Framatome ANP, Inc.

Appendix A

Extension of the HTP CHF Correlation Ranges

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A.1 Introduction and Summary

This Appendix represents Revision 1 to the original version of the topical report EMF-92-153(P)(A) (Reference 1). The purpose of this revision is to extend the range of applicability of the correlation in terms of its independent variables. The need to extend the range of applicability of the independent variables exists because conditions are generated in plant specific analyses which are outside of the original range.

The HTP CHF correlation is based on [ ]* data from [ ] separate CHF tests at the Columbia University Heat Transfer Research Facility (HTRF). These tests were conducted in the late 1980s to early 1990s time frame. The HTRF was officially closed by the university on December 31, 2003.

The HTP CHF correlation is [ ]. This type of correlation is termed a [ ] correlation. Its major independent variables, in addition to quality, are system pressure and local mass velocity. The CHF calculated from these local thermal hydraulic conditions is modified by a [ ]. All of these terms are applied multiplicatively as shown in Section 2 of the main body of this report.

Other examples of [ ] correlations are the Westinghouse W-3 correlation (Reference 5) and the Framatome ANP BWC and BWCMV correlations, References 6 and 7, respectively. This type of correlation is generally limited to relatively low qualities at CHF (well below 40%), mass velocities above 0.8 Mlb/hr-sq ft and pressures above about 1400 psia. The specific ranges of the HTP correlation, as approved in Reference 1, are shown in Table A.1. These are the ranges over which the HTP correlation was optimized (correlated).

* *Note: The original issue of EMF-92-153(P)(A), Reference 1, documented [ ] data. A letter was supplied to the NRC, in Reference 8, that explained minor changes in the HTP data base.*

Table A.1 Approved Range of Independent Variables for the HTP CHF Correlation

Independent Variable	Minimum Value	Maximum Value
System Pressure, psia	1775	2425
Mass Velocity, Mlbm/hr-ft^2	0.936	3.573
Thermodynamic Quality at CHF	-0.125	0.358

The revised range of applicability of the HTP correlation justified in this Appendix is shown in Table A.2 below. The changes in the range of applicability are:

1. A reduction in the lower pressure limit, lower mass velocity limit, and lower quality limit, and
2. An increase in the upper pressure limit and upper quality limit.

Table A.2 Revised Range of Independent Variables for the HTP CHF Correlation

Independent Variable	Minimum Value	Maximum Value
Pressure, psia	1385	2540
Mass Velocity, Mlbm/hr-ft^2	0.498	3.573
Thermodynamic Quality at CHF	No Lower Limit*	0.515

* because of increasingly conservative trend of lower quality extrapolation

The previously approved range of inlet enthalpy and the fuel design parameters from Tables 1.1 and 1.2, respectively, of Reference 1 will remain applicable.

A.2 Methods of Extending the Independent Variable Ranges

There are three methods to extend the range of applicability of the HTP correlation:

Method 1: Obtain CHF data in the extended ranges and reoptimize the correlation. For this method the new broader limits are automatically based on the range of the enlarged data base.

Method 2: Obtain CHF data in the extended ranges and apply the original correlation without reoptimization. If the additional (uncorrelated) data is correctly predicted by the original correlation or is conservative with respect to the CHF predicted by the original correlation, the new limits are verified.

Method 3: The original correlation can be simply applied in the extended ranges. Here, of course, sufficient demonstrations of the suitability and/or conservatism of the extrapolations are necessary.

The use of Method 1 would require reanalysis of current plant specific results and thus will not be used. Method 2 will be used to extend the lower pressure limit, the lower mass velocity limit and the upper quality limit. Method 3 will be used to extend the lower quality limit and the upper pressure limit with multiple justifications of the suitability and conservatism of this approach.

The justification for the extension of the range of applicability of the HTP correlation independent variables is presented in two parts:

Part 1 – Extension of the Ranges Using Data with Method 2, and

Part 2 – Extension of the Ranges by Extrapolation with Method 3.

A.3 Part 1 – Extension of the Ranges Using Data with Method 2

A.3.1 *Data Base for Justification*

A significant amount of HTP CHF data were obtained at the Columbia HTRF beyond the approved applicability ranges defined in Table A.1. These additional CHF data were not utilized in the establishment of the HTP CHF correlation. The additional data were obtained in [ ] of the [ ] tests and consisted of [ ] data overall. The additional data are in pressure groups of 1400, 1000 and 600 psia, mass velocities down to 0.25 Mlb/hr-ft^2 and thermodynamic qualities at CHF of up to 58 percent.

These [ ] tests covered the range of physical fuel design parameters in the correlation as defined in Table 1.2 of the body of the report (Reference 1). The data at 600 and 1000 psia were obtained in only 5 of the tests and did not cover a sufficiently wide range of fuel design parameters. Thus, only the 1400 psia data will be used to justify the extension to lower pressure, lower mass velocity and higher quality [ ].

In addition, there were only two of the 1400 psia data at low mass velocities (0.25 Mlb/hr-ft^2) and one point at high quality (at 58 percent). These three data were removed from the 1400 psia group of data leaving [ ] data with which to justify the extensions. This [ ] data base will be referred to as the "New" or "Uncorrelated" data while the original [ ] data base will be referred to as the "Original" or "Correlated" data.

The test conditions (experimental) for the New data are contained in Table A.8. Table A.99 contains the resulting local conditions and P/M CHF values resulting from the application of the original HTP CHF correlation with the XCOBRA-IIIC thermal-hydraulic analysis code (Reference 2).

A.3.2 *Extension of the Upper Quality Limit*

The New data range in thermodynamic quality from –0.019 to 0.515. The Original and New data are plotted against quality (using the original HTP CHF correlation) in Figures A.1 and A.2, respectively. Both data sets are combined and shown in Figure A.3. The New data is generally conservative with respect to the Original data, P/M values below 1.0 are conservative in that the Measured (M) CHF obtained in the test are greater than the value Predicted (P) by the HTP correlation. The New data is about 10 percent conservative overall with an average P/M of 0.8922 versus the Original average P/M of 0.9938.

The upper limit in thermodynamic quality at CHF can be extended to 0.515 (51.5 percent) based on these data and analysis with the original HTP correlation,.

A.3.3 *Extension of the Lower Mass Velocity Limit*

The New data range in mass velocity from 0.498 to 3.542 Mlb/hr-ft^2. The Original and New data are plotted against mass velocity (using the original HTP CHF correlation) in Figures A.4 and A.5. The data sets are combined and shown in Figure A.6. The New data is generally conservative with respect to the Original data as shown in Figures A.5 and A.6.

The data below one million lb/hr-ft^2 is the most important data for the extension of the lower mass velocity limit. In this subgroup of [ ] data the mean P/M is 0.979 (2.1 percent conservative) with [ ] data having a P/M less than 1.0. The combined scatterplot (Figure A.6) shows good performance about the 1.0 line with no slope (bias). The conservative trend of the New data is most evident in the medium mass velocity range (1.0 to 2.0 Mlb/hr-ft^2).

The lower limit in mass velocity can be extended to 0.498 Mlb/hr-ft^2 based on these data and analysis with the original HTP correlation.

A.3.4 *Extension of the Lower Pressure Limit*

The New data is comprised of the 1400 psia data group (1385 to 1430 psia). The 1400 psia data is conservative by about 10 percent overall with the vast majority of P/M values below a value of 1.0 ([ ]). The conservatism of the data is shown in Figure A.7.

The lower limit in pressure can be extended to 1385 psia based on these data and analysis with the original HTP correlation,

A.3.5 *Effect of Different Geometries on the Extended Data*

The extension of the HTP correlation was examined to verify that the extension of the HTP correlation is conservative for each approved assembly geometry. The examination was performed for each test section since each tests section represents a single geometry.

The Average P/M CHF values are shown for each test section in Figure A.8. The test section averages for the original data are represented by the open bars. The shaded bars (which overlay the open bars) represent the average of the extended data only.

Note that there is extended data for [ ] tests: only tests 62, 63 and 66 through 68 lacked extended data. Further note that in each test section that had extended data, the average of the extended data is conservative with respect to the original data (the extended data P/M is lower than the original data P/M in all cases).

This comparison indicates that in no case does the differing geometry produce a non-conservative trend when the HTP correlation is applied to the extended data. Therefore, it is concluded that the entire set of the [ ] extended data can be used to conservatively extend the range of independent variables of the HTP correlation.

**Figure A.1 P/M CHF versus Thermodynamic Quality at CHF
Original HTP Data Base with HTP Correlation**

**Figure A.2 P/M CHF versus Thermodynamic Quality at CHF
New (Uncorrelated) HTP Data with HTP Correlation**

Figure A.3 P/M CHF versus Thermodynamic Quality at CHF Original and New (Uncorrelated) HTP Data with HTP Correlation

Range of Independent Variables for the HTP CHF Correlation with the Extension of the Upper Quality Limit

	As Approved		Extended	
Independent Variable	Minimum Value	Maximum Value	Minimum Value	Maximum Value
System Pressure, psia	1775	2425	1775	2425
Mass Velocity, Mlbm/hr-ft^2	0.936	3.573	0.936	3.573
Thermodynamic Quality at CHF	-0.125	0.358	-0.125	**0.515**

**Figure A.4 P/M CHF versus Local Mass Velocity
Original HTP Data Base with HTP Correlation**

**Figure A.5 P/M CHF versus Local Mass Velocity
New (Uncorrelated) HTP Data with HTP Correlation**

Figure A.6 P/M CHF versus Local Mass Velocity
Original and New (Uncorrelated) HTP Data with HTP Correlation

Range of Independent Variables for the HTP CHF Correlation with the Extension the Upper Quality and Lower Mass Velocity Limits

	As Approved		Extended	
Independent Variable	Minimum Value	Maximum Value	Minimum Value	Maximum Value
System Pressure, psia	1775	2425	1775	2425
Mass Velocity, Mlbm/hr-ft^2	0.936	3.573	**0.498**	3.573
Thermodynamic Quality at CHF	-0.125	0.358	-0.125	**0.515**

Figure A.7 P/M CHF versus System Pressure
Original and New (Uncorrelated) HTP Data with HTP Correlation

Range of Independent Variables for the HTP CHF Correlation with the Extension of the Upper Quality and Lower Mass Velocity and Pressure Limits

	As Approved		Extended	
Independent Variable	Minimum Value	Maximum Value	Minimum Value	Maximum Value
System Pressure, psia	1775	2425	**1385**	2425
Mass Velocity, Mlbm/hr-ft^2	0.936	3.573	**0.498**	3.573
Thermodynamic Quality at CHF	-0.125	0.358	-0.125	**0.515**

Figure A.8 Histogram of Test Section P/M CHF Averages For the Original HTP Data Base and for the New Data

A.4 Part 2 – Extension of the Ranges by Extrapolation with Method 3

A.4.1 *The Question of Extrapolation*

The justification of the extension of a correlation's independent variable range using new or previously uncorrelated data is relatively straightforward. Part 1 of this appendix demonstrates that such an extension is valid if the predicted CHF under the new conditions is accurate or conservative as long as the safety limit remains valid (or is changed to preserve the original margin).

The correlation must be extrapolated, rather than extended, when no data exists in the range where it is desired to use the correlation. Three questions will be considered as part of the justification of extrapolating the correlation:

A.4.2 *Trends When Extrapolating the HTP CHF Correlation (Technique 1)*

[ ]

A.4.2.1 Q_{CHF} Versus Pressure in Parameters of Quality

[ ]

A.4.2.2 Q_{CHF} Versus Mass Velocity in Parameters of Quality

[ ]

A.4.2.3 Q_{CHF} Versus Pressure in Parameters of Mass Velocity (Low Quality)

[ ]

A.4.2.4 Q_{CHF} Versus Pressure in Parameters of Mass Velocity (High Quality)

[ ]

[ ]

A.4.2.5 Results of the "Trend" Investigations

[ ]

Figure A.9 CHF Versus System Pressure Parameters of Quality at Constant Mass Velocity

Figure A.10 CHF Versus Mass Velocity Parameters of Quality at Constant Pressure

Figure A.11 CHF Versus System Pressure
Parameters of Mass Velocity at Constant Low Quality

Figure A.12 CHF Versus System Pressure Parameters of Mass Velocity at Constant High Quality

A.4.3 *Re-correlation and Extrapolation of Subsets of the Original Data (Technique 2)*

A.4.3.1 Direction of Extrapolation (Quality)

[ ]

A.4.3.2 Length of Extrapolation (Pressure)

[ ]

Figure A.13 P/M CHF Versus Thermodynamic Quality at CHF Study Showing Negative Extrapolation (High to Low)

Figure A.14 P/M CHF Versus Thermodynamic Quality at CHF Study Showing Positive Extrapolation (Low to High)

Figure A.15 P/M CHF Versus Thermodynamic Quality at CHF Study Showing Negative and Positive Extrapolation

**Figure A.16 P/M CHF Versus System Pressure
Extrapolation of 50 and 150 Percent of Correlated Range**

A.4.4 *Extrapolation to Lower Qualities and Higher Pressure*

A.4.4.1 Justification of Extrapolation to Lower Quality

[ ]

A.4.4.2 Justification of Extrapolation to Higher Pressure

[ ]

Figure A.17 P/M CHF Versus Thermodynamic Quality at CHF Original HTP Data Base With HTP-HIGH Correlation

**Figure A.18 P/M CHF Versus Thermodynamic Quality at CHF
Original HTP Data Base With HTP-HIGH Correlation**

Figure A.19 P/M CHF Versus Thermodynamic Quality at CHF Original HTP Data Base With HTP-HIGH Correlation

**Figure A.20 P/M CHF Versus System Pressure
Original HTP Data Base With HTP-LOW Correlation**

Figure A.21 P/M CHF Versus System Pressure
Mark B and Mark C Non-Mixing Grid Data With BWU Correlation

A.4.5 *Consequences of Extrapolation (Technique 3)*

A.5 Summary

In Section A.2 the objectives of this topical addendum were stated to be:

1. Extend the lower pressure limit, the lower mass velocity limit and the upper quality limit using "new" (previously uncorrelated) data from the HTP data base.

2. Extend the lower quality limit and the upper pressure limit using a conservative extrapolation method (providing multiple justifications of the suitability and conservatism of this approach).

The following three tables show the progression in achieving these objectives.

Table A.3 Range of Independent Variables for the HTP CHF Correlation as Approved With Original Data

Independent Variable	Minimum Value	Maximum Value
Pressure, psia	1775	2425
Mass Velocity, Mlbm/hr-ft^2	0.936	3.573
Thermodynamic Quality at CHF	-0.125	0.358

Table A.4 Range of Independent Variables for the HTP CHF Correlation With New (Uncorrelated) Data

Independent Variable	Minimum Value	Maximum Value
Pressure, psia	**1385**	2425
Mass Velocity, Mlbm/hr-ft^2	**0.498**	3.573
Thermodynamic Quality at CHF	-0.125	**0.515**

Table A.5 Range of Independent Variables for the HTP CHF Correlation With Extrapolated Low Quality and High Pressure

Independent Variable	Minimum Value	Maximum Value
Pressure, psia	1775	**2540**
Mass Velocity, Mlbm/hr-ft^2	0.936	3.573
Thermodynamic Quality at CHF	**No Lower Limit***	0.358

* because of increasingly conservative trend of lower quality extrapolation

A.6 Conclusion

It has been shown here through both the application of new (uncorrelated) data and conservative extrapolation techniques that the HTP correlation can be extended to the following ranges and statistical parameters. The previously approved range of inlet enthalpy and the fuel design parameters from Tables 1.1 and 1.2, respectively, of Reference 1 will remain applicable.

Table A.6 Range of Independent Variables for the HTP CHF Correlation

Independent Variable	Minimum Value	Maximum Value
Pressure, psia	1385	2540
Mass Velocity, Mlbm/hr-ft^2	0.498	3.573
Thermodynamic Quality at CHF	No Lower Limit*	0.515

* because of increasingly conservative trend of lower quality extrapolation

Table A.7 Statistical Parameters for the HTP CHF Correlation

A.7 References

1. EMF-92-153(P)(A), *HTP: Departure From Nucleate Boiling Correlation for High Thermal Performance Fuel*, March 1994.

2. EMF-CC-093(P) Revision 5, *XCOBRA-IIIC Theory and User's Manual*, April 2004.

3. Norman R. Draper and Harry Smith, Applied Regression Analysis, John Wiley & Sons, Third Edition, 1998.

4. BAW-10199PA, *The BWU CHF Correlations*, D. A. Farnsworth and G. A. Meyer, December 1999.

5. L. S. Tong, "Prediction of Departure from Nucleate Boiling for an Axially Non-Uniform Heat Flux Distribution," Journal of Nuclear Energy, Volume 21, 1967, pp.241-248.

6. BAW-10143P-A, *BWC Correlation of Critical Heat Flux*, R. H. Wilson, D. A. Farnsworth, and R. H. Stoudt, April 1985.

7. BAW-10159P-A, *Correlation of Critical Heat Flux in Mixing Vane Grid Fuel Assemblies*, D. A. Farnsworth and G. A. Meyer, July 1990.

8. Letter, J. Mallay (Framatome ANP) to the NRC Document Control Desk, "Topical Report EMF-92-153(P)(A) and Supplement 1, *HTP: Departure from Nucleate Boiling Correlation for High Thermal Performance Fuel*", NRC:03:010, January 28, 2003.

Table A.8 Additional HTP Data – Bundle Conditions

Following are the bundle conditions (test conditions) of the [ ] additional data. These data are used for justification of the extension of the independent variables beyond the applicability ranges defined by the original HTP data base in Reference 1.

Units:

ID : XXYYY where XX is the test section number and YYY is the run number
P : Pressure, psia
Tin : Inlet Temperature, F
G : Mass Velocity, Mlb/hr-ft^2
Q" : Average Heat Flux, MBtu/hr-ft^2

Table A.9 Additional HTP Data – Local Conditions and HTP Results

Following are the results of applying the original HTP CHF correlation to the [ ] additional data. These data are used for the justification of the extension of the independent variables beyond the applicability ranges defined by the original HTP data base in Reference 1.

Units:

ID - XXYYY where XX is the test section number and YYY is the run number
P/M CHF : Predicted to Measured CHF Ratio
CHF : Measured CHF, Btu/hr-ft^2
P : Pressure, psia
G : Mass Velocity, lb/hr-ft^2
Zchf : Location of CHF, inches
F Fact : Non-uniform AFS factor
Hin : Inlet Enthalpy, Btu/lb