

KCE-1 Critical Heat Flux Correlation

for PLUS7 Thermal Design (APR1400-F-C-TR-12002)

Technical Meeting to Support RAI 3-7443

May 1, 2014

Overview

Background of Assumptions applied to KCE-1 CHF Correlation

Key of Draft Response to RAI and Strategy

Discussion

Overview

- **PLUS7 Developed for APR1400 & OPR1000***
 - April 1999 ~ March 2002 (Collaboration with WEC)
- **CHF Test for PLUS7 (~ July 2001)**
 - Two (2) Test Section Configuration
 - 6x6 Bundle (with/without GT Simulator), 1.5 Cosine APD
 - HTRF (Columbia Univ., Closed @ 2003)
 - Procedure & Criteria, QA System : WEC Requirements
- **KCE-1 CHF Correlation (~ November 2001)**
 - PLUS7 CHF Data
 - Same Functional Formula with CE-1
 - Specific Considerations/Assumptions to Guarantee Conservatism
 - WEC Criteria & Technical Support
- **RAI 3-7443**
 - 18 Topics
 - 3 Questions in 30 days of response cycle
 - 15 Questions in 60/90 days of response cycle

* OPR1000 : Optimized Power Reactor with 1000MWe

Background of Assumptions applied to KCE-1 CHF Correlation -1/15

Non-Proprietary

- **Proven Test Facility**
 - HTRF
 - Procedure & Acceptance Criteria
 - Quality Assurance
- **Proven Functional Formula**
 - CE-1 Correlation Formula
 - Energy Balance + Macbeth/Barnett Assumption + Local Fluid Condition
- **Proven/Approved Computer Code**
 - TORC Subchannel Code (CENPD-161-P-A, 1986)
 - Design Constitutive Relations of TORC
 - * PLUS7 Specific Input
 - Loss Coefficient of Spacer Grids
 - Mixing Factor
- **Specific Consideration/Assumptions**
 - Conservatism

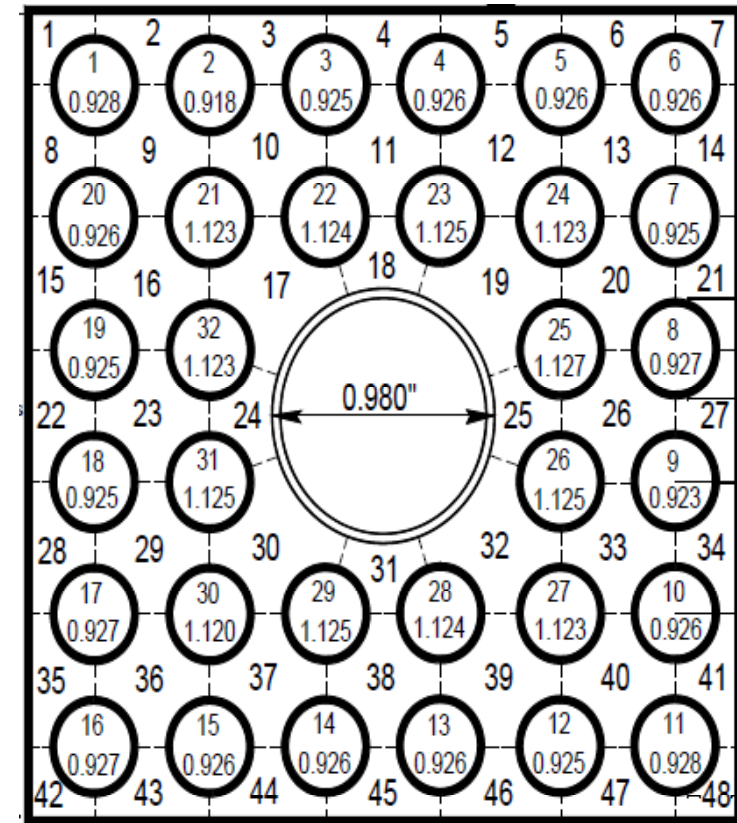
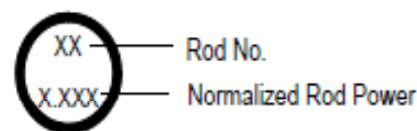
Background of Assumptions applied to KCE-1 CHF Correlation -2/15

Non-Proprietary

• Specific Consideration-1 :

- []^{TS}
- []^{TS}
- []^{TS}
- []^{TS} Conservatism in 95/95 Limit
- Relaxation leads Mild M/P Trends

Legend

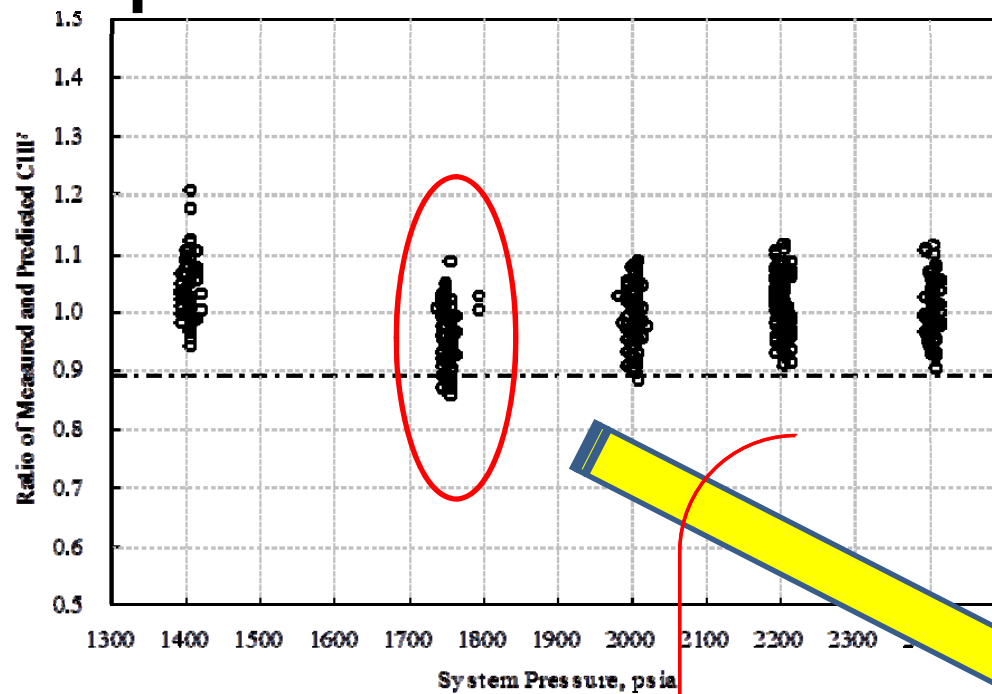


(Numbers inside dashed lines are the subchannel number of TORC model)

Background of Assumptions applied to KCE-1 CHF Correlation -3/15

Non-Proprietary

- Specific Consideration-1 :



TS

Background of Assumptions applied to KCE-1 CHF Correlation -4/15

Non-Proprietary

- **Specific Consideration-2 : Application of Tong Fc (F_{Tong})**
 - Development Stage (CHF Data)
 - **DNBR** = $q''_{CHF, Pred} / q''_{CHF, Meas}$
 - $q''_{CHF, Meas} = \left[\right]^{TS}$
 - $q''_{CHF, Pred (development)} = q''_{CHF, KCE-1} \sim \left[\right]^{TS}$
 - Application Stage (Reactor Thermal Design)
 - **DNBR** = $q''_{CHF, Pred} / q''_{local, Actual}$
 - Tong Fc = $\left[\right]^{TS}$: Correct the effects of Non-Uniform Axial Power Distribution (NU APD) on CHF
 - $q''_{CHF, Pred (application)} = q''_{CHF, KCE-1} / F_{Tong} \leq \left[\right]^{TS}$
 - Note that $q''_{CHF, NU} \leq q''_{CHF, U}$
 - $\left[\right]^{TS}$ **Conservatism in DNBR (inverse of M/P)**

Background of Assumptions applied to KCE-1 CHF Correlation -5/15

Non-Proprietary

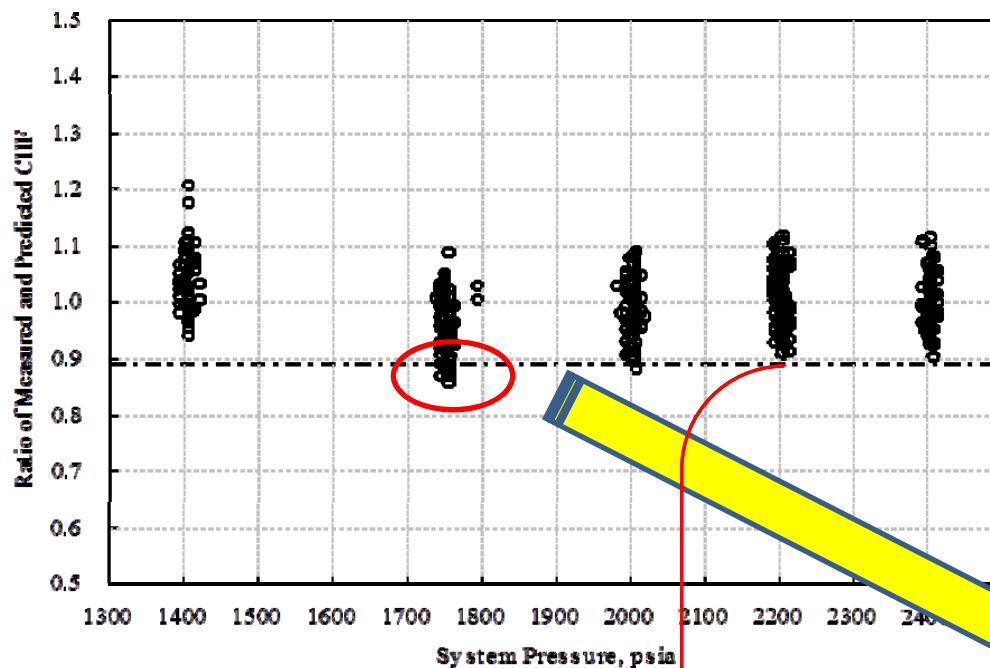
- **Specific Consideration-2**
 - Comparison of M/P for CHF Data : w/ F_{Tong} vs. as Developed

TS

Background of Assumptions applied to KCE-1 CHF Correlation -6/15

Non-Proprietary

- Specific Consideration-2
 - M/P Parametric Trend vs. as Developed



TS

Background of Assumptions applied to KCE-1 CHF Correlation -7/15

Non-Proprietary

- **F_{Tong} : Correction Factor for the effects of NU APD on CHF**
 - $F_{\text{Tong}} = q''_{\text{CHF, U}} / q''_{\text{CHF, NU}}$
 - Relevant References : Applicability & Experiences
 - Tong L.S., et. al., "Influence of Axially Non-Uniform Heat Flux on DNB," AIChE Preprint 17, 8th National Heat Transfer Conference, LA California, 1965.
 - Tong, L.S., "Prediction of Departure from Nucleate Boiling for an Axially Non-Uniform Heat Flux Distribution," Journal of Nuclear Energy 21, 1967.
 - Tong, L.S., "Boiling Crisis and Critical Heat Flux," TID-25887, USAEC, 1972.
 - Rosal, E.R., et. al., Nuclear Engineering and Design 31 (1974)
 - WCAP-8762-P-A (1978), WCAP-10444-P-A (1985)
 - CENPD-207-P-A (1984)

Background of Assumptions applied to KCE-1 CHF Correlation -8/15

Non-Proprietary

- **F_{Tong} : Correction Factor for the effects of NU APD on CHF**

- Energy Eq. for the Bubble Layer

$$\frac{d(H(z) - H_B)}{dz} + C(H(z) - H_B) = C \frac{c_p q''}{h}$$

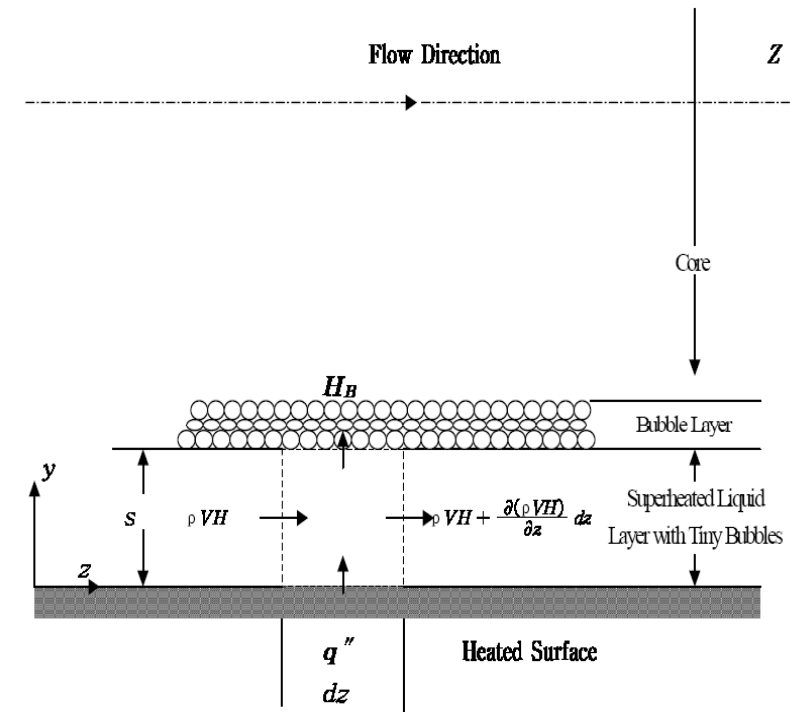
$$[H(z) - H_B]_{CHF,U} = [H(z) - H_B]_{CHF,NU}$$

- $F_{Tong} = q''_{CHF,U} / q''_{CHF,NU}$

$$\begin{cases} = 1.0 & \text{for uniform} \\ = \frac{C}{q''_l \cdot [1.0 - \exp(-C \cdot l)]} \cdot \int_{z_s}^l q''(z) \cdot \exp[-C \cdot (l - z)] dz & \text{for non-uniform} \end{cases}$$

where

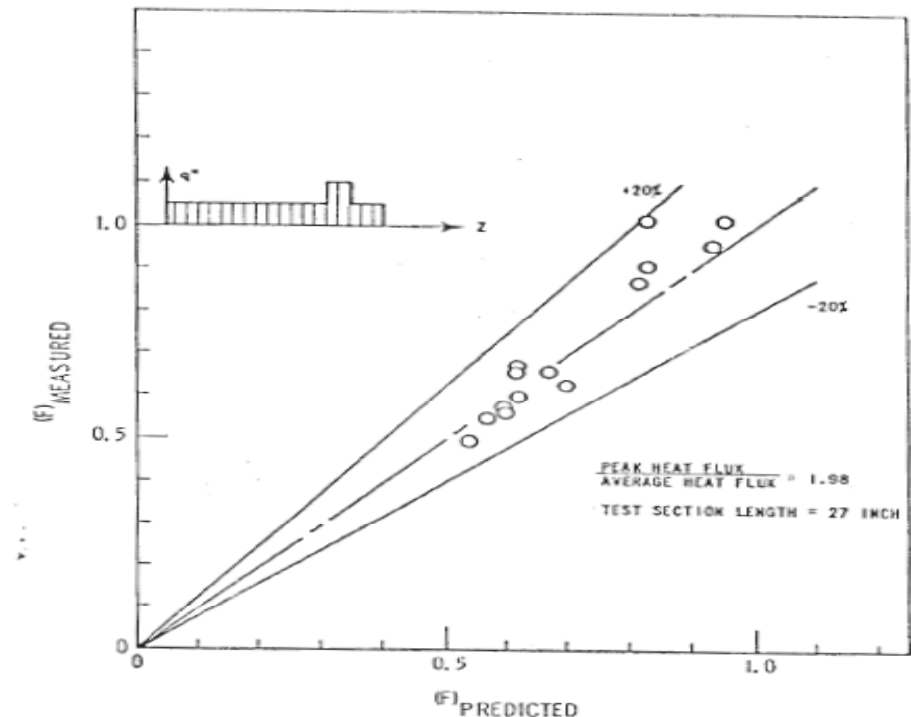
$$\begin{aligned} d_1 &= 1.50E-01 \\ d_2 &= 4.31E+00 \\ d_3 &= 4.78E-01 \end{aligned}$$



Background of Assumptions applied to KCE-1 CHF Correlation -9/15

Non-Proprietary

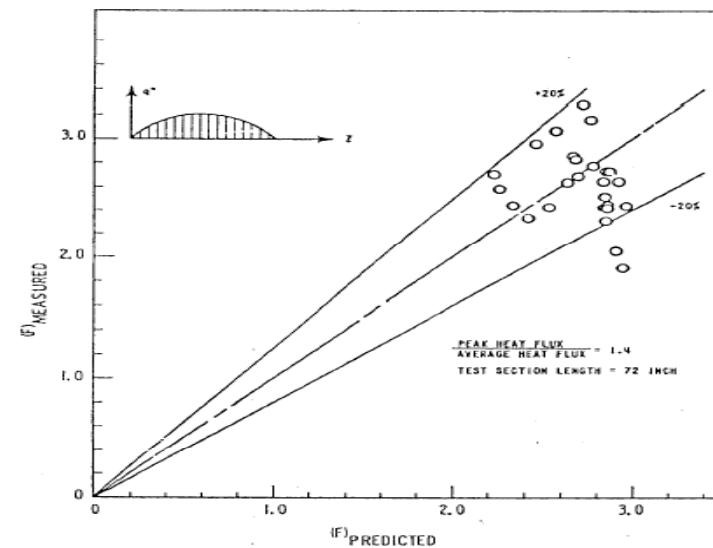
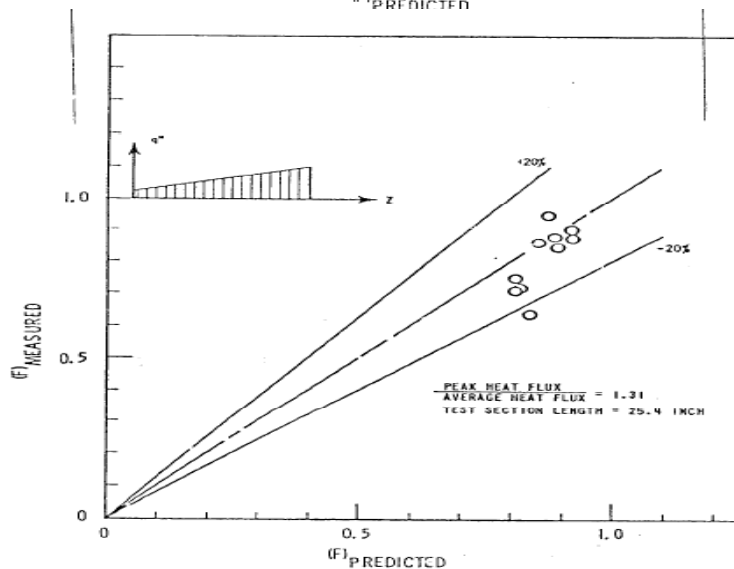
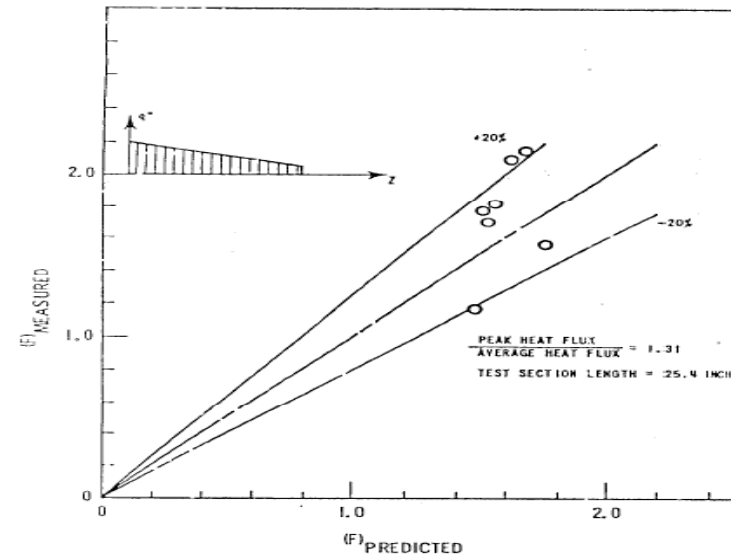
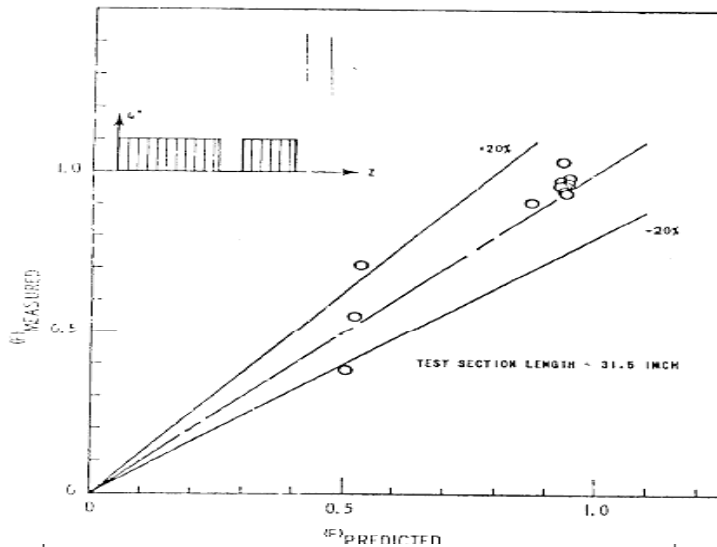
- F_{Tong} : Correction Factor for the effects of NU APD on CHF
 - First Proposal
 - Tong1965
 - 5 Non-Uniform Axial power Distribution
 - Hot Patch
 - Interrupted Uniform
 - Decreasing Ramp
 - Increasing Ramp
 - Symmetric Cosine
 - Good Agreement with Data



Background of Assumptions applied to KCE-1 CHF Correlation -10/15

Non-Proprietary

- F_{Tong} : Correction Factor for the effects of NU APD on CHF
 - First Proposal

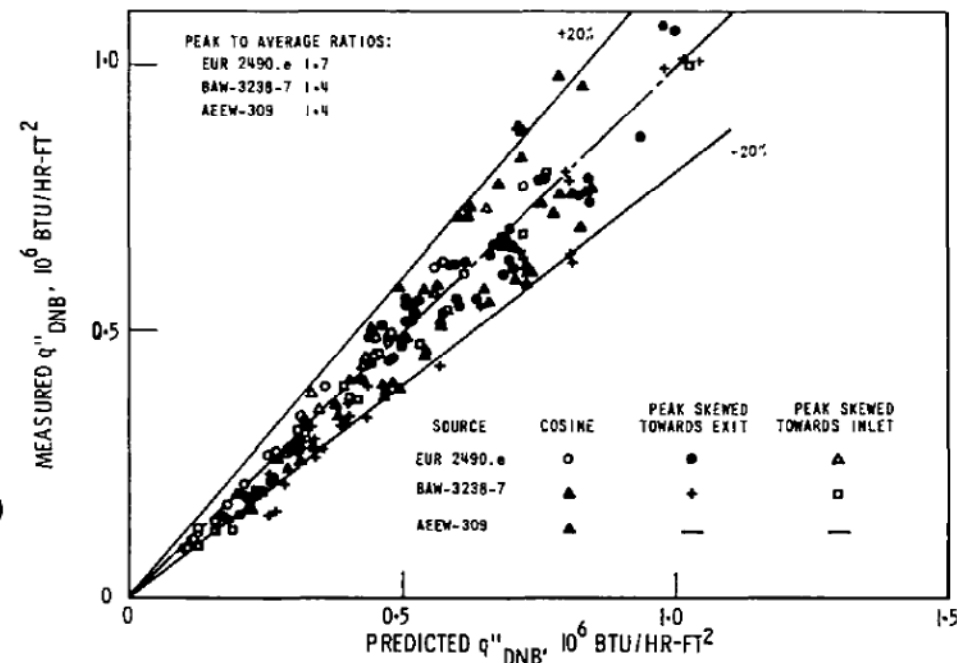
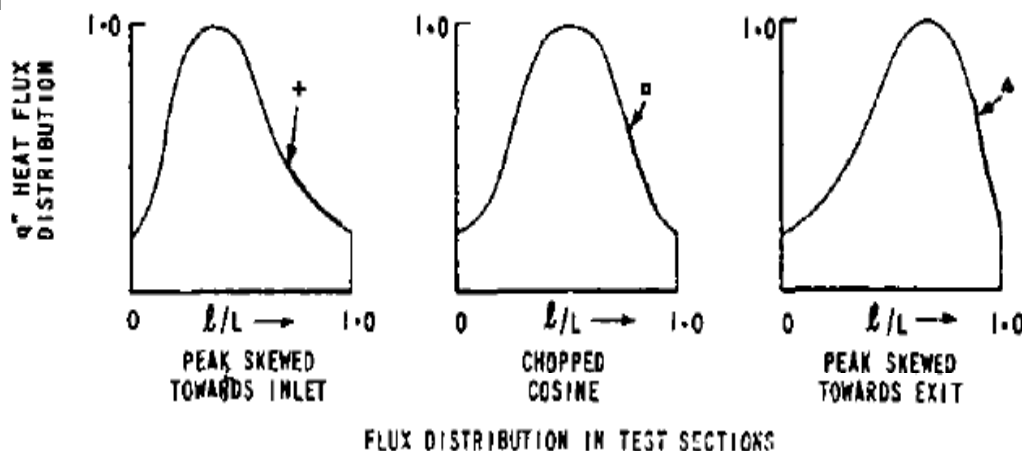


Background of Assumptions applied to KCE-1 CHF Correlation -11/15

Non-Proprietary

- F_{Tong} : Correction Factor for the effects of NU APD on CHF
 - Proposal to Nuclear Reactor Design Application with W-3
 - Tong1967
 - 3 Non-Uniform Axial power Distribution
 - Skewed toward Inlet (Bottom Skewed)
 - Symmetric Cosine
 - Skewed toward Outlet (Top Skewed)

➤ Good Agreement with Data



Background of Assumptions applied to KCE-1 CHF Correlation -12/15

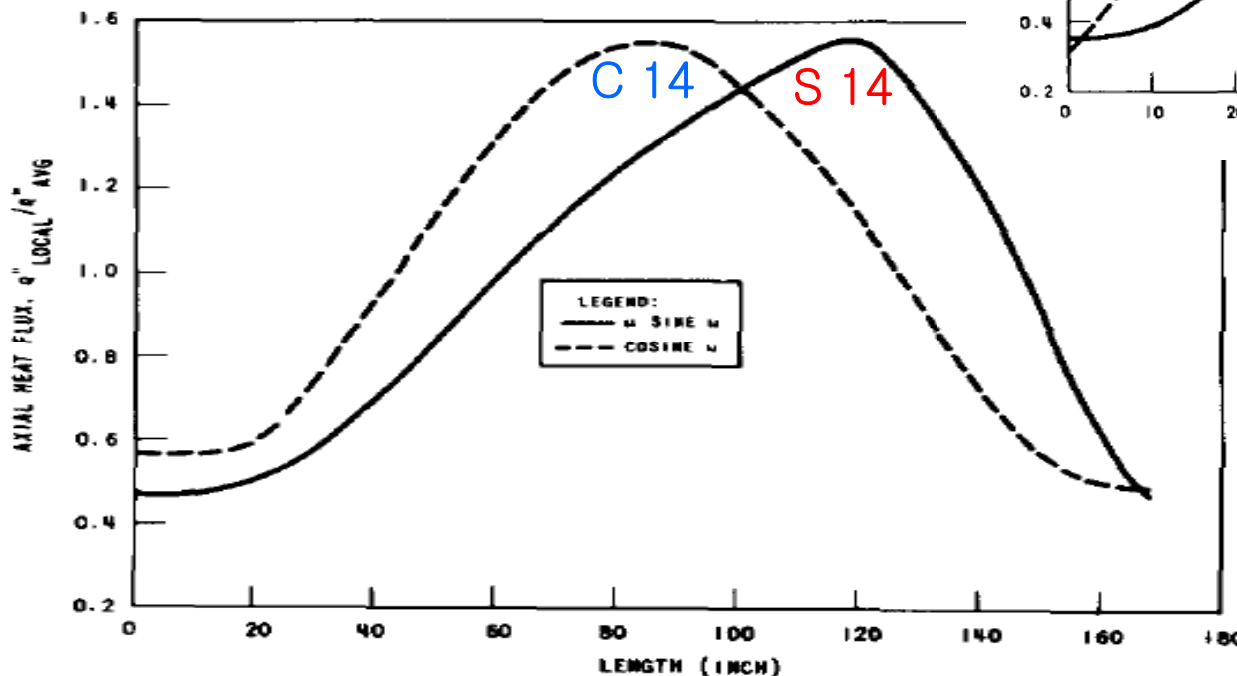
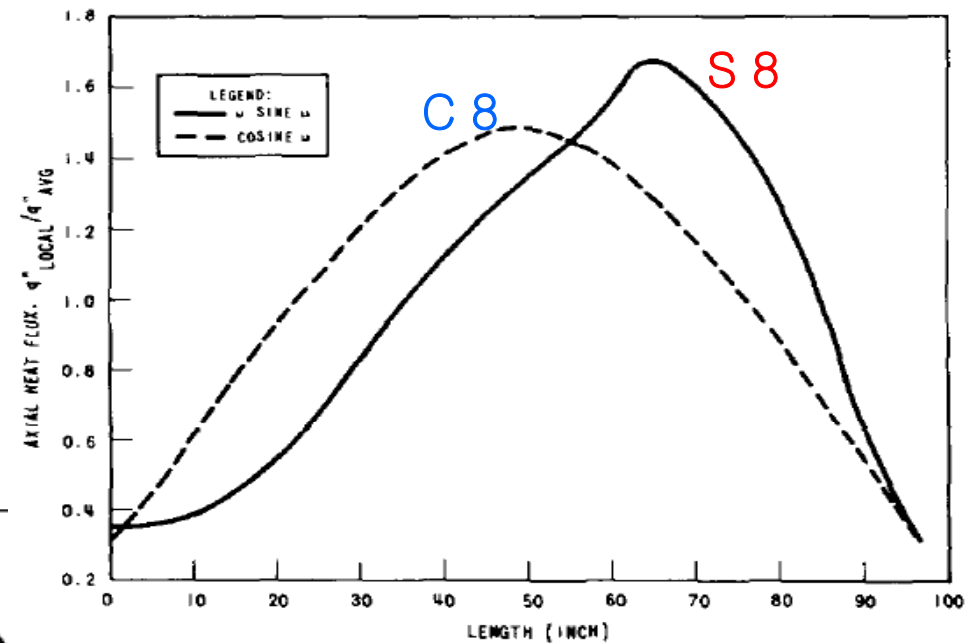
Non-Proprietary

- **F_{Tong} : Correction Factor for the effects of NU APD on CHF**
 - To Rod Bundle Data
 - Rosal1974, NED 31
 - 2 (4) Non-Uniform Axial power Distribution
 - Symmetric Cosine : 8 ft/14ft Heated Length
 - Skewed toward Outlet (Top Skewed) : 8 ft/14ft Heated Length
 - 4 Types of Spacer Grids / 3 Different Grid Spacing
 - Good Agreement with Data (12 Test Sections)
 - Standard Tong F_c in Slide 9
 - Applied with KCE-1 CHF Correlation to Design Analyses

Background of Assumptions applied to KCE-1 CHF Correlation -13/15

Non-Proprietary

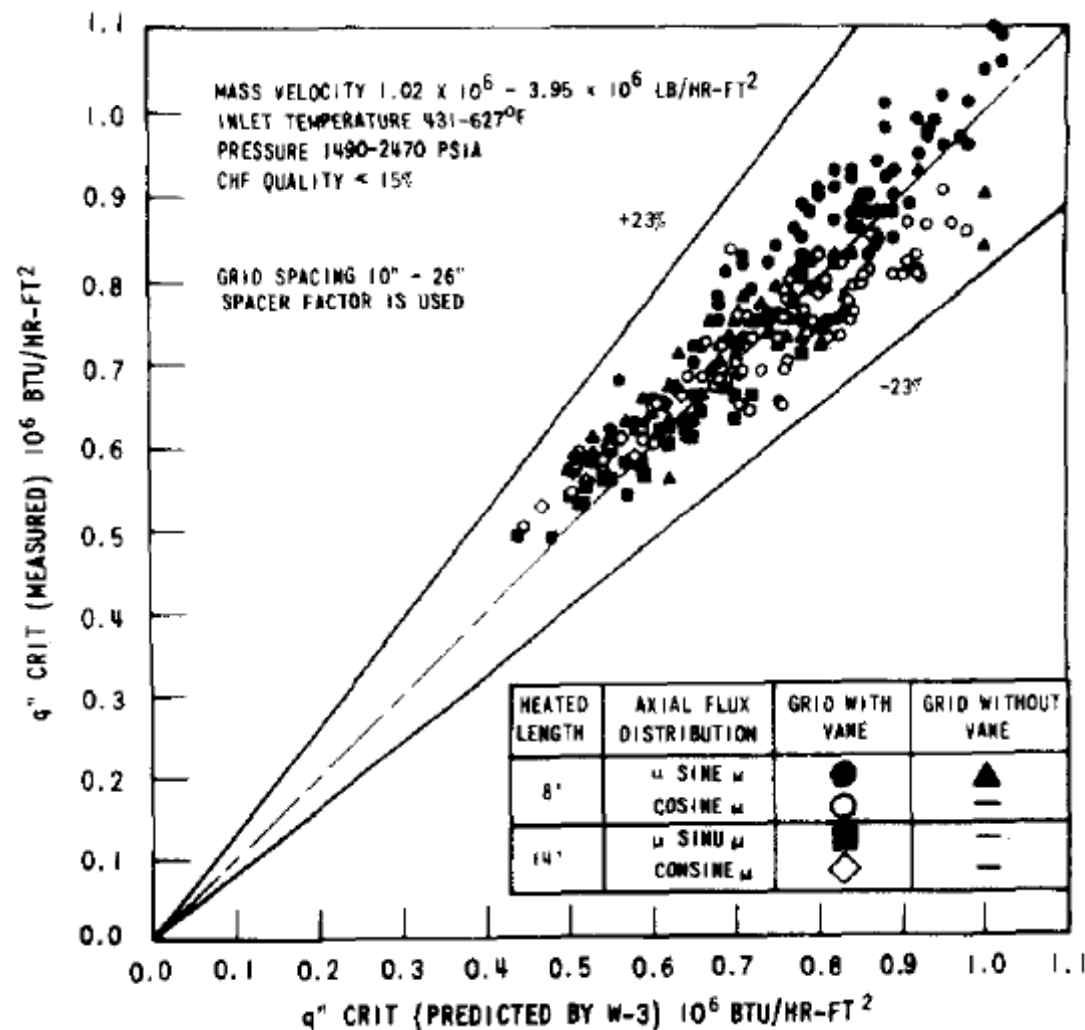
- F_{Tong} : Correction Factor for the effects of NU APD on CHF
 - To Rod Bundle Data



Background of Assumptions applied to KCE-1 CHF Correlation -14/15

Non-Proprietary

- F_{Tong} : Correction Factor for the effects of NU APD on CHF
 - To Rod Bundle Data



Background of Assumptions applied to KCE-1 CHF Correlation -15/15

Non-Proprietary

- **KCE-1 CHF Correlation** : $q''_{CHF} = q''_{base,u} * CWF / F_{Tong}$
 - $q''_{base,u} : f(P, G, X, hfg)$
 - Effects of Fluid Conditions on CHF
 - PLUS7 Geometry (Matrix Subchannels)
 - Test Data : Non-uniform Axial Power Distribution
 - CWF : $f(DH/DHM)$
 - Effects of Guide Tube on CHF
 - PLUS7 Geometry (Guide Tube Subchannels)
 - $F_{Tong} : f(G, X, z)$
 - Effects of Axial Power Distribution on CHF
 - Conservatisms
 - Specific Consideration-1
 - Specific Consideration-2 (double counting the effects on CHF)

Key of Draft Response to RAI and Strategy – 1/14

- **Classification of RAI (3-7443) given in following slides**
 - 7443-1 ~ 7443-18
- **Class 30 : Response Due ~ April 24, 2014**
 - 7443-2 : Testing Technique & Criteria (was Class 60)
 - 7443-3 : Test Section Design
 - 7443-5 : Test Measurement
- **Class 60 : Response Due ~ May 24, 2014**
 - Draft Responses would be prepared
- **Class 90 : Response Due ~ June 23, 2014**
 - Draft of Assessment & Strategy to Response would be prepared
- **Some of Key of Draft Response and Strategy addressed on “Background of Assumptions ...”**

Key of Draft Response to RAI and Strategy – 2/14

- **Class 60 : 7443-1 (Test Acceptance Criterion)**
 - Heat Balance Measurements
 - Acceptance criterion
 - Effectiveness to overall test range
 - Acceptance Criteria : []^{TS}
 - Effectiveness
 - Addressed based on the main purpose of heat balance measurement
 - Heat loss did not mean loss in electrical power
- **Class 60 : 7443-4 (Test Facility)**
 - Flow Measurements
 - Logic / Calibration to ensure accurate flow measurements
 - Post-test Inspection / Information to Test Facility
 - additional Request during Clarification Meeting on March 20, 2014
 - would not be addressed on the response to 7443-4
 - would be addressed upon corresponding requests

Key of Draft Response to RAI and Strategy – 3/14

- **Class 60 : 7443-10 (Test Data & Applicable Range)**
 - Technical basis to applicable range
 - local quality & envisions to exceeding range : design methodology & restriction to design analysis out of range (DNB limiting cases)
 - Request to additional plot in topical report
 - measured CHF vs. local quality
 - terminology : CHF elevation and MDNBR elevation

TS

Key of Draft Response to RAI and Strategy – 4/14

- **Class 60 : 7443-11 (Test Data)**
 - Request to additional plot in topical report
 - measured CHF vs. correlation variables (pressure, mass velocity, d/dm)
 - Description to key parameters in Tables A-1/A-3
 - upgrade as-was description on page A-1
 - examples would be included in response to 7443-11
 - Request to include the outlet temperature test data
 - []^{TS} corresponding pressure

TS

Key of Draft Response to RAI and Strategy – 5/14

- **Class 60 : 7443-12 (Application of KCE-1 Correlation)**
 - No term to heated length & grid spacing in KCE-1 Correlation
 - Local Condition Hypothesis
 - Same CHF where same fluid condition
 - Effects of geometry : adjustment factor (d/d_m)
 - Effects of power shape : Tong F_c
 - Developed with PLUS7 CHF Data, Applied to PLUS7 Geometry
 - Reasonable M/P per MDNBR elevation
 - No impact on PLUS7 design analyses

TS

Key of Draft Response to RAI and Strategy – 6/14

- **Class 60 : 7443-18 (Test Data & Applicable Range)**
 - Applicable Range of KCE-1 Correlation
 - Pressure : 2415 psia (Data : ~ 2490 psia)
 - Mass Velocity : 3.15 Mlbm/hr-ft² (Data : ~ 3.7 Mlbm/hr-ft²)
 - envisions to exceeding range : design methodology & restriction to design analysis out of range (DNB limiting cases)

Key of Draft Response to RAI and Strategy – 7/14

- **Class 90 : 7443-6 (Test Plan)**

- Appropriateness of test plan (1.47 Cosine, no Uniform/STT/STB)
 - Specific assumption of KCE-1 CHF Correlation
 - Tong Fc to adjust the effects of power shape
- Representative of tested power distribution to actual operational experiences
 - Intro. To Nuclear Engineering 3 e/d, JR Larmarsh & AJ Baratta
 - Technical basis of Tong Fc (See slides 8~15 & response to 7443-7)

Key of Draft Response to RAI and Strategy – 8/14

- **Class 90 : 7443-7 (Tong Fc)**
 - Standard Tong Fc rather than Optimized Fc for PLUS7
 - 1.47 Cosine shape only, no Uniform/STT/STB
 - Technical basis to Tong Fc : See slides 8 to 15.
 - Reasonable M/P per MDNBR elevation
 - Apply Standard Tong Fc []^{TS} to Design Analyses

TS

Key of Draft Response to RAI and Strategy – 9/14

- **Class 90 : 7443-8 & 9 (95/95 Limit)**
 - Subgroup for Pressure / Mass Velocity
 - Unfavorable M/P Parametric Trends : NRC Staffs
 - Region between grouped data by Pressure
 - Validity of single 95/95 limit
 - Assessment to Subgroup for Pressure / Mass Velocity
 - Statistical 95/95 vs. limiting 95/95
 - Original DB vs. Data with Relaxed Assumption
 - Assessment to Region between Pressure Subgroup
 - On going
 - Current 95/95 limit expected to be valid

Key of Draft Response to RAI and Strategy – 10/14

- **Class 90 : 7443-13 (Design Methodology to support AOO)**
 - not a Technical but a Strategic
 - Relevant Requests
 - Applicable Range : 7443-10 & 7443-18
 - Design Computer Codes & Methodology : 7443-14 ~ 7443-16
 - Strategic decision & Update to corresponding document(s)
 - On going
 - Keep the reference to AOOs

Key of Draft Response to RAI and Strategy – 11/14

- **Class 90 : 7443-14 (Sources of Uncertainty)**
 - Measurement Uncertainty
 - Instrumentation
 - Fabrication tolerances
 - Prediction Uncertainty
 - ...
 - Information will be included in topical report Uncertainty
 - requested information for uncertainties
 - evaluation of repeated data (replication)
 - design methodology including computer code uncertainty

Key of Draft Response to RAI and Strategy – 12/14

- **Class 90 : 7443-15 (Sources of Computer Code Input)**
 - Constitutive Relations
 - sources/references of them applied to CHF data analysis
 - applicable range of them
 - Information will be included in topical report Uncertainty
 - update corresponding references
 - justification to the input selections
 - Assessment results
 - effect of out-of-range for constitutive relations, if any

Key of Draft Response to RAI and Strategy – 13/14

- **Class 90 : 7443-16 (CETOP-D Computer Code)**
 - not a Technical but a Strategic
 - Topical Report for the CETOP-D code & Methodology
 - would be submitted to NRC
 - updates to corresponding document : on-going
 - Keep the reference to AOOs

Key of Draft Response to RAI and Strategy – 14/14

- **Class 90 : 7443-17 (Overfitting & Number of Test Data)**
 - Concept/Concern of Overfitting (no validation data)
 - Definition/Clarification : done
 - Assessment : on-going
 - Number of Test Data vs. Number of Data in DB
 - Corresponding information would be provided with clarification to prevent confusing

Discussions

- May 1, 2014.