, "Inverted Liquid Slug Regime," explains that for the liquid slug regime "the interfacial area is calculated assuming that the liquid slugs are spherical, and have a diameter

[ ] of the channel diameter, as described in WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Section 4.3.3. The interfacial area is specified in Equation (5-104) as:

$A_{i,IVS} = 4A_X\alpha_l / D_h$.

Assuming that the above expression provides the interfacial slug area per unit length along the X axis, the volumetric concentration for the slug interfacial area is obtained from Equation (5-104):

$A'''_{i,IVS} = A_{i,IVS} / A_X = 4\alpha_l / D_h$.

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 4.3.3, "Inverted Liquid Slug Flow Regime," estimates the interfacial area for the liquid slugs making the same assumption that continuous liquid slugs are spherical. An expression for the volumetric interfacial area concentration is provided in Equation (4-58):

$A'''_{i,S} = 6\alpha_l / D_S$.

Using the assumption that "the slugs have a diameter **[ ]**" the volumetric concentration for the slug interfacial area is provided in Equation (4-59):

[ ]

The above assumed slug diameter of **[ ]** is practically identical to a slug diameter of "**[ ]** of the channel diameter" used in WCAP-16996-P/ WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.6.

From the above expressions for the volumetric concentration for the slug interfacial area, the ratio of the volumetric concentration for the slug interfacial area provided in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 4.3.3, Equation (4-58) to the same quantity given in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.6, Equation (5-104) is determined to be:

[ ]

Please explain why the slug interfacial area volumetric concentrations for the Inverted Liquid Slug flow regime, as defined in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 4.3.3, "Inverted Liquid Slug Flow Regime," and Subsection 5.4.6, "Inverted Liquid Slug Regime," differ by **[ ]** Please take into consideration that it appears, as discussed above, that practically identical assumptions have been introduced and used for determining the slug interfacial area volumetric concentrations in both subsections.

Question #65: Interfacial Drag for Inverted Slug Flow

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.6, "Inverted Liquid Slug Regime," defines the interfacial drag coefficient for this "Hot Wall" flow regime in Equation (5-103):

$K_{iX,IVS} = f_{i,IVS}\, \rho_v\, |\underline{U}_{vl}|\, A_{i,IVS}$.

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.6 explains that the interfacial friction factor "is calculated assuming an unstable liquid film surface exists on the large liquid ligaments or drops." To account for such flow conditions, the friction factor is assumed to be a factor **[ ]** compared to the friction factor for stable liquid films defined in Equation (5-92) for the FD flow regime. Thus, Equation (5-102) provides the interfacial friction factor for Inverted Slug flow as:

[ ]

The interfacial slug area per unit length of the flow is defined in Equation (5-104):

$A_{i,IVS} = 4A_X\alpha_l / D_h$.

Further, Equation (5-105) calculates the interfacial drag coefficient, $K_{iX,vl,IVS}$, as the maximum value from two different expressions as follows:

[ ]

(1) Please provide the technical basis for calculating the interfacial friction factor for unstable liquid films for Inverted Slug flow. In particular, please explain the basis for the assumed factor of **[ ]** between the Inverted Slug liquid film friction coefficient, $f_{iX,IVS}$, given by Equation (5-102), and the annular film friction coefficient, $f_{i,W}$, defined by Equation (5-92).

(2) Equation (5-105) that defines the interfacial friction factor in Inverted Slug flow $K_{iX,vl,IVS}$, as the maximum value from two expressions. As given, the first expression is provided by Equation (5-104), which defines the interfacial slug area as discussed above. At the same time, the second expression:

[ ]

does not include a relative velocity $|\underline{U}_{vl}|$, which is used in defining the interfacial drag coefficient, according to Equations (5-81), (5-103) and others. Please explain this apparent inconsistency. If necessary, please make corrections and provide justifications.

(3) The interfacial drag coefficient is denoted in Equation (5-103) of WCAP-16996-P/ WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.6 as $K_{iX,IVS}$ and, in Equation (5-105), as $K_{iX,vl,IVS}$. Please explain if both notations refer to the same parameter and, if so, why the nomenclature is not consistent.

Question #66: Annular Film Flow Interfacial Drag

In a FD flow regime, the interfacial drag “between the vapor and continuous liquid for the wetted wall film flow regime” is calculated from Equation (5-81) in WCAP-16996-P/ WCAP-16996-NP, Volumes I, II and III, Revision 0, Subsection 5.4.4, “Film/Drop Flow Regime: Model Basis”:

[ ]

The subsection clarifies that “when the vapor content in the flow exceeds a critical void fraction, and the wall is below the wetted wall temperature criteria, the film is assumed to become stable and liquid can no longer bridge the channel.”

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.4, “Film/Drop Flow Regime: Model as Coded,” defines the interfacial drag also in Equation (5-94) as follows:

[ ]

The interfacial drag coefficient in the Falling Film regime of the “Hot Wall” flow map, $K_{iX,lv,FF}$, provided in Equation (5-114) in Subsection 5.4.8, “Falling Film Flow Regime,” of WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, is defined in a way consistent with Equation (5-94) above.

[

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[ ]

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(1) As Equation (5-81) and Equation (5-94) apparently define the same interfacial drag quantity, please clarify if the parameters appearing on the right-hand side of these two equations and standing for the interfacial friction factor, relative velocity and interfacial area are defined in the same manner and mean the same physical quantity. If this is the case, please explain why different nomenclature is used in both equations. Please examine the nomenclature and revise as needed so that it is appropriately consistent throughout Volume I of the WCAP-16996-P/ WCAP-16996-NP, Volumes I, II, and III, Revision 0 TR.

(2) If Equation (5-81) and Equation (5-94) define the same interfacial drag quantity, please explain why the interfacial drag from Equation (5-81) and that from Equation (5-94) differ by a factor of 2:

[$K_{iX,vl,FD}$ from Equation (5-94)] / [$K_{iX,vl,FD}$ from Equation (5-81)] = 2.

(3) Please provide the ranges of applicability for the interfacial friction factors as given by Equation (5-92) and attributed to stable films in annular flow and by Equation (5-86) and attributed to unstable films in co-current and countercurrent film flow. Please define the applicability range for each participating parameter. Describe the test conditions for the data that were used to develop these two correlations. Please compare these applicability ranges to typical flow conditions of interest for PWR LOCA analysis.

(4) Please provide the technical basis for calculating the interfacial friction factor for unstable liquid films using Equation (5-90) as described in Subsection 5.4.4, "Film/Drop Flow Regime: Model as Coded."

(5) According to WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.4, "Film/Drop Flow Regime: Model as Coded," the interfacial friction factor for unstable films is defined as **[** **]** At the same time, WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.6, "Inverted Liquid Slug Regime," defines the interfacial friction factor in the case of an unstable liquid film surface as **[ ]** times the annular flow friction factor defined in Equation (5-92) for stable liquid films in the FD flow regime. Please explain this discrepancy and compare the relevant technical bases used to demonstrate the validity of WCOBRA/TRAC-TF2 interfacial drag models for unstable liquid films as implemented in the FD flow of the "Cold Wall" flow regime map and in the Inverted Slug flow of the "Hot Wall" flow map.

(6) Please describe availability and quality of test data, describing two-phase film flow, and any supporting analyses performed to demonstrate the applicability of WCOBRA/TRAC-TF2 interfacial drag models for FD flow prediction. Identify references for such validation analyses, if available, including source references for applied film flow test data. Present comparisons between model predictions for the friction factor and test data under typical conditions of relevance to PWR LOCA analyses.

Question #67: Bubbly Flow Interfacial Drag "Ramping" to "Hot Wall" Inverted Annular Drag

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.1, "Small Bubble Flow Regime Interfacial Drag," explains that in a SB regime of the "Cold Wall" flow map, the interfacial drag is calculated by interpolation between the SB value and the value for an Inverted Liquid Slug regime of the "Hot Wall" flow map "if there is significant vapor generation at the wall." To account for the presence of "significant vapor generation at the wall," the interfacial drag coefficient, $\overline{K}_{iX,vl,SB}$, is computed from Equation (5-67b) by interpolating or "ramping" between the drag coefficient for SB flow,

$K_{iX,vl,SB}$, given by Equation (5-67a), and the drag coefficient for Inverted Annular regime of the "Hot Wall" flow map, $K_{iX,vl,HW}$, defined by Equation (5-105):

[ ]

In the above equation, the interpolated drag coefficient is multiplied by the ratio of the limited relative velocity, U_r, found in Equation (5-66), to the absolute value of the axial relative phase velocity, $|\underline{U}_{vl}|$. The dimensionless interpolation factor, F_Γ, is calculated from Equation (5-68) using the terminal relative velocity, U_{rb}, between a bubble with a Webber number of 10 and the liquid as determined by Equations (5-59) and (5-60):

[ ]

The axial vapor velocity accounting for vapor generation in a computational cell, U_Γ, is calculated from Equation (5-69) as follows:

[ ]

In the above equation, α_v is the vapor void fraction with an upper limit of 0.2 for SB flow, ρ_v is the vapor density, A_X is the is the cell momentum flow area in the axial direction, and Γ_v is the interfacial vapor generation rate for the cell calculated in accordance with Equation (6-101). Q_{wl} is the rate of heat transfer between the wall and the combined liquid fields (continuous liquid and entrained liquid) and Q_b is the rate of heat transfer at the wall that results in vapor generation from subcooled boiling. Both hest transfer rates correspond to the entire node surface area present in a computational cell.

(1) To take account for "significant vapor generation at the wall," WCOBRA/TRAC-TF2 computes the interfacial drag coefficient for the SB regime, $\overline{K}_{iX,vl,SB}$, through interpolation between a bubbly flow drag coefficient calculated without the assumption of vapor film existence at the wall, $K_{iX,vl,SB}$, and a drag coefficient for "Hot Wall" Inverted Annular flow, $K_{iX,vl,HW}$. The dimensionless interpolation factor, F_Γ, accounts for wall heat transfer and associated vapor generation through a velocity parameter U_Γ. The rate of vapor generation at the wall surface in the cell is divided by the void fraction, α_v, and axial momentum flow area, A_X, to compute an equivalent axial vapor velocity, which is used to determine U_Γ. As U_Γ and F_Γ are based on the vapor generation rate at wall surfaces associated with a certain cell size, these parameters are nodalization dependant. Thus, for a cell in the core region with a defined axial area, A_X, the interfacial vapor generation rate, Γ_v, the wall heat transfer rates, Q_{wl} and Q_b, are dependent on the axial cell length, ΔX:

    $\Gamma_v \sim \Delta X$, $Q_{wl} \sim \Delta X$, $Q_b \sim \Delta X$.

    Accordingly, F_Γ and $\overline{K}_{iX,vl,SB}$ will depend on ΔX: $U_\Gamma \sim \Delta X$ and $\overline{K}_{iX,vl,SB} \sim \Delta X$. Please demonstrate that the implementation of nodalization dependant parameters in the WCOBRA/TRAC-TF2 interfacial drag model for SB flow is appropriate considering the intended purposes of obtaining best estimate code predictions. Provide results from relevant sensitivity studies examining the effect of noding.

(2) Please provide the technical basis that demonstrates the applicability of the interpolation correlation in Equation (5-67b) and used for "ramping" the SB flow drag

coefficient in the presence of “significant vapor generation at the wall,” $\overline{K}_{iX,vl,SB}$, and define the applicability conditions for this correlation:

[ ]

Define the validity ranges for the parameters used to calculate it from the above equation. Please clarify if such “ramping” technique is also applied to surfaces associated with passive heat structures.

(3) Please provide the technical basis that demonstrates the applicability of the correlation for computing the dimensionless interpolation factor, F_Γ, defined by Equation (5-68):

[ ]

Define the acceptable range for F_Γ and the validity ranges for the parameters used to calculate it from the above equation.

(4) The axial vapor velocity accounting for vapor generation in a computational cell, U_Γ, is calculated from Equation (5-69) using the minimum of two quantities. Accordingly, under saturated liquid boiling conditions when vapor is being generated only at the wall surface, the lack of interfacial vapor generation rate in a cell will produce a zero outcome for U_Γ regardless of the wall vapor generation. Please explain the appropriateness of the relationship defined by Equation (5-69) and used to calculate U_Γ and demonstrate its applicability.

Question #68: Approach to Interfacial Drag “Ramping” Between “Cold Wall” and “Hot Wall” Regimes

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.1, “Small Bubble Flow Regime Interfacial Drag,” states that in a SB regime of the “Cold Wall” flow map, the interfacial drag is calculated by interpolation between the SB value and the value for an Inverted Liquid Slug regime of the “Hot Wall” flow map “if there is significant vapor generation at the wall.” It is explained that the “Hot Wall” drag coefficient used for the purpose of SB flow drag “ramping” is calculated from Equation (5-105). Equation (5-67b) defines how the interfacial drag is “ramped:”

[ ]

Subsection 5.4.2, “Small-to-Large Bubble Flow Regime Interfacial Drag,” clarifies that “for conditions in which there is a large vapor generation rate at the wall, the bubble drag coefficient is ramped to the interfacial drag used in the hot wall flow regime.” It is explained that the “Hot Wall” drag coefficient used for the purpose of SLB flow drag “ramping” is calculated from Equation (5-106). The SLB drag “ramping” is performed according to Equation (5-73):

[ ]

According to Subsection 5.4.3, “Churn-Turbulent Flow Regime Interfacial Drag,” interfacial drag ramping is applied for the CT flow regime as well.

It is explained that "The same ramp as in Section 5.4.2 of WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, is applied to consider the vapor generation rate at the wall-by-wall heat transfer."

Table 1 below summarizes the approach to interfacial drag "ramping" used in various flow regimes modeling by WCOBRA/TRAC-TF2.

Table 1: Approach to Interfacial Drag Ramping Between "Cold Wall" and "Hot Wall" Flow Regimes in WCOBRA/TRAC-TF2 Vessel Component

"Cold Wall" Flow Regime	Drag Ramping Criterion	"Hot Wall" Regime Cited in Ramping	Referenced "Hot Wall" Drag Coefficient
Small Bubble	"Significant vapor generation at the wall"	Inverted Liquid Slug	Equation (5-105). Related drag factor: **[** **]** (Equations (5-92) and (5-102))
Small-to-Large Bubble	"A large vapor generation rate at the wall"	Dispersed Droplet	Equation (5-106). Related drag factor: $K_{iX,ve,DD} = 0.375\ C_{Db}\alpha_v\rho_v\lvert\underline{U}_{ve}\rvert/r_b$ **[ ]** (Equations (5-106) and (5-108))
Churn-Turbulent	"The vapor generation rate at the wall-by-wall heat transfer"	Dispersed Droplet	Equation (5-106). Related drag factor: $K_{iX,ve,DD} = 0.375\ C_{Db}\alpha_v\rho_v\lvert\underline{U}_{ve}\rvert/r_b$ **[ ]** (Equations (5-106) and (5-108))

(1) Interfacial drag "ramping" between "Cold Wall" and "Hot Wall" drag coefficients is used to account for wall vapor generation in modeling SB, SLB, and CT two-phase flow regimes when recognized by the "Cold Wall" flow map. In the case of SB flow, film drag for "Hot Wall" Inverted Liquid Slug flow, as suggested by Equation (5-105), is used to "ramp" the bubbly flow drag as described in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.1.

In contrast to this approach and as explained in Subsections 5.4.2 and Subsection 5.4.3, interfacial drag for both SLB and CT flow regimes is "ramped" using droplet drag for entrained liquid droplets in "Hot Wall" Dispersed Droplet flow defined by Equation (5-106) and calculated using **[**
] which is representative for a solid sphere in the Newton regime at high Reynolds numbers.

Please clarify this modeling disparity. If Subsection 5.4.2 erroneously refers on page 5-20 to Equation (5-105) instead of Equation (5-106), please provide a proper modeling description. Otherwise, please justify the difference in the modeling approaches.

(2) Please explain the technical rationale behind interfacial drag ramping for "Cold Wall" SB, SLB, and CT flow regimes using interfacial drag defined for "Hot Wall" flow regimes. Present supporting phenomenological considerations and refer to specific

experimental observations and data. Please provide and explain the criterion used for detection of “significant vapor generation at the wall” in SB flow and that applied for identification of “a large vapor generation rate at the wall” in SLB flow. In the case of CT flow, please define and explain the criterion used to identify the need “to consider the vapor generation rate at the wall-by-wall heat transfer” and clarify the meaning of the expression “vapor generation rate at the wall-by-wall heat transfer” on page 5-21 in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.3.

(3) Please explain if the criteria for recognition of “significant vapor generation at the wall,” as considered in item (2) above, were used to classify existing two-phase flow data sets into separate groups that can be used to validate “Cold Wall” interfacial drag models with no drag ramping, such that are appropriate for “Hot Wall” interfacial drag model validation, and data sets that are applicable for validation of “Cold Wall” interfacial drag models with drag ramping. Please provide references to such validation analyses, if available, and summarize analysis results that demonstrate the applicability of the applied interfacial drag “ramping” approach in WCOBRA/TRAC-TF2 for each individual flow regime. Please present comparisons of code predictions obtained with interfacial drag “ramping” being present and absent against void fraction data measurements. In particular, consider an appropriate data set for which interfacial drag “ramping” is supposed to be applied and present code comparisons obtained with and without drag “ramping” versus measured data.

Question #69: Calculation Results for Bubbly Flow Interfacial Drag

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.1, “Small Bubble Flow Regime Interfacial Drag,” refers to Figure 5-3(a), “Effect of Ramps on Interfacial Friction Factor: (a) SB Regime,” as an illustration of the effect of ramps and limits, described in this subsection, on the interfacial drag for the SB flow regime. The figure plots a quantity denoted K_i referred to as “interfacial drag factor” versus relative velocity U_v-U_l. It is explained that the drag factor is plotted in Figure 5-3(a) for “typical fluid conditions.” As seen from the graph, the two-phase flow conditions correspond to a SB flow regime with a vapor void fraction of α_v=0.1 and a pressure of 40 psia (0.276 MPa). The plot depicts four curves for the interfacial drag factor calculated at different cell vapor generation rates that correspond to values of 0, 1, 1.1, and 1.2 for the ratio between the axial velocity of vapor generation in a computational cell and the terminal relative velocity, U_Γ/U_{rb}.\

Figure 5-3(a), “Effect of Ramps on Interfacial Friction Factor: (a) SB Regime,” does not provide units for both plotted quantities: the interfacial drag factor, K_i, and the relative velocity, U_v-U_l. The figure also does not include geometric characteristics that describe channel geometry, heated surfaces and cell nodalization parameters nor does it define inlet and boundary conditions related to mass flow rates and surface heat flux. As such, the results presented in the figure are not amenable to assessment.

(1) Please provide, in a table format, prediction results presented in Figure 5-3(a) to document the following information: (i) parameter, (ii) unit, (iii) correlation used to calculate the parameter, (iv) range of applicability, (v) values and units for input parameters, and (vi) calculated result. Include each of the indentified items in a separate column and use a separate raw to present individual parameters. Analyze

and include results for three U_{Γ}/U_{rb} ratio values of 0, 1, and 1.2. Please provide the results at relative velocities equal, in units used for the horizontal axis in Figure 5-3(a), to 0 (or an appropriately defined low value), 0.5, the value at which the gradient of the curves, shown in Figure 5-3(a) for U_{Γ}/U_{rb} of 0, 1, and 1.1, changes a sign from positive to negative (value appears very close to unity), and 10. Please include the results for $K_{iX,vl,SB}$, $K_{iX,vl,HW}$, and $\overline{K}_{iX,vl,SB}$, as computed from Equations (5-67a), (5-105), and (5-67b). The numerical results provided should be self-contained and allow for independent verification of the values. For this purpose, all applied inlet and boundary conditions need to be given along with other assumed parameters such as bubble diameter or terminal relative velocity. Please include used fluid properties as well.

(2) Using the obtained results for $\overline{K}_{iX,vl,SB}$ from Equation (5-67b), please calculate and provide the values for the corresponding dimensionless drag coefficient, $\overline{C}_{Db}$, that is commonly used in the relevant literature to calculate drag force for a single dispersed element through its projected cross-sectional area and continuous phase kinetic head corresponding to the relative velocity. To obtain $\overline{C}_{Db}$, please use the general form of the interfacial drag coefficient for bubbly flow as given by Equations (5-45) and (5-67a):

[ ]

In addition, please calculate the dimensionless drag coefficient, C_{Db}, which corresponds to the drag coefficient, $K_{iX,vl,SB}$, determined from Equation (5-67a) prior to "ramping" in order to account for "significant vapor generation at the wall:"

[ ]

Include the results for $\overline{C}_{Db}$, C_{Db}, and $f_{iX,IVS}$ in the tables prepared according to item (1) above.

(3) Please provide figures that plot the results for the following parameters as functions of the relative velocity, U_v-U_l, including the units for the displayed quantities: (1) "ramped" dimensionless drag coefficient, $\overline{C}_{Db}$, (2) uncorrected for wall vapor generation dimensionless drag coefficient, C_{Db}, (3) interfacial friction factor for "Hot Wall" Inverted Liquid Slug flow, $f_{iX,IVS}$, as applied in bubbly flow drag "ramping," (4) $K_{iX,vl,SB}$ drag coefficient, (5) $K_{iX,vl,HW}$ drag coefficient, and (6) $\overline{K}_{iX,vl,SB}$ drag coefficient.

(4) Please provide results for the WCOBRA/TRAC-TF2 interfacial drag model for the vessel component SLB flow regime by providing prediction results as requested in items (1) through (3) above for SB flow. Apply the same conditions as those used to produce Figure 5-3(b), "Effect of Ramps on Interfacial Friction Factor: (b) Large Bubble Regime."

(5) Please provide results for the WCOBRA/TRAC-TF2 interfacial drag model for the vessel component CT flow regime by providing prediction results as requested in items (1) through (3) above for SB flow. Apply the same conditions as those used to produce Figures 5-3(a) and 5-3(b) except for using a void fraction of 0.6 instead of 0.1 and 0.4, respectively.

Question #70: Film Flow Drag Assessment Using Thermal Hydraulic Test Facility Test Data

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5, “Interfacial Drag in the Core Region,” presents the treatment of film flow interfacial drag in WCOBRA/TRAC-TF2 uncertainty assessments. It is explained that “The FDRAG multiplier is the sole contributor for void fractions α_v greater than α_{crit} ~0.8.” In addition, “in the interpolation region between the small and small-to-large bubbly flow regime ($\alpha_v < 0.5$) and the annular film flow regime ($\alpha_v > \alpha_{crit}$ ~0.8) both YDRAG and FDRAG have an effect.” According to WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5, the film drag multiplier, FDRAG, is applied directly to the interfacial drag as calculated for the FD flow regime using Equation (5-81) in Subsection 5.4.4, “Film/Drop Flow Regime: Model Basis”:

[ ]

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.4.2, “ORNL-THTF Small Break Tests,” explains that “the parameter FDRAG has been introduced to facilitate WCOBRA/TRAC-TF2 ranging of film interfacial drag, which tends to impact the drag most significantly in the transition and annular flow regimes. It is specified on an individual cell basis.” The subsection also describes the approach to determining FDRAG in plant calculations. It involved sensitivity calculations performed with WCOBRA/TRAC-TF2 for 12 ORNL THTF tests. The FDRAG sensitivity studies included 6 bundle uncovery and 6 level swell tests as summarized in Table 1.

Table 1: ORNL THTF Tests Used in FDRAG WCOBRA/TRAC-TF2 Sensitivity Analysis

Test Facility	Test Bundle	Test Runs	Number and Type of Test Runs		FDRAG and Number of Test Runs Analyzed	
			Bundle Uncovery	Level Swell	**[ ]**	**[ ]**
ORNL THTF	8×8	12	6	6	12	12

The WCOBRA/TRAC-TF2 void fraction predictions with **[ ]** are compared against ORNL THTF bundle void fraction measurements in Figures 13.4.2-4 through 13.4.2-15. From the results predicted in these figures, it was concluded **[**

] It is also explained that **[**

]

(1) Figures 13.4.2-4 through 13.4.2-15 contains 9 measured void fraction data points for each of the analyzed THTF test runs. Please identify the void fraction data points measured in these THTF tests, for which WCOBRA/TRAC-TF2 predicts an annular flow configuration with a stable liquid film at the wall based on the interfacial drag

model and document the data in a table. For each point, provide the measured void fraction value, void fraction measurement uncertainty (shown in Figures 13.4.2-4 through 13.4.2-1), corresponding liquid, vapor and entrained liquid mass flow rates, liquid film thickness, criteria used to identify the data points, such as α_{crit} and entrained liquid fraction, α_e, along with their numerical values, predicted nominal interfacial drag coefficient, f_i. Include corresponding void fraction predictions for **[** **]** Please document each data point in a separate row and present the above identified quantities in separate columns. Please provide a plot comparing predicted void fractions (with **[** **]**) versus measured data showing void fraction measurement accuracy. Please explain why the identified data points were considered representative of a stable film configuration. Please apply the nominal YDRAG value (YDRAG=1) in code predictions. In a separate table, please compare the flow conditions characterizing each measured data point against the applicability range for the interfacial drag correlations used in the code void fraction predictions.

(2) Please identify the measured void fraction data points in the analyzed THTF test runs, for which the unstable liquid film model was used in predicting the interfacial drag coefficient. For these data points, please provide the information as requested in item (1) above for annular flow with a stable liquid film at the wall. Please apply the nominal YDRAG value (YDRAG=1) in code predictions and provide a separate table, which compares the flow conditions characterizing each measured data point against the applicability range for the interfacial drag correlations used in the code void fraction predictions.

(3) Please identify the measured void fraction data points in the analyzed THTF test runs, for which the flow is predicted to exist in a CT flow regime ($0.50 < \alpha \le \alpha_{crit}$). For these data points, please provide the information requested in item (1) above for annular flow. Please apply the nominal YDRAG value (YDRAG=1) in code predictions and provide a separate table, which compares the flow conditions characterizing each measured data point against the applicability range for the interfacial drag correlations used in the code void fraction predictions.

(4) Please clarify what was the value for the YDRAG multiplier that was used in the code predictions shown in Figures 13.4.2-4 through 13.4.2-15.

(5) Considering items (1) through (4) above, please explain why the ORNL THTF test data, analyzed in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.4.2, “ORNL-THTF Small Break Tests,” represent a suitable and sufficient technical basis to demonstrate the applicability and treatment of film flow interfacial drag in WCOBRA/TRAC-TF2 PWR LOCA analyses. Please provide validation results for the WCOBRA/TRAC-TF2 film drag model based on appropriately selected data describing annular film flow under conditions typical for PWR LOCA analyses.

Question #71: Film Drag Impact on Bubbly Flow Void Predictions for Thermal Hydraulic Test Facility Tests

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5, “Interfacial Drag in the Core Region,” states that “The YDRAG multiplier is the sole contributor for void fractions α_v less than 0.5." Explaining the development of a proposed PDF for the film drag multiplier FDRAG, the subsection refers to WCOBRA/TRAC-TF2 ORNL THTF void fraction predictions obtained with **[ ]** and compared against ORNL THTF test bundle void fraction measurements as described in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.4.2, "ORNL-THTF Small Break Tests," and illustrated in Figures 13.4.2-4 through 13.4.2-15. In particular, Figure 13.4.2-12 shows the comparison between WCOBRA/TRAC-TF2 code predictions and void fraction measurements for THTF Test 3.09.10CC. In this test, both the measured void fractions and the code prediction results are less than 0.5. As seen from Figure 13.4.2-12, changing the FDRAG multiplier **[ ]** had a significant impact on the predicted void fraction results under flow conditions corresponding to SB and SLB flow regimes used in the WCOBRA/TRAC-TF2 vessel component "Cold Wall" flow map. Such an effect, although to a smaller degree, is also seen in Figure 13.4.2-11 for Test 3.09.10BB, in Figure 13.4.2-5 for Test 3.09.10J, in Figure 13.4.2-7 for Test 3.09.10L, and in Figure 13.4.2-13 for Test 3.09.10DD.

(1) Please explain why changing the interfacial drag multiplier for film flow, FDRAG, causes such a pronounced effect on WCOBRA/TRAC-TF2 void fraction predictions for the identified ORNL THTF tests at elevations below the two-phase mixture level where measured void fractions are less than 0.5. Relate the explanation to the statement in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5, "Interfacial Drag in the Core Region," that "The YDRAG multiplier is the sole contributor for void fractions α_v less than 0.5."

(2) WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.1, "Small Bubble Flow Regime Interfacial Drag," explains that in a SB regime of the "Cold Wall" flow map, the interfacial drag is calculated by interpolation between the SB value and the value for an Inverted Liquid Slug regime of the "Hot Wall" flow map "if there is significant vapor generation at the wall." Similarly, WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 5.4.2, "Small-to-Large Bubble Flow Regime Interfacial Drag," clarifies that "for conditions in which there is a large vapor generation rate at the wall, the bubble drag coefficient is ramped to the interfacial drag used in the hot wall flow regime." Please clarify if interfacial drag "ramping" caused the observed effect on WCOBRA/TRAC-TF2 void fraction predictions as exhibited by varying the film flow interfacial drag multiplier, FDRAG, in the code simulation for THTF Test 3.09.10CC for flow conditions with void fractions less than 0.5 that correspond to SB and SLB flow regimes.

(3) Please explain what is unique for THTF tests, such as 3.09.10CC, for which FDRAG variation had a pronounced impact on the void fraction predictions at low voids according to Figure 13.4.2-12, in comparison to other analyzed THTF tests as seen in Figure 13.4.2-6 for Test 3.09.10K, in Figure 13.4.2-8 for Test 3.09.10M, in Figure 13.4.2-9 for Test 3.09.10N, in Figure 13.4.2-10 for Test 3.09.10AA, in Figure 13.4.2-11 for Test 3.09.10BB, in Figure 13.4.2-14 for Test 3.09.10EE, and in Figure 13.4.2-15 for Test 3.09.10FF.

(4) If interfacial drag "ramping" caused the exhibited effect on WCOBRA/TRAC-TF2 void fraction predictions for the identified THTF tests, please present the technical basis that validates the implemented approach to interfacial drag "ramping" in

WCOBRA/TRAC-TF2 for applications aimed at obtaining realistic thermal-hydraulic predictions of PWR core level swell under typical SBLOCA conditions.

Question #72: Bubbly Flow Drag Assessment Using Thermal Hydraulic Test Facility Test Data

WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Subsection 13.4.2, "ORNL-THTF Small Break Tests," clarifies that "YDRAG is a multiplier on the interfacial drag value that is used to bias the value computed by the code. It is specified on an individual cell basis, and 1.0 is the default value." The bubbly flow drag multiplier, YDRAG, is applied directly to the interfacial drag as calculated for SB flow from Equation (5-67a) and for Large Bubble flow from Equation (5-72):

[ ]
[ ]

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5 explains that "The YDRAG multiplier is the sole contributor for void fractions α_v less than 0.5." It is also clarified that "in the interpolation region between the small and small-to-large bubbly flow regime ($\alpha_v < 0.5$) and the annular film flow regime ($\alpha_v > \alpha_{crit}$ ~0.8) both YDRAG and FDRAG have an effect." Subsection 29.1.5 of WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, states that YDRAG "is applied directly to the small bubble, large bubble and hot wall interfacial drag calculations."

Subsection 13.4.2 of WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, examines the effect of three different YDRAG values **[ ]** on WCOBRA/TRAC-TF2 axial void fraction predictions for 12 ORNL THTF test runs as summarized in Table 1.

Table 1: ORNL THTF Tests Used in YDRAG WCOBRA/TRAC-TF2 Sensitivity Analysis

Test Facility	Test Bundle	Test Runs	Number and Type of Test Runs		YDRAG and Number of Test Runs Analyzed		
			Bundle Uncovery	Level Swell	**[ ]**	**[ ]**	**[ ]**
THTF	8×8	12	6	6	12	12	12

The WCOBRA/TRAC-TF2 void fraction predictions with **[ ]** are compared against ORNL THTF bundle void fraction measurements in Figures 13.4.2-16 through 13.4.2-27. Sensitivity studies were performed **[ ]** WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.4.2.7, "Summary and Conclusions," states **[ ]** As such, it is concluded that the YDRAG range determined from the boil-off experiments adequately captures the data for the ORNL bundle uncovery and level swell simulations."

(1) Please identify the measured void fraction data points in the analyzed THTF tests, for which WCOBRA/TRAC-TF2 predicts a SB configuration and document the data in a table. For each point, provide the measured void fraction value, void fraction measurement uncertainty (shown in Figures 13.4.2-16 through 13.4.2-27),

corresponding liquid and vapor mass flow rates, criteria used to identify the data points, predicted nominal interfacial drag coefficient, C_{Db} along with parameters that entered into its calculation. Include corresponding void fraction predictions for

[ ] Please document each data point in a separate raw and present the above identified quantities in separate columns. Please provide a plot comparing predicted void fractions versus measured data showing void fraction measurement accuracy. Please apply the nominal **[ ]** in code predictions. In a separate table, please compare the flow conditions characterizing each measured data point against the applicability range for the interfacial drag correlations used in the code void fraction predictions.

(2) Please identify the measured void fraction data points in the analyzed THTF test runs, for which WCOBRA/TRAC-TF2 predicts existence of a SLB flow regime ($0.20 < \alpha \leq 0.50$). For these data points, please provide the information requested in item (1) above for SB flow. Please **[ ]** in code predictions and provide a separate table, which compares the flow conditions characterizing each measured data point against the applicability range for the interfacial drag correlations used in the code void fraction predictions.

(3) Please explain predicted instances of decreasing void fraction with increasing bundle axial elevation as observed in void fraction results shown in Figure 13.4.2-6 for Test 3.09.10K, in Figure 13.4.2-12 for Test 3.09.10CC (at **[ ]**), in Figure 13.4.2-14 for Test 3.09.10EE, and in Figure 13.4.2-15 for Test 3.09.10FF. Provide the causes for void fraction decrease at higher axial elevations taking into consideration, among other relevant factors, the fact that the flow area does not increase with height.

(4) WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Subsection 29.1.5 states that YDRAG "is applied directly to the SB, large bubble and hot wall interfacial drag calculations." Please provide a detailed description of and justification for YDRAG application to "Hot Wall" interfacial drag.

Question #73: Bubbly Flow Drag Assessment Using G-1 and G-2 Test Data

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.4.3, "Simulation of G-1 Core Uncovery Tests," explains that 16 core uncovery test runs conducted in the Westinghouse ECCS HPTF with the G-1 15×15 grid test bundle were used to define an uncertainty range for YDRAG. From the G-1 tests, 33-level swell data points were identified for the 10-foot, 8-foot, and 6-foot elevations, experiencing uncovery, and were compared against WCOBRA/TRAC-TF2 predictions. The YDRAG uncertainty range study also included 9 core uncovery test runs conducted in the Westinghouse ECCS HPTF with the G-2 19×19 grid test bundle (336 heater rods) as described in Subsection 13.4.4, "Simulation of G-2 Core Uncovery Tests," of WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0. From the G-2 tests, 18-level swell data points were identified for the 10-foot and 8-foot elevations, exhibiting uncovery, and were compared against code predictions. Figures 13.4.3-9 and 13.4.4-8 compare measured versus predicted level swell using nominal YDRAG multiplier. Table 1 summarizes the Westinghouse ECCS HPTF G-1 and G-2 runs used to assess the bubbly flow interfacial drag.

Table 1: Westinghouse HPTF G-1 and G-2 Tests Used in YDRAG Range/Distribution Analysis

Test Facility	Test Bundle	Test Runs	Data Points	Note
Westinghouse ECCS HPTF	G-1 (15×15)	16	33	**[ ]**
Westinghouse ECCS HPTF	G-2 (19×19)	9	18	**[ ]**

Please provide additional information as described in the items below using the nominal YDRAG value (**[ ]**) in relevant analyses and, for consistency with previous results, with **[ ]**

(1) The YDRAG uncertainty study is based on calculated (or secondary) G-1 and G-2 test data representing the collapsed liquid level in the test bundle. As described in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.4.3.6, “Simulation of G-1 Core Uncovery Tests,” and in Subsection 13.4.4.6, “Simulation of G-2 Uncovery Tests,” the collapsed level data were based on differential pressure/level transducer readings at points in time when heater rod thermocouples (TCs) located at selected axial elevations started indicating temperature rise above the saturation level due to mixture level falling below the TC elevations. Please provide the accuracy of the calculated collapsed liquid level data in the G-1 and G-2 tests using instrumentation accuracies for the measured test data. Derive the associated accuracy for the average level swell data provided in Table 13.4.3-3, “G-1 Simulation Results Summary at Model Nominal YDRAG,” and in Table 13.4.4-4, “G-2 Simulation Results Summary at Model Nominal YDRAG.” Present the results in a separate column in both tables and show accuracy bars for the data plotted in Figures 13.4.3-9 and 13.4.4-8.

(2) Table 2 provides the TC elevations used to identify the mixture level and the associated collapsed liquid level in the examined G-1 and G-2 tests. In addition, the table lists the corresponding elevations reported in the WCOBRA/TRAC-TF2 runs in Tables 13.4.3-3 and Table 13.4.4-4. Also listed are elevations for cell interfaces nearest to the TC elevations according to the noding diagrams provided in Figure 13.4.3-6, “WCOBRA/TRAC-TF2 Model of the G-1 Test Bundle” and in Figure 13.4.4-6, “WCOBRA/TRAC-TF2 Model of the G-2 Test Bundle.” It is seen that there is a difference of up to about **[ ]** between the TC elevations and those reported in the WCOBRA/TRAC-TF2 runs. A difference of **[ ]** between the TC elevations and the nearest cell interface elevations in the WCOBRA/TRAC-TF2 G-1 model is evident. For the G2 model, this difference is smaller and it is limited to **[ ]** Please describe the reason for these discrepancies, which, in combination with a large cell size, can introduce errors in the comparison between data and code predictions for level swell. Present analysis results obtained with modified G-1 and G-2 WCOBRA/TRAC-TF2 models in which TC elevations coincide with cell interface elevations and the heated conductors are modified accordingly and provide the updated Figures 13.4.3-9 and 13.4.4-8.

Table 2: G-1 and G-2 TC Elevations and Elevations Reported in WCOBRA/TRAC-TF2 Runs

Reference Elevation (ft)	TC Elevation				Elevations Reported in WCOBRA/TRAC-TF2 Runs				Cell Interface Elevations[×] in WCOBRA/TRAC-TF2 Models			
	G-1 Bundle		G-2 Bundle		G-1 Model		G-2 Model		G-1 Model		G-2 Model	
	(in)	(ft)	(in)	(ft)	(in)	(ft)	(in)	(ft)	(in)	(ft)	(in)	(ft)
10	[ ]	[ ]	118.9	9.908	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
8	[ ]	[ ]	94.3	7.858	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
6	[ ]	[ ]	69.7	5.808	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

[×] Elevation provided from the bottom of heated length.
[+] Elevation did not uncover.
[Δ] Nearest cell interface is bellow TC.
[†] Nearest cell interface is above TC.

(3) It is seen from the predicted cladding temperature shown in Figure 13.4.4-7, “Collapsed Liquid Level and Predicted Cladding Temperatures at the 8- and 10- Foot Elevations, G-2 Test 716,” that the 7.96-ft elevation uncovers shortly after 1,200 second (s). From the plots of the liquid and mixture levels in the test bundle measured in G-2 Run 716 on pages 716-24 and 716-28 in EPRI Report AN-1692, Volume 2, it is estimated that the TC at the 94.3-inch elevation uncovers at approximately 1,900 s. Please explain this large timing discrepancy between test data and code prediction. Please clarify which void fraction value is plotted in Figure 13.4.3-8, “Void Fraction and Predicted Cladding Temperature at the 10- Foot Elevation, G-1 Test 62,” referring to the noding diagram shown in Figure 13.4.3-6.

(4) Using the G-2 TC elevations and the elevations reported in WCOBRA/TRAC-TF2 G-2 runs provided in Table 2, it is possible to reproduce both the data and code predictions for the level swell values provided in Table 13.4.4-4 assuming that the liquid is saturated at the bottom of heated length. However, the observed and predicted level swell values documented in Table 13.4.3-3 for G-1 test runs cannot be reproduced in the same manner. Please explain the reason for this inconsistency and provide corrected values if necessary.

(5) The heated length of the G-1 test bundle is 144 inch (12.0 ft) and the G-2 test bundle heated length is 164 inch (13.667 ft). According to the noding diagrams provided in Figures 13.4.3-6 and 13.4.4-6, this length is represented using 12 cells in the WCOBRA/TRAC-TF2 G-1 model and 16 cells in the WCOBRA/TRAC-TF2 G-2 model. After resolving the above identified items, please present code prediction results for the bundle level swell obtained with doubling the number of axial cells used to represent the heated bundle length for both test facilities. Present the updated Tables 13.4.3-3 and 13.4.4-4 with the obtained results and present them graphically by updating Figures 13.4.3-9 and 13.4.4-8.

(6) Please provide comparisons of code predictions for clad temperatures and sink temperatures against test data for all test data axial locations for G-2 Test 718. Also show comparisons for the two-phase level and collapsed liquid level predictions against test data for this test. Please provide comparisons of code predictions obtained with drag multipliers **[** **]** against test data.

Question #74: Interfacial Drag Sampling Approach

The capabilities of WCOBRA/TRAC-TF2 to predict the core void and the resultant mixture level swell for SBLOCAs are assessed in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 13, "Core Void Distribution and Mixture Level Swell." WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 13.2, "Physical Processes," clarifies that "in SBLOCA scenarios, the steam velocities are too low to entrain droplets at the two-phase interface, and thus entrainment is negligible." It is also explained that "…the liquid and vapor flow rates are low, which make wall drag due to form and friction losses negligible compared to the interfacial drag." Thus, "…the mixture level swell is most directly affected by the interfacial drag between vapor and liquid, and the bubble rise velocity and bubble size."

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 29, "Assessment of Uncertainty Elements," identifies three categories of uncertainty parameters: (1) nominal without uncertainty, (2) bounded, and (3) nominal with uncertainty. Model uncertainties related to "thermal-hydraulic global models" and belonging to the third category of uncertainty parameters are presented in Table 29-2, "Uncertainty Elements – Thermal-Hydraulic Models," which includes the bubbly and film flow drag multipliers YDRAG and FDRAG, among others.

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5, "Interfacial Drag in the Core Region," presents the PDFs proposed for the interfacial drag multipliers in WCOBRA/TRAC-TF2 uncertainty assessments. The subsection explains that "Rather than calibrating multipliers or adjustments to each individual closure relationships, the level swell is 'globally' ranged by applying the same multiplier to the interfacial drag coefficient calculated in each cell of the two-phase region." Accordingly, "Two multipliers were added in the code to allow ranging capability on interfacial drag." The multipliers, YDRAG and FDRAG, are applied directly to the drag coefficient in the expression for the interfacial drag force, $\tau'_{iX,\,vl}$:

$\tau'_{iX,\,vl} = (\mathrm{YDRAG} \times K_{iX,\,vl})\,\underline{U}_{vl}$ and $\tau'_{iX,\,vl} = (\mathrm{FDRAG} \times K_{iX,\,vl})\,\underline{U}_{vl}$.

YDRAG and FDRAG are specified on an individual cell basis and apply to different flow regimes of the "Cold Wall" two-phase flow regime map in the WCOBRA/TRAC-TF2 vessel component.

Table 1 provides a summary description of the interfacial drag multipliers.

Table 1: “Global” Interfacial Drag Multipliers Used in Two-Phase Flow Regimes of the WCOBRA/TRAC-TF2 Vessel Component “Cold Wall” Flow Map

Flow Regime	Void Fraction α (%)	Applicable Multiplier	Applicable Drag Multiplier		Note
			YDRAG	FDRAG	
Small Bubble	$0 < \alpha \le 20$	YDRAG	[ ]	[ ]	Specified on an individual cell basis
Small-to-Large Bubble	$20 < \alpha \le 50$				
Churn-Turbulent	$50 < \alpha \le \alpha_{crit}$	YDRAG FDRAG	[ ]	[ ]	Specified on an individual cell basis
Film/Drop	$\alpha_{crit} < \alpha \le 100$	FDRAG	[ ]	[ ]	Specified on an individual cell basis

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5 describes the application of Westinghouse ECCS HPTF G-1 and G-2 test data to assess an uncertainty range for YDRAG. In code simulations of G-1 and G-2 test runs, **[**

] For the G-1 simulations, **[**

] In the calculations for the G-2 data set, **[**

]

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5 concludes that **[**

] Table 2 summarizes the Westinghouse ECCS HPTF G-1 and G-2 uncertainty assessment for YDRAG.

Table 2: Westinghouse HPTF G-1 and G-2 Tests Used in YDRAG Range/Distribution Analysis

Test Facility	Test Bundle	Test Runs	Data Points	Data Points and YDRAG Values to Recover Level Swell			Average YDRAG	Note
				[ ]	[ ]	[ ]		
W ECCS HPTF	G-1 (15×15)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
W ECCS HPTF	G-2 (19×19)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

[ ]

(1) RG 1.157, Revision 0, “Best-Estimate Calculations of Emergency Core Cooling System Performance,” states that “A best-estimate model should provide a realistic calculation of the important parameters associated with a particular phenomenon to the degree practical with the currently available data and knowledge of the phenomenon.” In addition, RG 1.157 requires that “If it is not possible or practical to consider a particular phenomenon, the effect of ignoring this phenomenon should not normally be treated by including a bias in the analysis directly, but should be included as part of the model uncertainty.”

Figure 1 below illustrates the impact of the proposed range limits and nominal YDRAG values on WCOBRA/TRAC-TF2 void fraction predictions for ORNL THTF Test 3.09.10CC according to results documented in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Figure 13.4.2-24. Please explain the technical rationale and requirements behind the approach of determining and assigning a sampling range to a physical quantity, which is amenable to quantification using experimental measurements, in quantifying the impact of its variation on assessing the uncertainty in predicting other physical parameters that can depend on that sampled quantity. Consider relevant factors such as: (a) state of knowledge, availability and accuracy of pertinent data, (b) uncertainty range versus measurement accuracy for individual physical parameters, (c) uncertainty assessment for individual governing parameters, and (d) need for adequacy, quality, and rigor of prediction tool qualification and assessment.

(2) WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5 states that YDRAG “is applied directly to the SB, large bubble and hot wall interfacial drag calculations.” Explain the rationale for assigning a sampling range “globally” to multiple parameters that describe different processes and phenomena (e.g., SB, large bubble, CT flow, “Hot Wall” interfacial drag) without qualifying uncertainties associated with each individual model considering the possibility for compensating errors.

[

]

(3) The aspect of WCOBRA/TRAC-TF2 approach to interfacial drag calculation that involves implementation of "global" input drag multipliers, YDRAG and FDRAG, used to directly modify, also as part of the uncertainty sampling process, closure terms in the momentum conservation equations is questionable from a methodological point of view. The proposed approach to sampling of interfacial drag interferes with the quantification of specific physical quantities that have been a subject to extensive experimental and analytical studies aimed at their quantification using deterministically established and experimentally validated constitutive models. The questionability of such an approach is particularly exacerbated by the safety relevance of these models as they impact level swell prediction, which, in turn, has a strong impact on SBLOCA PCT predictions. Equally relevant, availability of two-phase flow data measurements for interfacial drag quantification for both pipe and rod bundle geometries leaves little tolerance space for such an approach.

Constitutive correlations need to be demonstrated as applicable and appropriate under the intended conditions of code applications. Please explain how the proposed interfacial drag sampling approach that effectively varies a physical quantity, otherwise amenable to quantification from measured physical parameters, by a factor of **[ ]** applied across an entire spectrum of two-phase flow regimes, demonstrates the applicability of WCOBRA/TRAC-TF2 to predict realistically core level swell and resulting PCT predictions.

(4) If WCOBRA/TRAC-TF2 is applied to quasi-steady unidirectional two-phase flow in a channel with well defined boundary and geometry conditions, thus rendering interfacial drag as the only thermal-hydraulic model parameter of relevance in assessing code uncertainty, how should void fraction and level swell predictions relate to accuracy of void/level measurements when drag has been subjected to sampling?

(5) RG 1.157, Revision 0, states that “A best-estimate model should provide a realistic calculation of the important parameters associated with a particular phenomenon to the degree practical with the currently available data and knowledge of the phenomenon.” More specifically with regard to level swell prediction, RG 1.157, Revision 0, clarifies that “A correlation or model to be used in ECCS evaluation to calculate level swell should be checked against an acceptable set of relevant data and should recognize the effects of depressurization, boil-off, power level, fluid conditions, and system geometry.” As proposed in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5, “Interfacial Drag in the Core Region,” an interfacial drag multiplier ranging from **[ ]** suggests that the two-phase flow drag models implemented in WCOBRA/TRAC-TF2 are deficient. It is recognized that even small variations in swelled levels amounting to 3 to 6 inches during protracted periods of core uncovery under limiting break conditions can result in pronounced changes in PCT predictions. Improved physical models for two-phase flow interfacial drag prediction can be associated with a reduced drag sampling range or even eliminate the need for drag sampling altogether. Please discuss and provide a resolution approach for interfacial drag modeling and sampling in WCOBRA/TRAC-TF2.

Question #75: Interfacial Drag Sampling Impact on ROSA-IV Large Scale Test Facility Test Predictions

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 29, “Assessment of Uncertainty Elements,” identifies the bubbly flow drag multiplier, YDRAG, as a parameter that describes model uncertainties related to “thermal-hydraulic global models.” YDRAG, described in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 29.1.5 as being “applied directly to the small bubble, large bubble and hot wall interfacial drag calculations,” is characterized by **[ ]** According to Table 29-2, “Uncertainty Elements – Thermal-Hydraulic Models,” it has **[ ]**

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 13, “Core Void Distribution and Mixture Level Swell,” assesses WCOBRA/TRAC-TF2 interfacial drag and level swell prediction capabilities using SET data. An additional interfacial drag study is presented in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 21.15, “YDRAG Sensitivity Calculations,” also comparing code predictions against test data from an IET performed at the LSTF as part of the Rig-of-Safety Assessment No. 4 (ROSA-IV) Program. The effect of YDRAG variation for the core channels on transient calculations was analyzed and results compared against data for ROSA-IV LSTF Test SB-CL-18 simulating a 5 percent cold leg break. The YDRAG multiplier in the core region was set **[ ]** and the sensitivity results are presented in Figures 21.15-1 through 21.15-6. The difference in the PCT predictions following core boil-off amounts to approximately 100 °F (55.6 K) according to Figure 21.15-6, “Peak Cladding Temperatures.” This ROSA-IV reference transient, Test SB-CL-18, is first analyzed in Subsection 21.4, “Simulation of SB-CL-18, 5-Percent Cold Leg Side Break,” using **[ ]** in the core region. According to WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, Subsection 21.3, this YDRAG value was used for all analyses presented in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 21, “ROSA-IV Test Simulations,” except for the YDRAG sensitivity studies for Test SB-CL-18 discussed in Subsection 21.15. As explained in Subsection 29.1.5, **[ ]**

In assessing code compensating error, Subsection 24.8, “Core Level Prediction in SB-CL-18 Test,” presents Figure 24.8.3-2, “Impact of YDRAG Variation on Predicted Level Swell,” showing level swell predictions obtained with YDRAG values **[ ]** for Test SB-CL-18 and with YDRAG values **[ ]** for Test SB-CL-01 (2.5 percent cold leg break) against the estimates from test measurements.

(1) Please provide two additional assessments for ROSA-IV LSTF Test SB-CL-18 using the YDRAG sampling range upper limiting value of **[ ]** and its model nominal value of 1.0. Provide comparisons of WCOBRA/TRAC-TF2 predictions against measured data including clad temperature measurements at deferent axial elevations. Include comparisons for the axial void distribution in the core at the time of PCT occurrence as well as for the collapsed liquid level and two-phase mixture level as functions of time. Document the predicted maximum PCT values following core boil-off and compare them against the measured PCT value including the measurement accuracy as well.

(2) Please analyze and provide code predictions for ROSA-IV LSTF Test SB-CL-01 (2.5 percent cold leg side break), Test SB-CL-02 (2.5 percent cold leg bottom break), and Test SB-CL-03 (2.5 percent cold leg top break). In all three experiments, the measured PCTs reached a maximum value of approximately 1,205 °F (925 K). In addition to the results obtained for these tests with **[ ]** and presented in Subsection 21.7, please provide code predictions for YDRAG drag multipliers **[ ]** and compare code results against test data. Include also comparisons for the axial void distribution in the core at the time of PCT occurrence as well as for the collapsed liquid level and two-phase mixture level as functions of time.

Question #76: WCOBRA/TRAC-TF2 Interfacial Drag Assessment

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 13, “Core Void Distribution and Mixture Level Swell,” assesses WCOBRA/TRAC-TF2 level swell prediction capabilities using SETs that are mostly steady state and characterized by relatively low clad temperature. The analyzed tests include ORNL THTF uncovered bundle tests, Westinghouse G-1 and G-2 core uncovery tests, and Japan Atomic Energy Research Institute (JAERI) TPTF critical heat flux bundle tests. To evaluate WCOBRA/TRAC-TF2 performance under test conditions that have not been addressed in WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 13, Subsection 23.1.1, “GE Vessel Blowdown Tests,” assesses WCOBRA/TRAC-TF2 prediction results for transient level swell during rapid depressurization (blowdown), while WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 23.1.2, “Semiscale Tests,” analyzes code level swell and post-CHF heat transfer prediction capabilities at high clad temperatures.

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Subsection 23.1.1, “GE Vessel Blowdown Tests,” assesses WCOBRA/TRAC-TF2 prediction results for transient level swell during rapid depressurization (blowdown) using General Electric (GE) vessel blowdown test facility. The analyzed tests include 7 top-break blowdown experiments: 8-21-1, 8-25-1, 8-28-1, 9-1-1, 9-15-1, 1004-2, and 1004-3. The tests were performed with the small-tank blowdown vessel characterized by an inside diameter of 1 ft for the cylindrical portion of the vessel. The orifice opening diameters ranged from 3/8 to 1 in and a variety of different flow restrictions at the midpoint of the vessel were used. The figure of merit for the code assessment was the ability of WCOBRA/TRAC-TF2 to predict void distribution in the blowdown vessel. For this purpose, code predictions with **[ ]** were obtained to examine the effect of interfacial drag on prediction results and compared against measured void fractions in Figures 23.1.1-4 through 23.1.1-45.

WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 23.1.2, “Semiscale Tests,” assesses WCOBRA/TRAC-TF2 level swell and post-CHF heat transfer prediction capabilities using IET data from Semiscale Mod-3 10 percent cold leg break integral effects Test S-07-10D. The test, designated as a U.S. NRC Small Break Experiment (SBE), featured deep core uncovery and elevated heater rod temperatures due to manually delayed ECCS injection. WCAP-16996-P/WCAP-16996-NP, Volumes I, II, and III, Revision 0, Section 23.1.2 does not provide assessment results with regard to interfacial drag and does not specify the value of YDRAG applied in the analysis.

Please provide additional assessment results for the WCOBRA/TRAC-TF2 vessel component interfacial drag model using available experimental data as described below.

(1) Please compare WCOBRA/TRAC-TF2 predictions against the following tests performed with the CSE test facility: B-50TN, B-51TN, B-53BTN, and B-50MN. For test description, please see Battelle Northwest Laboratories Report BNWL-1463, “Coolant Blowdown Studies of a Reactor Simulator Vessel Containing a Perforated Sieve Plate Separator,” February 1971, by R. T. Alleman et al. In addition, provide code assessment results for CSE Test B-10 as described in Battelle Northwest Laboratories Report BNWL-1411, “Experimental High Enthalpy Water Blowdown from a Simple Vessel through a Bottom Outlet,” June 1970. Please provide

comparisons against data for all of the above CSE tests using YDRAG drag multipliers of **[ ]**

(2) The GE Vessel Blowdown test facility was also used to perform level swell tests using a large-tank blowdown vessel with an inner vessel diameter of 47 in (1.194 m). The top-break, large-tank GE level swell tests employed a blowdown venturi nozzle with a throat diameter ranging from 2.125 in (54 mm) to 3.625 in (92.1 mm). Please assess WCOBRA/TRAC-TF2 against GE large-tank level swell test data, including tests 5702-16, 5801-13, 5801-15, and 5801-19, using YDRAG drag multipliers of **[ ]** Please provide history plots of time-dependent system pressure responses at the top of the blowdown vessel and two-phase mixture levels that compare code predictions and test data showing also accuracy bars for the two-phase mixture level measurements. In addition, please provide plots of axial void fraction profiles as a function of the axial vessel height, which compare core results with axial void fraction data along with accuracy bars for all seven axial levels as measured at the four transient points in time in each test. Assess the interfacial drag models in WCOBRA/TRAC-TF2 by presenting a plot, which compares axially-dependent void fraction data measured at the four transient times at all seven axial levels for each experiment against code predicted values. Please analyze and provide the code assessment for the GE large-tank level swell tests using YDRAG drag multipliers of **[ ]**

(3) Please provide comparisons of WCOBRA/TRAC-TF2 predictions against measured data including, among other important parameters, clad temperature measurements at deferent axial elevations for the following Semiscale IETs: Semiscale Mod-3 10 percent cold leg break Tests S-07-10 (SG secondaries isolated at 17 s into the transient) and S-07-10D (broken loop SG allowed to blowdown throughout the transient), Semiscale Mod-2A 5 percent cold leg break Test S-UT-08, Semiscale Mod-2C 5 percent centerline cold leg break Tests S-LH-1 (0.9 percent core bypass flow) and S-LH-2 (3.0 percent core bypass flow). Please analyze and provide the code assessment for these Semiscale tests using YDRAG drag multipliers of **[ ]** Provide comparisons of WCOBRA/TRAC-TF2 predictions against measured data for PCTs at deferent axial elevations. In addition, please provide comparisons for the axial void distribution in the core at the time of PCT occurrence as well as for the collapsed liquid level and two-phase mixture level as functions of time. Document the predicted maximum PCT values following core boil-off and compare them against the measured PCT value including the measurement accuracy as well.

(4) A WCOBRA/TRAC-TF2 component model assessment study was performed to assess the discharge of nitrogen from the accumulator and the effect on the PWR reflood transient using ACHILLES International Standard Problem (ISP) Test No. 25. In addition to the assessment results documented in Section 20.1.4, “Effect of Accumulator Nitrogen on PWR Reflood Transients,” please analyze and provide the code predictions for this test using YDRAG drag multipliers of **[ ]** Provide comparisons of WCOBRA/TRAC-TF2 predictions against measured data including clad temperature measurements at deferent axial elevations. Include comparisons for the axial void distribution in the core at the time of PCT occurrence as well as for the collapsed liquid level and two-phase mixture level as functions of time.

(5) Please present results from studies assessing variation in WCOBRA/TRAC-TF2 PCT predictions for a representative limiting PWR SBLOCA case when modifying YDRAG from **[ ]** is the only model change. Compare the obtained maximum PCT values against the one obtained with the nominal YDRAG value of 1.0. Use a limiting axial power shape for the sensitivity study. Please explain how the impact on PCT due to YDRAG variation compares to those resulting from variation of other uncertainty parameters considered of governing importance for SBLOCA modeling.

Question #77: Follow-up to RAI #45

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