DNB TESTS FOR US-APWR FUEL

Non-Proprietary Version

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Revision History

Revision	Page	Description
0	All	Original issue
1	vi 28	- Acronyms “BOC” and “HFP” were added in the list of acronyms. - Supplemental explanations *3 to *8 were added in Table 7.2-2.
2	27, 31-35 28, 36, 39 59-74	- Figures 7.2-1 through 7.2-5 were modified by indicating data outside the applicable range of WRB-1/2 correlation. Description was modified accordingly. - M/P statistics and Limit DNBR were calculated by excluding data outside the applicable range of WRB-1/2 correlation. Table 7.2-1, Table 7.3-3 and related descriptions were modified accordingly. - Data outside the applicable parameter range of WRB-1/2 correlation were identified in Table C-1 through C-4.

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Abstract

Mitsubishi Heavy Industries, Ltd. (MHI) conducted additional DNB tests for 14-foot test bundles, which are representative for the US-APWR fuel design. The objective of the DNB tests is to provide a confirmation of the applicability of the existing WRB-1 and WRB-2 correlations for 14-foot-long fuel. It serves as the supplement to Topical Report "MUAP-07009-P, THERMAL DESIGN METHODOLOGY" which described VIPRE-01M code and DNB correlations for the US-APWR design applications.

MHI previously conducted 12-foot DNB tests using the US-APWR grid designs at the Heat Transfer Research Facility of Columbia University (HTRF) in New York. However, because of the shutdown of HTRF, the current tests were conducted at Karlstein Thermal-Hydraulic Facility of AREVA NP GmbH (KATHY). [

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Then, the DNB tests for 14-foot test bundles were conducted to collect the data for fluid conditions which bound coolant conditions for DNB analyses relevant to all the normal operation and anticipated operational occurrences of the US-APWR core. The DNB test data were evaluated using WRB-1/VIPRE-01M and WRB-2/VIPRE-01M to obtain *M/P* values. As a result, it was confirmed through the current DNB test for 14-foot heated length that *M/P* values are randomly distributed and there is no significant dependency on the fluid conditions. [

] It was confirmed that the limit DNBR deduced from the original database for WRB-1 and WRB-2 can be conservatively applied for DNB related safety analysis of US-APWR. This result can justify that WRB-2 correlation with the limit DNBR based on the original database is adopted in the US-APWR safety analyses.

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List of Acronyms

ANOVA	Analysis of Variance
BOC	Beginning of Cycle
DNB	Departure from Nucleate Boiling
DNBR	Departure from Nucleate Boiling Ratio (predicted-to-actual DNB heat fluxes ratio)
HFP	Hot Full Power
HTRF	Heat Transfer Research Facility of Columbia University
KATHY	Karlstein Thermal-Hydraulic Facility in AREVA NP GmbH
MHI	Mitsubishi Heavy Industries, Ltd.
M/P	Measured-to-Predicted DNB heat fluxes ratio
NRC	United States Nuclear Regulatory Commission
RPF	Rod Power Factor
SS	Simple Support
TS	Test Section

1.0 INTRODUCTION

Mitsubishi Heavy Industries, Ltd. (MHI) issued a Topical Report “MUAP-07009-P, THERMAL DESIGN METHODOLOGY”, which described the VIPRE-01M code and DNB correlations for the US-APWR design applications (Reference 1.0-1). During the review of the topical report, the applicability of the proposed DNB correlations, WRB1 and WRB-2, to the US-APWR fuel design has been discussed between the United States Nuclear Regulatory Commission (NRC) and MHI (References 1.0-2 and 1.0-3). The point of concern from the NRC staff was that the 14-foot-long heated length of the US-APWR fuel design might not be covered by the 12-foot DNB test data which was presented in the topical report. As a result, MHI determined to conduct additional DNB tests using 14-foot test bundles, which are representative for the US-APWR fuel design, to confirm the applicability of the existing WRB-1 and WRB-2 correlations for both the 12-foot and 14-foot heated lengths. These additional DNB test data are used as supplementary data base to those in MUAP-07009-P.

The DNB test plan of the 14-foot-bundle test program for the US-APWR fuel was submitted to the NRC (References 1.0-4 and 1.0-5). This program consisted of a series of DNB tests using two test bundles with different geometries, i.e. typical cell test and thimble cell test. The test bundles simulated the US-APWR fuel designs that utilize 14-foot heated length and Z3 grid spacers. The DNB heat flux data were collected for fluid conditions which bound coolant conditions for DNB analyses relevant to all the normal operation and anticipated operational occurrences of the US-APWR core.

MHI used to conduct DNB tests at the Heat Transfer Research Facility of Columbia University (HTRF) in New York. Because of the shutdown of HTRF, this DNB test program for US-APWR was conducted at Karlstein Thermal-Hydraulic Facility of AREVA NP GmbH (KATHY) (References 1.0-6 and 1.0-7). [

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This report presents the DNB test program for US-APWR conducted by MHI, in relation to the Topical Report “MUAP-07009-P”. The report covers the information of the test loop, the test section, test procedures and test conditions, as well as the results of test data evaluation and the limit DNBR for the design applications.

2.0 QUALITY ASSURANCE PROGRAM

The DNB test program was conducted by MHI under the quality assurance program applicable to the US-APWR (Reference 2.0-1) in compliance with 10 CFR 50 Appendix B, ANSI/ASME NQA-1 1994 and 10 CFR 21. The heater rods were manufactured by AREVA NP GmbH and the test bundle was also assembled by AREVA NP GmbH. DNB measurements and test bundle inspections were provided by AREVA NP GmbH as well. The test program activities at AREVA NP GmbH were performed under the quality assurance program of AREVA NP GmbH reviewed and accepted by MHI in compliance with 10 CFR 50 Appendix B, ANSI/ASME NQA-1 1994 and 10 CFR 21.

3.0 TEST LOOP

This supplementary DNB test program for the US-APWR fuel design was conducted using a high pressure and high temperature water loop at KATHY in Germany.

KATHY is one of the several heat transfer test facilities available to obtain the thermal-hydraulic data for nuclear fuel bundle designs (References 3.0-1 and 3.0-2). The schematic drawing of the KATHY loop is shown in Figure 3.0-1. The loop is capable of conducting heat transfer tests for both the PWR and BWR fuel geometries and various fluid conditions. For PWR fuel, the system pressure and the flow rate can be controlled up to 18.5MPa and 150m^3/h, respectively, and the test rod bundle is electrically heated by 15MW DC power. As shown in Table 3.0-1, the operating range of fluid conditions of KATHY spans wider than that of HTRF and can effectively cover the needed DNB test conditions for the US-APWR core. [

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KATHY has been well recognized that it can be used for DNB measurements corresponding to the PWR operating range and can provide results consistent with HTRF (Reference 3.0-2). [

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Table 3.0-1 Comparison of Loop Capability between KATHY and HTRF

	KATHY	HTRF
Max. Pressure	18.5MPa	17.2MPa
Max. Flow Rate	150m^3/h	120m^3/h
Max. Electrical DC Power	15MW DC	11.5MW DC

Table 3.0-2 Comparison of Instrumentation Errors between KATHY and HTRF

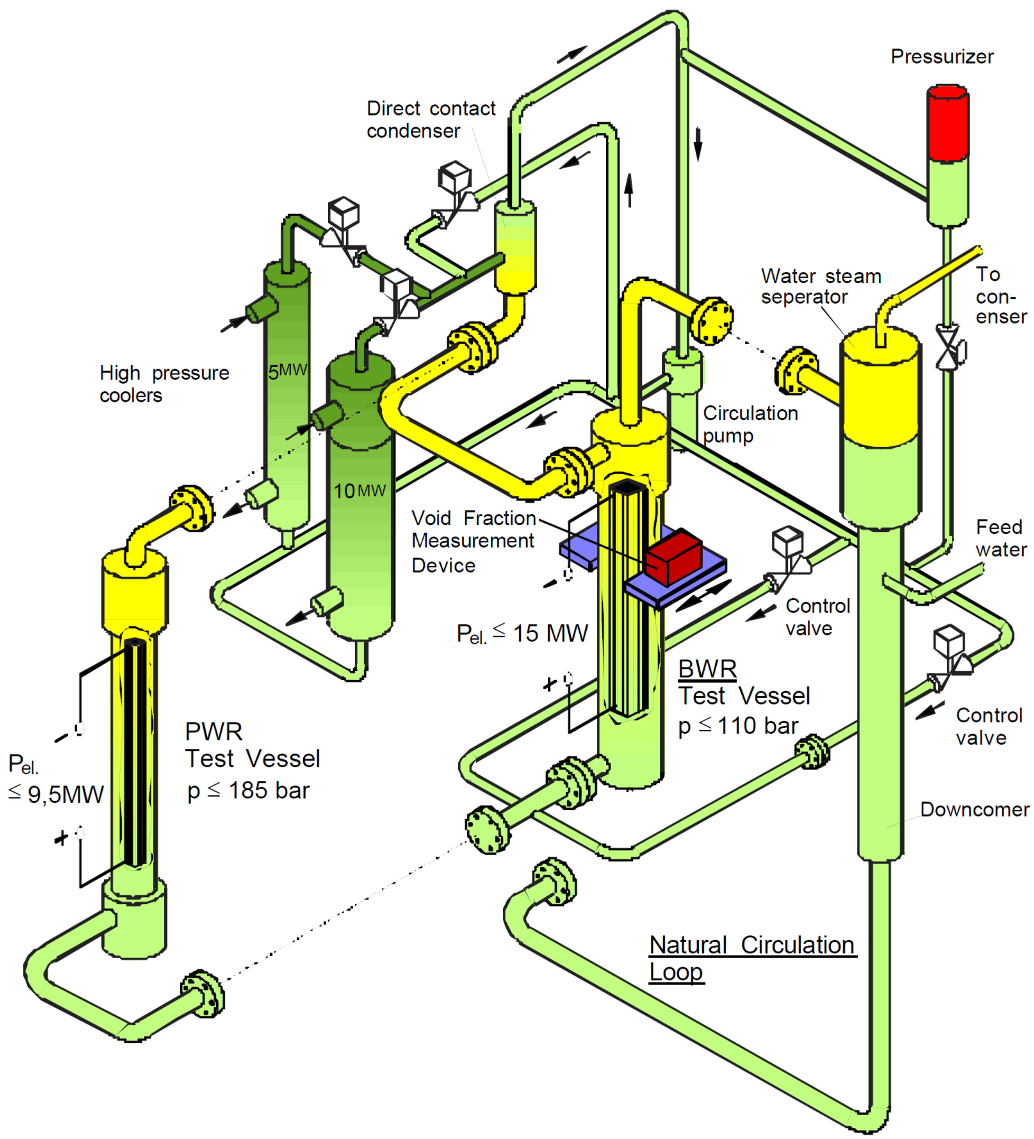

Figure 3.0-1 Schematic Drawing of KATHY Loop

4.0 TEST SECTION

The typical cell test was conducted from August 31 through September 9, 2010. A portion of the test run was observed by the NRC staff. The thimble cell test was conducted from November 11 through November 16, 2010. Two test bundles, “K5800” and “K5801”, were involved in the typical cell test due to the following reason.

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In the thimble cell test, on the other hand, all of the data were collected with the single test bundle “K6000”.

4.1 Geometry and Power Profile

The DNB tests were conducted using 5x5 rod bundles. As shown in Figures 4.1-1 and 4.1-2, the test bundles for the typical cell (K5800 and K5801) consist of 25 electrical heater rods, and the test bundle for the thimble cell (K6000) consists of 24 heater rods and one unheated rod. All the heater rods are made of Inconel tube and directly heated by DC current. High power heater rods are arranged in the center surrounded by low power heater rods. The unheated rod is placed in the center of the 5x5 array for the thimble cell test run to simulate the effect of control rod guide thimble.

The relative power factors for each individual heater rod are specified as RPF (Rod Power Factor) in Figures 4.1-1 and 4.1-2. [

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The axial geometry is identical between the typical cell and thimble cell test bundles and is presented in Figure 4.1-4. [

] In order to prevent the heater rods from bowing due to the electric-current-induced electromagnetic force between adjacent rods, a simple support grid spacer is placed at the middle of each span and there are a total of 10 such simple support grid spacers in each test bundle. [

] The thermocouples are installed inside the heater rods and are axially located at slightly upstream of the mixing

vane grids and simple support grids in the upper region of the test bundle where DNB is expected to occur.

The specifications of the test bundle geometries are compared to the US-APWR fuel design in Table 4.1-1. The geometry of the current test is representative of the US-APWR fuel design utilizing the same grid spacer type and heated length. [

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Table 4.1-1 Comparison of the Test Bundle Specifications

Figure 4.1-1 Radial Geometry for Typical Cell Test (K5800 and K5801)

Figure 4.1-2 Radial Geometry for Thimble Cell Test (K6000)

Figure 4.1-3 Axial Power Profile for DNB Tests (K5800, K5801 and K6000)

Figure 4.1-4 Axial Geometry for DNB Tests (K5800, K5801 and K6000)

Figure 4.1-5 Comparison of Grid Spacing between US-APWR Fuel Design and DNB Test Bundle

4.2 Grid Spacers

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] The photographs for all the grids with representative dimensions are shown in Figures 4.2-1 through 4.2-3. Mitsubishi Zircaloy grid spacers Z3 were used as the mixing vane grids. [

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The simple support grids have been used only in the DNB tests so as to prevent the heater rods from bowing due to the electric-current-induced electromagnetic force between adjacent rods and to keep nominal flow area of each sub-channel. [

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Figure 4.2-1 Photographs for [ ]

Figure 4.2-2 Photographs for [ ]

Figure 4.2-3 Photographs for [ ]

5.0 TEST PROCEDURE AND CONDITIONS

5.1 Pre-Test Checks

In order to confirm the acceptability of the test section and the instrumentation system, the following items were checked prior to the DNB measurements. Axial electrical resistance distributions of the heater rods were measured before the bundle assembling. The dimensions of the test bundle such as rod-to-rod gaps and the axial position of grid spacers were checked during the assembling process. Loop functionality including measurement devices for bundle power, pressure, flow rate and temperature was checked during commissioning. The axial pressure drops were measured across the test bundle and between adjacent pressure taps. The heat balances were checked by comparing the enthalpy rise across the test section with the heat input.

5.2 DNB Measurements

DNB heat flux was measured at steady-state flow conditions as described in Subsection 5.4. The entire process to acquire one data point is shown in Figure 5.2-1. At the beginning of measurement, test parameters, such as inlet pressure, inlet mass flux, inlet temperature and power of test bundle were set at specified initial conditions. Then, the power of test bundle was gradually increased without changing other test parameters, until the thermocouples inside the heater rods detect DNB as a result of the increasing in the heater rod temperature. [ ] After DNB was detected, the power of test bundle was automatically decreased to protect the test bundle. DNB heat flux was determined from the power of test bundle when DNB occurred. The measured data were acquired from the beginning of the power increase until the end of power decrease [ ] and were stored in the data server. This process was repeated to acquire all data points. [ ]

During the DNB tests, repeatability tests were periodically performed [ ]

Figure 5.2-1 DNB Measurement Process

5.3 Post-Test Checks

After the completion of the DNB measurements, heat balance check, pressure drop measurement, and test bundle inspections were performed and compared with the results of pre-test checks to confirm the integrity of test bundle.

5.4 Test Conditions

Tables 5.4-1 and 5.4-2 show the test conditions for typical cell test (K5800 and K5801) and thimble cell test (K6000), respectively. [

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Table 5.4-1 Test Condition Matrix for Typical Cell Test (K5800 and K5801)

Table 5.4-2 Test Condition Matrix for Thimble Cell Test (K6000)

6.0 EVALUATION PROCEDURE

The DNB test data are evaluated in terms of measured-to-predicted DNB heat fluxes ratio, *M/P*, which is defined as the ratio of measured heat flux, q''_{M-loc}, and predicted DNB heat flux based on a subchannel analysis code and a DNB correlation, q''_{P-loc}. In this section, the procedure utilized for deriving *M/P* from the DNB test data is described.

The procedure is schematically presented in Figure 6.0-1. DNB measurement is conducted with a given test section and radial and axial power distributions. After the data collection process for each data point, test bundle power *Pow* at the occurrence of DNB is acquired with the fluid conditions such as reference pressure P_{ref}, inlet mass flux G_{in}, and inlet temperature T_{in}. [ ] Those four parameters, *Pow*, P_{ref}, G_{in} and T_{in}, along with the geometry of test section as well as the axial and radial power distributions are used as input conditions for VIPRE-01M. Then, VIPRE-01M produces local thermal-hydraulic conditions for mass flux G_{loc}, quality X_{loc}, and measured heat flux q''_{M-loc} at every heated node in the test section. The thermal-hydraulic parameters P_{ref}, G_{loc} and X_{loc}, are substituted into a DNB correlation, so that a predicted DNB heat flux q''_{P-loc} and the local heat flux ratio $(M/P)_{loc}$ is obtained at every heated node. The maximum value of $(M/P)_{loc}$ in the test section is finally picked up as the *M/P* value for the measurement. This means that the *M/P* value is evaluated at the minimum DNBR location, since the *M/P* is the inverse of DNBR which is the ratio of predicted-to-actual heat fluxes.

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The VIPRE-01M model for data evaluation is consistent with that described in Appendix B of MUAP-07009-P (Reference 6.0-1) in terms of geometry modeling and model option selections for void fraction and pressure drop calculations. All the heater rods and subchannels in a test section are simulated [ ] In the axial direction, the heated length was divided into a sufficient number of nodes as described in MUAP-07009-P. The hydraulic resistance and two-phase flow model adopted were described in Subsections 4.3 and 4.4 of MUAP-07009-P (Reference 6.0-1), respectively.

Figure 6.0-1 Procedure to Deduce *M/P* Based on DNB Test Data

7.0 RESULTS

7.1 Repeatability Tests

During the DNB tests, repeatability tests were performed [

] The *M/P* was calculated using the VIPRE-01M subchannel code and the WRB-2 correlation. A sequential plot of *M/P* through the typical cell test (K5800 and K5801) is shown in Figure 7.1-1. As show in the figure, [

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Figure 7.1-1 Repeatability Test Result for Typical Cell Test (K5800 and K5801)

Figure 7.1-2 Repeatability Test Result for Thimble Cell Test (K6000)

7.2 Evaluation Results of DNB Data

The DNB data evaluations were performed using WRB-1/VIPRE-01M and WRB-2/VIPRE-01M. Although the total number of data points from typical cell and thimble cell tests combined was [

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Figures 7.2-2 to 7.2-5 show distributions of measured versus predicted DNB heat fluxes, *M/P* versus mean pressure, *M/P* versus local mass flux and *M/P* versus local quality, respectively. These figures show that *M/P* plots are uniformly distributed and there is no significant dependency on the fluid conditions in either WRB-1 or WRB-2 evaluations. Table 7.2-1 shows the number of data points, mean and standard deviation of *M/P* in comparison with the results for 12-foot heated length test bundle described in Appendix C of MUAP-07009-P (Reference 7.2-1). It was confirmed from the table that [

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Table 7.2-2 shows the parameter ranges of the current test data, together with the applicable range of DNB correlations and safety analysis conditions for US-APWR for the purpose of comparison. The safety analysis conditions for the US-APWR were determined to cover the safety analysis parameters [

] It was confirmed in Table 7.2-2 that the parameter ranges of the current test data can sufficiently cover the safety analysis conditions for the US-APWR [

] The applicable ranges are shown in the following.

[

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Since the test conditions were determined so as to cover the applicable parameter range of WRB-1 and WRB-2 correlation, there are some data outside the applicable pressure and local quality range of WRB-1/2 correlation included in the data. Although these data are considered to be valid, the mean and standard deviation of M/P are also calculated excluding such data and shown in Table 7.2-1.

Table 7.2-1 Comparison of *M/P* between 12-foot Heated Length DNB Test at HTRF and 14-foot Heated Length DNB Test at KATHY

(a) WRB-1/VIPRE-01M

(b) WRB-2/VIPRE-01M

Table 7.2-2 Parameter Ranges

Table 7.2-3 DNBR Safety Analysis for US-APWR

(a) WRB-1/VIPRE-01M

(b) WRB-2/VIPRE-01M

Figure 7.2-1 Excluded DNB Data in Data Evaluation

(a) WRB-1/VIPRE-01M

(b) WRB-2/VIPRE-01M

Figure 7.2-2 Measured vs. Predicted DNB Heat Flux for US-APWR Fuel

(a) WRB-1/VIPRE-01M

(b) WRB-2/VIPRE-01M

Figure 7.2-3 *M/P* vs. Pressure for US-APWR Fuel

(a) WRB-1/VIPRE-01M

(b) WRB-2/VIPRE-01M

Figure 7.2-4 *M/P* vs. Local Mass Flux for US-APWR Fuel

(a) WRB-1/VIPRE-01M

(b) WRB-2/VIPRE-01M

Figure 7.2-5 M/P vs. Local Quality for US-APWR Fuel

7.3 Limit DNBR

Limit DNBR with 95% confidence level and 95% probability is deduced based on the values of *M/P* evaluated from typical cell (K5800 and K5801) and thimble cell (K6000) tests. Here, it is assumed that DNB test data from typical cell and thimble cell tests belong to the same population. This assumption can be justified from ANOVA (Analysis of Variance) test which can identify whether multiple data sets belong to the same population (Reference 7.3-1). In advance of the ANOVA test, the normality of each data set was checked by the D' normality test (Reference 7.3-2). The results for normality checks are shown in Table 7.3-1. The acceptable ranges of D' value for normality was determined with 95% confidence level and provided from Reference 7.3-2. The values of D' for typical cell and thimble cell tests are respectively within the acceptable range, and therefore each data set can be treated as normal distribution. Table 7.3-2 shows the result of ANOVA tests for WRB-1 and WRB-2 evaluation data to confirm whether the data from the typical cell and the thimble cell tests can be treated as the same population. The variance of *M/P* is divided into two components: a between-group component and a within-group component. The F-ratio is defined as the ratio of the between-group mean square and the within-group mean square. The F-critical was provided under the assumption that the critical level of significance is 5%. As shown in Table 7.3-2, the F-ratio is sufficiently smaller than the F-critical either in WRB-1 or WRB-2 evaluation data. It can be concluded that the data from the typical cell and the thimble cell tests can be treated as the samples from the same population.

Limit DNBR based on 95% confidence level and 95% probability is deduced based on the same procedure described in MUAP-07009-P (Reference 7.3-3). This procedure can be also found in the topical report for VIPRE-D code (Reference 7.3-4). Table 7.2-1 shows the number of data points (n), the mean of *M/P* (m) and the sample standard deviation of *M/P* (s) based on the evaluations by WRB-1/VIPRE-01M and WRB-2/VIPRE-01M. Using the statistical values in Table 7.2-1, limit DNBR based on 95% confidence level and 95% probability can be evaluated as follows;

$$Limit\ DNBR_{(95\times95)} = \frac{1}{m - k \cdot S}$$

where k is a one-sided tolerance factor based on 95% confidence level and 95% portion of the population covered, and S is a modified sample standard deviation of *M/P* which takes into account the degree of freedom. The details of statistical procedure to evaluate limit DNBR are shown in Table 7.3-3. The number of k can be obtained from Reference 7.3-5. As a result, it was confirmed that [

] the limit DNBRs deduced from the original database for WRB-1 and WRB-2 can be conservatively applied for DNB related safety analyses of US-APWR. This result can justify that WRB-2 correlation with the limit DNBR based on the original database is adopted in the US-APWR safety analyses.

The limit DNBR values are also calculated for the data set excluding the data outside the applicable range of WRB-1/2 correlation and shown in Table 7.3-3. Even with the higher limit DNBR value due to the reduced number of data, the limit DNBR values for original WRB-1/2 database can also be conservatively applied.

Table 7.3-1 Normality Check for *M/P* Values

(a) *M/P* Values Evaluated by WRB-1/VIPRE-01M

(b) *M/P* Values Evaluated by WRB-2/VIPRE-01M

Table 7.3-2 Analysis of Variance for *M/P* of Typical Cell and Thimble Cell Tests

(a) *M/P* Values Evaluated by WRB-1/VIPRE-01M

(b) *M/P* Values Evaluated by WRB-2/VIPRE-01M

Table 7.3-3 Statistical Procedure for Limit DNBR

(a) Based on WRB-1/VIPRE-01M

(b) Based on WRB-2/VIPRE-01M

8.0 CONCLUSION

MHI conducted additional DNB tests for 14-foot test bundles, which are representative for the US-APWR fuel design, to confirm the applicability of the existing WRB-1 and WRB-2 correlations for both the 12-foot and 14-foot heated lengths. It serves as the supplement to Topical Report "MUAP-07009-P, THERMAL DESIGN METHODOLOGY" which describes VIPRE-01M code and DNB correlations for the US-APWR design applications.

The DNB tests for typical cell and thimble cell geometries were conducted to collect the data for fluid conditions which bound coolant conditions for DNB analyses relevant to all the normal operation and anticipated operational occurrences of the US-APWR core. The DNB test data were evaluated using WRB-1/VIPRE-01M and WRB-2/VIPRE-01M to obtain *M/P* values. As a result, it was confirmed through the current DNB tests for 14-foot heated length that *M/P* values are randomly distributed and there is no significant dependency on the fluid conditions. [

] It was confirmed that the limit DNBR deduced from the original database for WRB-1 and WRB-2 can be conservatively applied for DNB related safety analysis of US-APWR. This result can justify that WRB-2 correlation with the limit DNBR based on the original database is adopted in the US-APWR safety analyses.

9.0 REFERENCES

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APPENDIX A BENCHMARK TESTS

APPENDIX B EFFECTS OF SIMPLE SUPPORT GRIDS ON DNB DATA

APPENDIX C DNB TEST DATA

C-1 DNB TEST DATA FOR US-APWR FUEL

C-2 DNB TEST DATA FOR [ ]

C-3 DNB TEST DATA FOR [ ]