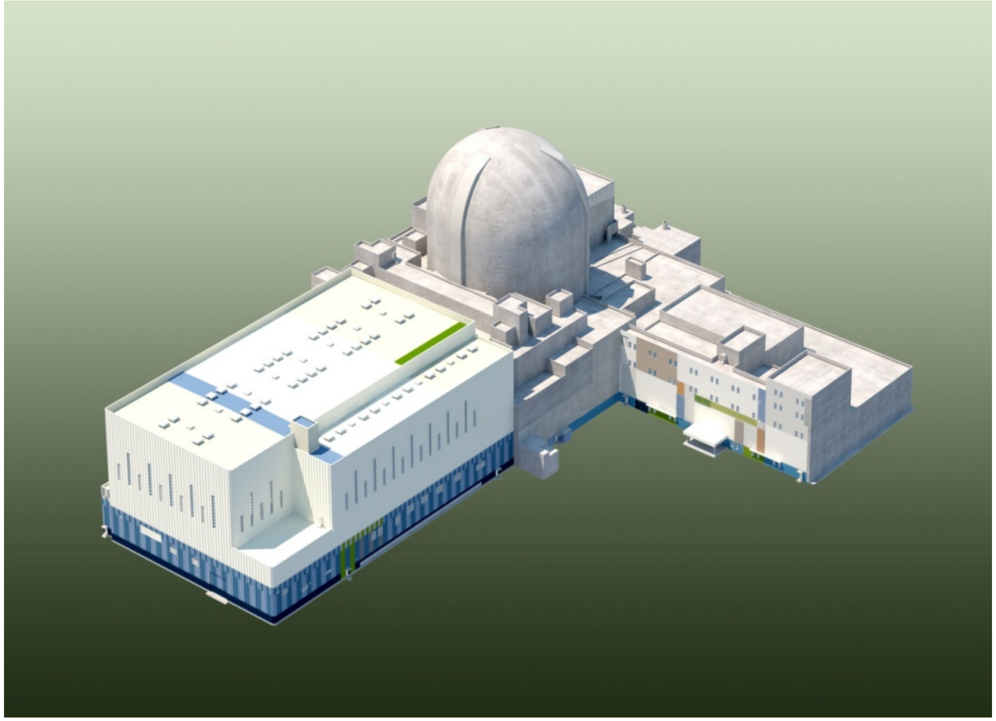
NON-PROPRIETARY

Meeting with NRC on KCE-1CHF Correlation for PLUS7 Thermal Design Topical Report



KEPCO/KHNP/Westinghouse

September 3, 2015

Public Meeting

Contents

- Introduction (KNF)
- Technical Presentation (Westinghouse)
- Conclusions (KNF)

Public Meeting

Introduction

Introduction

- **Timeline of Staff Review on KCE-1 CHF Correlation Topical Report (APR1400-F-C-TR-12002)**
  - ✓ Acceptance to Review : March 2013
  - ✓ Kick-off & Key Issues : August 2013
  - ✓ RAI 3-7443 : issued on March 2014
    - **Tech. Meeting : May 2014**
    - **Audit : January 2015**
    - **Updated Response to RAI 3-7443 : March 2015**
    - **Public Meeting – 1 : April 2015**
    - **Public Meeting – 2 : September 2015**
- **Pending Issue on 95/95 DNBR Limit**
  - ✓ Conservatisms in Tong Factor (*Fc*) application
  - ✓ M/P trends on specific subregion of Pressure
  - ✓ Validation data set
- **Assessment to Pending Issue : Technical Presentation**

Organizational Roles

- KHNP : Project/Licensing Lead
- KNF : Technical Lead
- WEC : Technical support to KNF/KHNP

Technical Presentation

Westinghouse

© 2015 Westinghouse Electric Company LLC. All Rights Reserved.

INTENTIONALLY BLANK

NON-PROPRIETARY

Technical Presentation Objectives

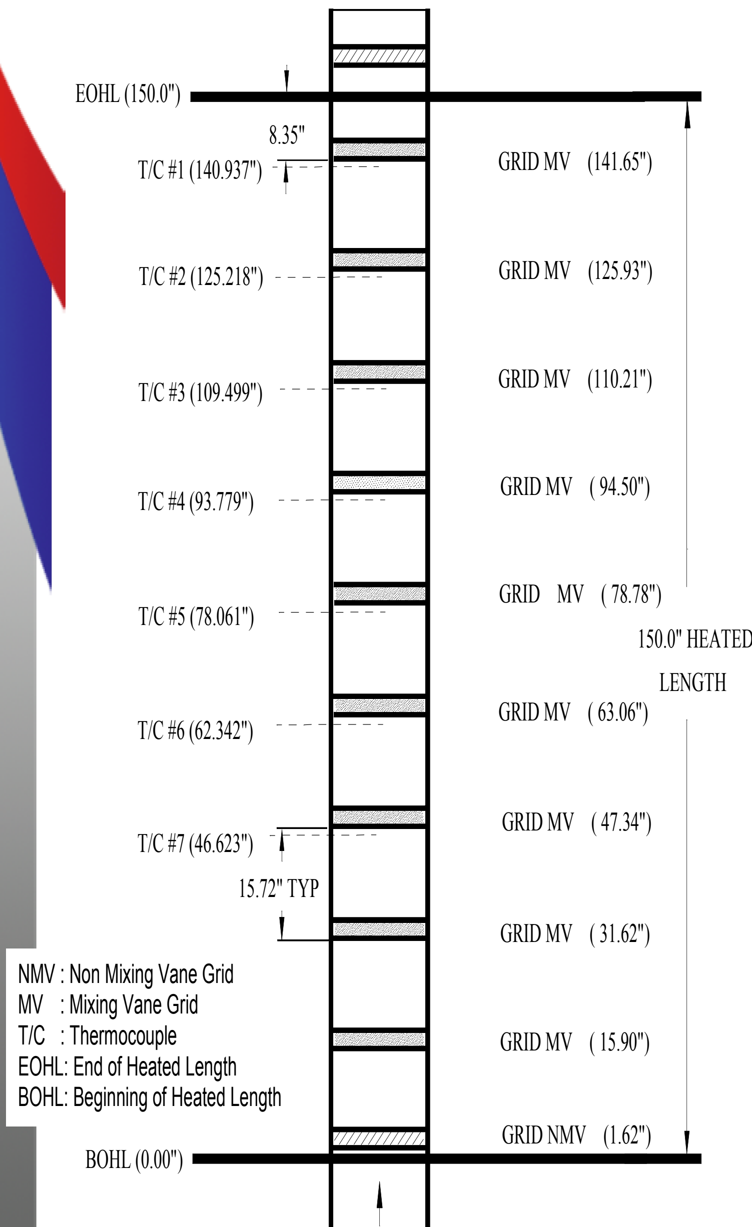
- **Additional response to following four RAI's:**
  - RAI #6
  - RAI #7
  - RAI #9
  - RAI #17
- **Justification on KCE-1 95/95 DNBR limit of 1.124**
- **Proposed supplemental submittal**

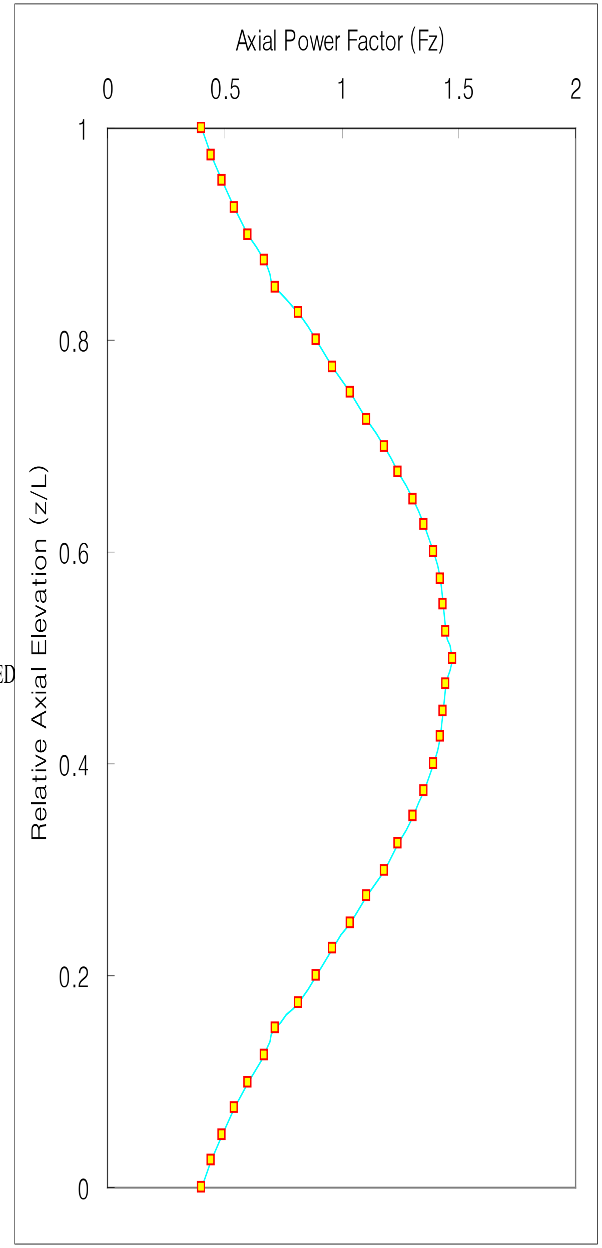
Public Meeting

Outline

- Axial Power Shapes and Tong (*Fc*) Factor
- Database for KCE-1 Development
- Database for KCE-1 Application
- Elements of Proposed Submittal

PLUS7 CHF Tests – Axial Diagrams





TS

Public Meeting

PLUS7 CHF Tests and Tong Factor (*Fc*)

- PLUS7 CHF data consistent with known physical phenomenon
  - CHF occurrences downstream the peak local heat flux

- Tong Factor (*Fc*) relates $q''_{CHF,NU}$ to $q''_{CHF,U}$
  - Fc defined in Section4.3 of APR1400-F-C-TR-12002-P

$$q''_{CHF,NU} = \frac{q''_{CHF,U}}{F_C}$$

Note that: $q''_{CHF,NU} < q''_{CHF,U}$ (*Fc* > 1)

Public Meeting

Fc and Cosine Shape

- ***Fc* accounts for "memory effect" of non-uniform axial power shape on CHF**
  - Memory effect as reflected in *Fc* is larger with cosine shape [ ][(a,c)]
- **Selection of cosine shape is appropriate for capturing effect of non-uniform axial power distribution on CHF**
  - Relatively large variations of Fc
  - [ ][TS] < *Fc* < [ ][TS] at DNB limiting elevations in the tests
  - Typical DNB limiting shape with a high radial peaking factor for design application

Original Tong Factor *Fc*

- Original *Fc* developed based on single tube and annuli data
  - Conservative with CE-1 based on comparisons with test data from several non-uniform axial shapes
  - Over-predicts axial power shape effect for fuel bundles with grid spacers
  - When uniform and non-uniform MV grid test data are available, *Fc* coefficient adjustments [

    ](a,c)
- Original Tong Factor applied to KCE-1
  - No coefficient adjustment

Original Tong Factor *Fc*

- **CE-1 Correlation based on uniform test data only, *Fc* = 1.0, CENPD-162-P-A.**
- **Per CENPD-207-P-A, CE-1 very conservative for tests with non-uniform axial power shapes and original Tong Factor**

Axial Power Shape	CE-1 M/P Avg.	CE-1 STD
1.68 Top Peaked	1.119	0.106
1.68 Bottom Peaked	1.287	0.130
1.46 Cosine	1.236	0.122
1.47 Top Peaked	1.254	0.083

- **KCE-1 more conservative than CE-1 since developed with non-uniform data and [ ] $^{TS,(a,c)}$**

Public Meeting

Fc and KCE-1 CHF Correlation

- Conservative approach for KCE-1 correlation development
  - Treatment of cosine data as [ ]TS,(a,c)
  - KCE-1 with [ ]TS,(a,c) under-predicts uniform CHF, because

$$q''_{CHF,NU} < q''_{CHF,U}$$

- Conservative application with original *Fc* for non-uniform axial power shapes
  - KCE-1 under-predicts cosine CHF by [ ]TS,(a,c)

$$q''_{CHF,NU} = \frac{q''_{CHF,U}}{F_C}$$

- Westinghouse experiences with WNG-1 and other DNB correlatio ns also indicate KCE-1 used with *Fc* contains DNBR margin for u niform and non-uniform axial shapes

Database for KCE-1 Correlation Development -1

- Database for correlation development contained [ ]TS,(a,c) data points (Table 5-3 of ToR)
  - Actual data points from 2 tests ~ 200
- Local fluid conditions from]TS,(a,c) were included
  - [ ]TS,(a,c)
    - [ ]TS,(a,c)
    - [ ]TS,(a,c)
    - [ ]TS,(a,c)

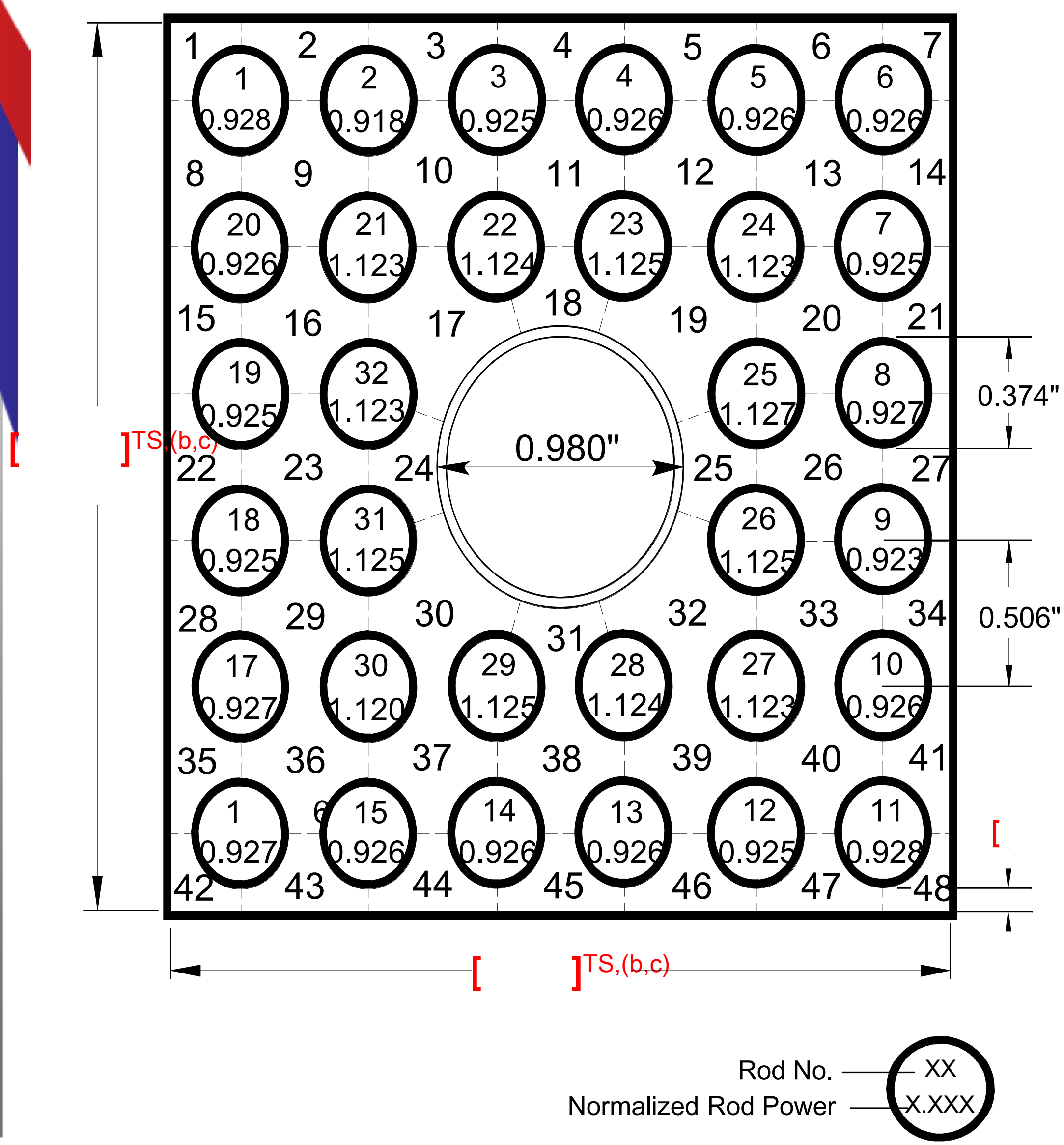
Public Meeting

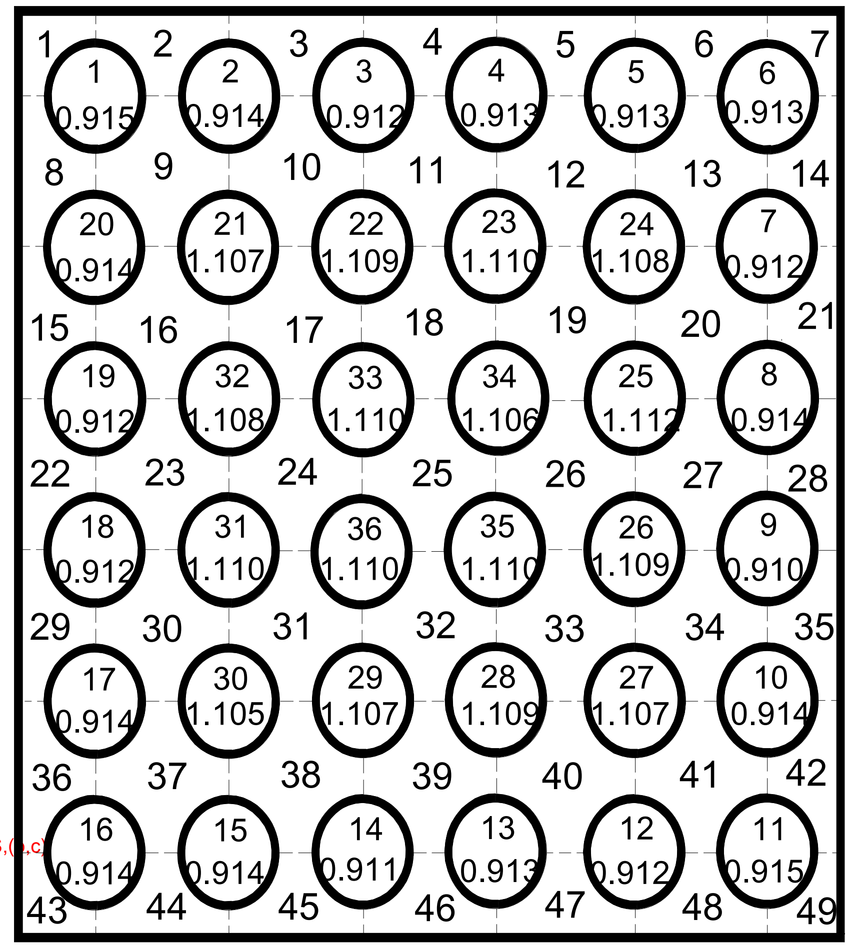
NON-PROPRIETARY

Database for KCE-1 Correlation Development -2

Test Section 101

Test Section 102





Public Meeting

NON-PROPRIETARY

Database for KCE-1 Correlation Development -3

- **The database for correlation development was used for deriving 95/95 DNBR limit of 1.124**
  - [ ]TS,(a,c)
  - [ ]TS,(a,c)

    ([ ]TS,(a,c))

- **Table 5-4 of Topical Report (KCE-1 development database M/P statistics with [ ]TS,(a,c))**

TS	N	M/P Avg.	M/P STD	Min. M/P	95/95 DNBR
101					
102					
ALL					

TS,(a,c)

Public Meeting

Database for KCE-1 95/95 Limit Justification -1

- KCE-1 test database (N = [ ]TS)
  - [
    ]TS
    - Tong (*Fc*) factor applied as in design application ([ ]TS)

- KCE-1 M/P statistics at MDNBR location among all subchannels
  - 95/95 DNBR [ ]TS < 1.124 [ ]TS conservatism

TS	N	M/P Mean	M/P STD	Min. M/P	95/95 DNBR	Remark
101						
102						
All						

TS

[

]TS

Public Meeting

Database for KCE-1 95/95 Limit Justification - 2

- M/P vs. Pressure plot shows the minimum M/P > 1/1.124 (DNBR limit) by ~ [ ]TS

TS

Public Meeting

Effect of Training and Validation Data Sets -1

- Training and Validation Data Sets evaluated based on correlation development database [ ]TS,(a,c)
  - 1000 cases for 80-20% random splits

- Evaluation confirmed effect of potential over-fitting without validation data (with [ ]TS basis) is less than conservatism in KCE-1 with Fc for design application
  - ~ [ ]TS

- Conservative uses of *Fc* in KCE-1 development and application result in significant margin to offset any potential overfitting without validation data set

NON-PROPRIETARY

Effect of Training and Validation Data Sets -

2. 95/95 DNBR Distribution (T80% vs. V20%)

TS

Public Meeting

Proposed Supplemental Submittal

- To clarify 95/95 DNBR limit conservatism, a supplemental response is proposed for submittal to NRC staff
  - Key technical results are shown in this presentation

- Elements in supplemental response include:
  - Clarification on databases for development and design application
  - M/P statistics with *Fc* at MDNBR locations and corresponding 95/95 DNBR values
  - M/P trend plots (conservatism in M/P with *Fc* as compared to limit of 1.124)
  - KCE-1 with Fc data table similar to A-3 (with A-2) ToR

Summary of Technical Presentation

- KCE-1 correlation and its 95/95 DNBR limit were conservatively developed using cosine test data [ ]TS,(a,c)

- KCE-1 applications are conservative using original *Fc* for non-uniform axial power shapes

- Within its applicable range, KCE-1 95/95 DNBR limit of 1.124 is conservative by about [ ]TS when used with [ ]TS

- Conservative uses of *Fc* in KCE-1 development and application result in significant margin to offset any potential overfitting without validation data set

Conclusions

Public Meeting

Conclusions

● KCE-1 CHF Correlation

✓ Quantified conservatism > the non-conservative perspective by the Staff

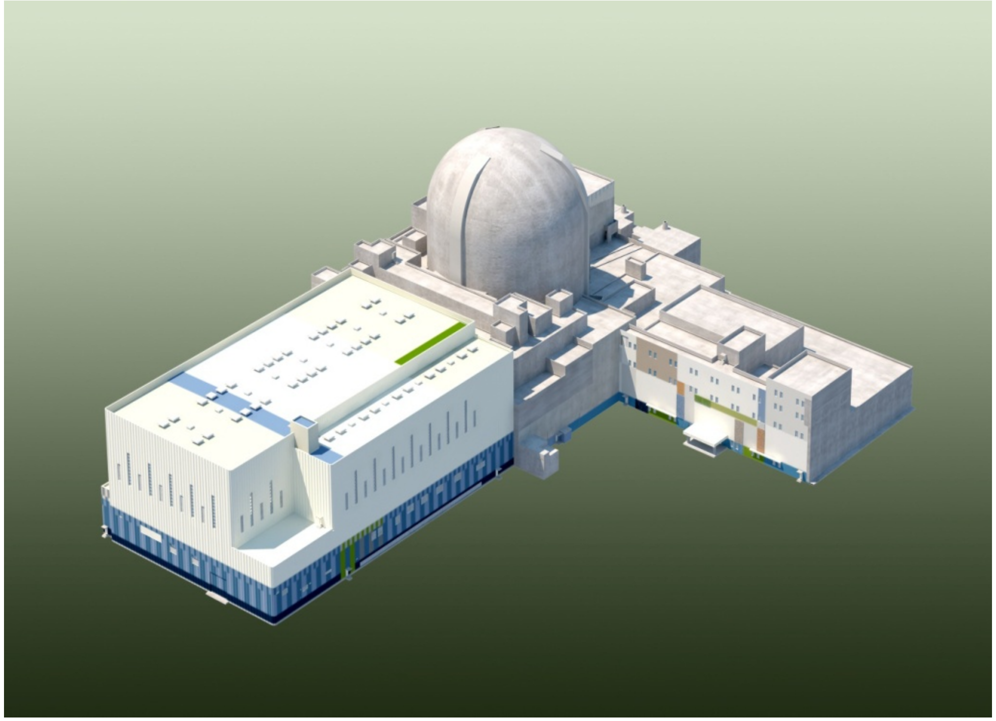
✓ 95/95 DNBR Limit (1.124) conservative with the limitations on

- Applicable range of variables in ToR and reduced pressure range of 1750 ~ 2415 psia
- Use of as-calculated Tong Factor ([ ]TS) described in ToR
- Subchannel code (TORC) with constitutive relations described in ToR

Public Meeting

NON-PROPRIETARY

Meeting with NRC on KCE-1CHF Correlation for PLUS7 Thermal Design Topical Report



KEPCO/KHNP/Westinghouse

September 3, 2015

Public Meeting

Supplemental Information

RAI #6

The CHF test data for the PLUS7 fuel geometry were obtained by using a non-uniform axial power distribution, a symmetric cosine power profile shape with a peak of 1.475. The applicant should explain the appropriateness of testing single axial profile and why the inlet/bottom or outlet/top peaked power profiles were not included in the test matrix. The applicant should describe how well the tested power distribution represents the actual profile experienced during the operation of the PLUS7 fuel.

RAI #7

As no testing was conducted with uniform axial power distribution, no "non-uniform axial power distribution correction factor, Tong factor *FC*," could be developed for the KCE-1 CHF correlation for the tested PLUS7 fuel geometry. Such an optimization of Tong factor for the PLUS7 fuel split vane mixing grid geometries would require testing both uniform and Non-uniform axial power distributions with and without guide thimbles, but it was not done for the tested PLUS7 fuel geometry. However, the applicant plans to conservatively use the Tong factor along with the KCE-1 correlation to predict the CHF in the design analyses. The applicant should justify using the CE-1 Correlation Tong factor not developed for the tested PLUS7 fuel geometry. Other CHF correlations generally use Tong factor developed by the test data taken with both uniform and non-uniform axial power profiles.

RAI #9

Detailed investigation of the test data, conducted by the staff, has revealed a potentially non-conservative sub-region at pressures near 1750 psia, qualities near 0.1, and local mass fluxes near 2 Mlbm/hr-ft^2. This Sub-region contains a higher than expected number of M/P values which were below the 95/95 statistic than can be explained by random chance. Provide justification for the use of the KCE-1 correlation in this sub-region, and the surrounding empty sub-regions.

RAI #17

In the development of a correlation, the potential for overfitting exists in which the correlation can predict the data used to develop the correlation well, but lacks in predictive capability on other data not used in the development of the correlation. It is not clear from the topical report whether some test data were initially excluded from the KCE-1 correlation coefficient generation and were used later as additional points for independent correlation validation. The applicant should address the potential for overfitting in the KCE-1 correlation.

The applicant should also resolve the inconsistencies among the number of data points reported in various parts of the report. During the PLUS7 fuel CHF tests, [ ]TS test data for the thimble subchannel test section Test Section 101 and [ ]TS data for the matrix subchannel test section Test Section 102 were collected, respectively. The [ ]TS test data points are listed in Table A-1 of APPENDIX A. Table A-2 lists [ ]TS test data points that were rejected during the correlation development process. The applicant needs to explain how this data processing has led to an overall KCE-1 CHF correlation database of [ ]TS."

The two hundred and twenty-five (225) data points cited in the abstract as well as in Section 5.2 of the report are also confusing.

Also provide clear descriptions identifying the following:

(A) The total number of test points for each test

(B) The total number of test points which were used for generating the coefficients of the correlation for each test.

(C) The total number of test points which were excluded from calculating the coefficients of the correlation for each test.

(D) The validation statistics (similar to that provided in the first table of Table 5-4) for both (B) and (C) above. Statistics should be provided for each test.

CHF with Non-Uniform Axial Shape

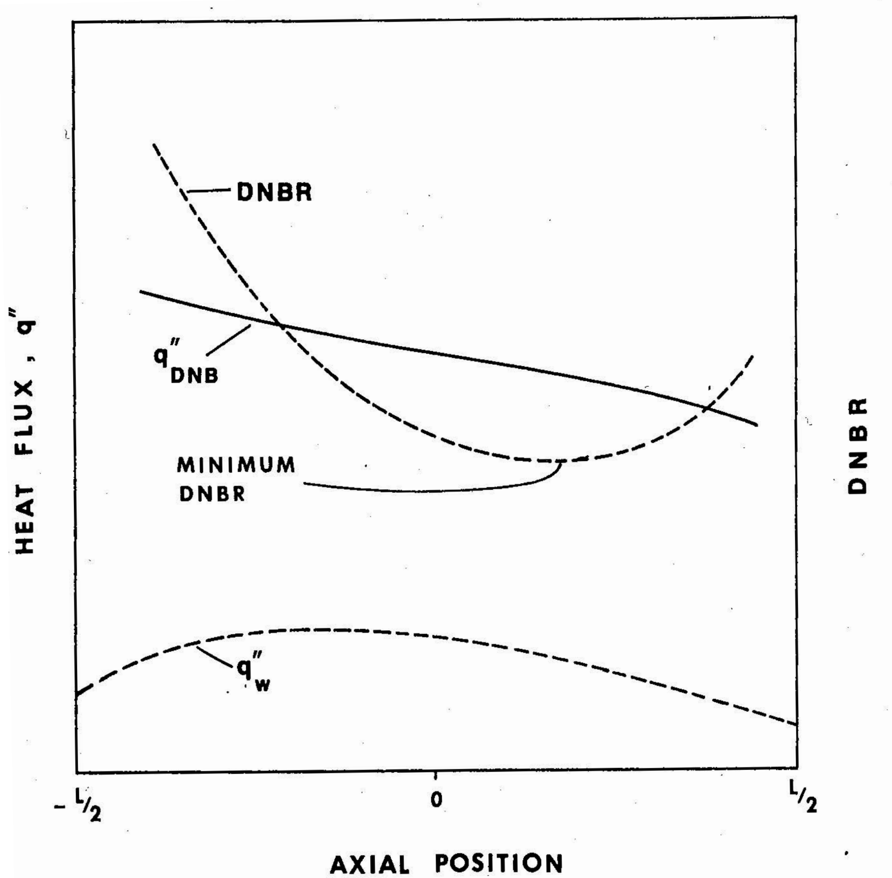


Fig. 7. 5. Channel axial distribution for q''_w, q''_{DNB}, and DNBR .

James H. Rust,
“Nuclear Power Plant Engineering”
Haralson, 1979

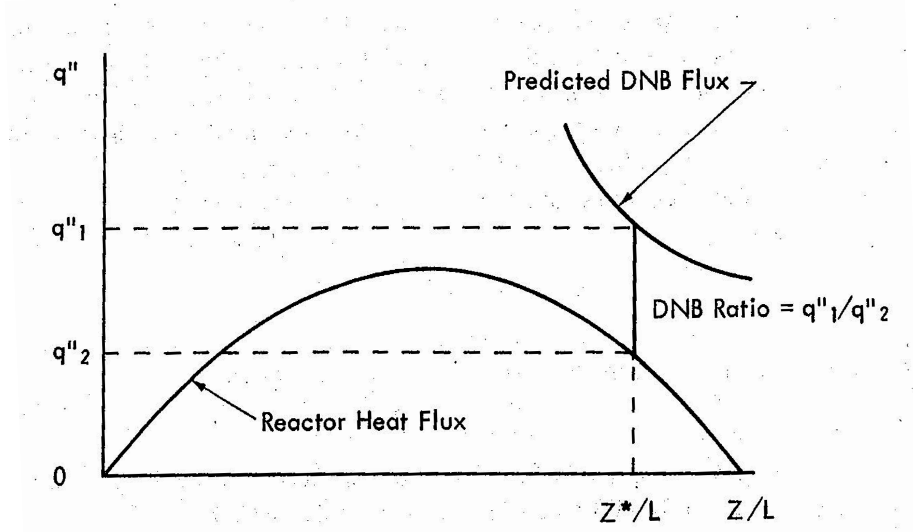


Fig. 5-3. The DNB ratio evaluation. [From *Nucl. Eng. Des.*, **6**, 301 (1967).]

Tong & Weisman,
“Thermal Analysis of Pressurized Reactors”
2nd Edition, ANS, 1979

Non-uniform MDNBR occurs at local q” < max local q”

WNG-1 and KCE-1 Results for Test 102

- **Test 102 is validation data sets for WNG-1 correlation, WCAP-16766-P-A. WNG-1 correlation has uniform and non-uniform data and Fc optimized based on that data. WNG-1 and KCE-1 M/P statistics for Test 102 are :**

Correlation	M/P Avg.	M/P STD
WNG-1 (Opt. Fc)	[ ]TS,(a,c)	[ ]TS,(a,c)
KCE-1 (Fc=1)	[ ]TS,(a,c)	[ ]TS,(a,c)
KCE-1 (Tong Fc)	[ ]TS	[ ]TS

- **$q''_{CHF,U}$ values for Test 102 can be calculated from KCE-1 with [ ]TS,(a,c) and WNG-1 with optimized *Fc* at the same elevation to quantify the conservatism in KCE-1**

Test 102	$q''_{WNG-1,U} / q''_{KCE-1,U}$
Average	[ ]TS,(a,c)

Public Meeting

Database for KCE-1 95/95 Limit Justification

- KCE-1 M/P with *Fc* Applied

TS

Database for KCE-1 95/95 Limit Justification

- KCE-1 M/P with *Fc* Applied

TS

Database for KCE-1 95/95 Limit Justification

- KCE-1 M/P with *Fc* Applied

TS

Public Meeting

Database for KCE-1 95/95 Limit Justification

- KCE-1 M/P with *Fc* Applied

TS

Public Meeting

Effect of Training and Validation Data Sets

- Same database for 95/95 DNBR limit of 1.124, [ ]TS,(a,c)
- 80% vs. 20% data random splits : 1000 Cases

TS

Public Meeting

Effect of Training and Validation Data Sets

- **Statistics of Avg. M/P Distribution (T80% vs. V20%)**

	Group	Case	Average	STD	Remark

TS

Public Meeting

Effect of Training and Validation Data Sets

- Effect of training and validation data sets with [ ]TS,(a,c) is less than conservatism in M/P with *Fc*
- Statistics of 95/95 DNBR Distribution

	Group	Case	Average	STD	Remark

TS

[ ]TS

cf. 5-fold result on Response to Question 17 of RAI 3-7443

Group	N	M/P Mean	M/P STD.	95/95 DNBR	Remark
Training					
Validation					
All					

TS

Effect of Training and Validation Data Sets

- Statistics of M/P for Case of [ ]TS 95/95 DNBR

Case	Group	n	Average	STD	Remark

TS

Public Meeting

Effect of Training and Validation Data Sets

- **Statistical Tests of M/P for Case of [ ]TS 95/95 DNBR**

Case	Test		Statistics*	P-value	Result

TS

Lilliefors, H., "On the Kolmogorov-Smirnov test for normality with mean and variance unknown",
Journal of the American Statistical Association, Vol. 62, pp.399-402.

Public Meeting

NON-PROPRIETARY

Effect of Training and Validation Data Sets

- M/P Trend Plots for Case of [ ]^{TS} 95/95 DNBR

TS

Public Meeting

List of Database for KCE-1 95/95 Limit Justification / Application

Public Meeting

See Separately Attached File : KCE-1 Database for Application (Appendix_APR1400-F-C-EC-15004-NP)

- Table A-1 : Similar to Table A-2 of ToR
- Table A-2 : Similar to Table A-3 of ToR