QUALIFICATION OF CHF TEST FACILITY AT STERN LABORATORIES USING MITSUBISHI PWR FUEL

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ABSTRACT

Mitsubishi Heavy Industries, Ltd. (MHI) and Mitsubishi Nuclear Fuel Co., Ltd. (MNF) conducted a series of benchmarking tests at Stern Laboratories Inc. (SL) to qualify its facility for acquiring Critical Heat Flux (CHF) test data for full scale Pressurized Water Reactor (PWR) licensing. The tests were performed with 5x5 rod bundles simulating 12-ft PWR fuel of the cosine axial power shape using Mitsubishi Z3 grid spacers. Two different bundle geometries, namely a typical cell bundle consisting of 25 heater rods and a thimble cell bundle consisting of 24 heater rods and one unheated rod, were tested, and approximately 200 data points were acquired for coolant parameters covering normal operation and anticipated operational occurrences of typical PWR. The data were analyzed by subchannel analysis code and CHF correlation, and the resulting Measured to Predicted CHF ratio (*M/P*) statistics were compared against the ones obtained in Heat Transfer Research Facility of Columbia University (HTRF) and KArlstein Thermal-HYdraulic facility in AREVA NP GmbH (KATHY) using the test bundles of the same design. Agreement of average *M/P*s was within less than 1%. In addition, it was confirmed that the data showed good repeatability throughout the tests within ±2% in measured CHF for the same coolant conditions.

This paper presents the result of benchmarking tests between SL facility and HTRF and KATHY, which demonstrates the qualification of SL facility for obtaining licensing basis CHF test data.

KEYWORDS

CHF test, DNB, PWR, Rod bundle

1. INTRODUCTION

Departure from Nucleate Boiling Ratio (DNBR) is a key parameter to quantify thermal margin in core thermal-hydraulic design and safety analysis for Pressurized Water Reactors (PWRs), which is defined as a ratio of predicted Critical Heat Flux (CHF) to actual local heat flux in reactor core. The CHF prediction relies on empirical correlations derived from measured CHF database, since the physical model for CHF mechanism has not yet been available for practical application. The CHF database should be acquired for each specific fuel design either for developing a fuel specific correlation or for validating the use of an existing correlation to the specific fuel, since the CHF characteristics highly depend on the fuel geometry and grid spacer design.

MHI had been conducting CHF tests for its fuel at the Heat Transfer Research Facility of Columbia University (HTRF), which was closed in 2003. Thereafter, several CHF tests for Mitsubishi PWR fuel were performed at the proven KArlstein Thermal-HYdraulic facility in AREVA NP GmbH (KATHY)[1][2]. In the meantime, MHI considers Stern Laboratories Inc. (SL) as another promising candidate to replace HTRF, because SL is an independent laboratory open for any fuel venders and has extensive experience in performing thermal-hydraulic/heat transfer tests for nuclear reactors including CHF tests for Canadian Deuterium Uranium (CANDU) reactors[3][4]. SL test facility has recently been upgraded to accommodate full scale PWR fuel.

MHI and MNF conducted a series of benchmarking tests at SL to qualify its facility for acquiring CHF test data for full scale PWR licensing. The tests were performed with 5x5 rod bundles simulating 12-ft PWR fuel of the cosine axial power shape using Mitsubishi Z3 grid spacers. Two different bundle geometries, namely a typical cell bundle consisting of 25 heater rods and a thimble cell bundle consisting of 24 heater rods and one unheated rod, were tested, and approximately 200 data points were acquired for coolant parameters covering normal operation and anticipated operational occurrences of typical PWR. The data were analyzed using subchannel analysis code and CHF correlation, and the resulting Measured to Predicted CHF ratio (*M/P*) statistics were compared against the ones obtained in HTRF and KATHY using the test bundles of the same design.

This paper presents the results of the benchmarking tests and demonstrates the qualification of SL facility for obtaining licensing basis CHF test data via comparison against the CHF data obtained in HTRF and KATHY.

2. EXPERIMENTAL FACILITY

2.1. Test loop description

The hydraulic test loop, shown schematically in Figure 1, is comprised of stainless steel components and rated at 20.8MPa and 371°C. The test loop is capable of conducting CHF tests for a 5x5 rod bundle simulating the fuel length PWR fuel rods (up to 14ft) with various coolant conditions covering normal operation of anticipated operational occurrences (AOOs) of typical PWRs. The primary loop which provides high temperature and pressure water to the test section consists of a high capacity main circulating pump, a preheater, venturi and orifice flow meters, mixers, heat exchangers, a pressurizer, a condenser, a storage tank, injection pumps, control valves and connecting piping. The loop design and operating conditions are given in Table I.

Table I Test Facility Loop Operating Ranges

Loop Design Conditions	
Design Pressure	20.8 MPa
Design Temperature	371°C
Coolant Flow Rate to Test Section	12kg/sec
Loop Operating Conditions	
Test Section Pressure	6 to 18MPa
Test Section Temperature	150 to 340°C
Test Section Coolant Flow	3 to 12 kg/sec
Subcooling	20 to 150 °C

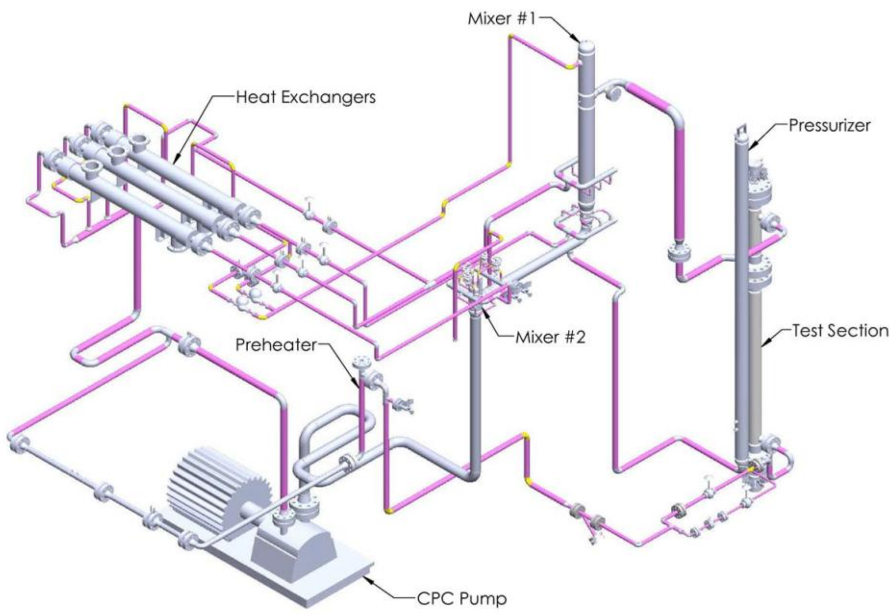


Figure 1 Isometric view of SL Test Loop

2.2. Loop Operation

The coolant conditions are controlled by the loop operator in the control room using a control panel equipped with automatic and manual valve controllers. Feedback is provided from instrumentation installed in the loop for flow, pressure, differential pressure, temperature and water chemistry measurements. The loop instrumentation signals are recorded by the data acquisition system along with test data. The loop pressure is maintained by a pressurizer at the downstream of the test section. It involves the non-condensable nitrogen/air cover gas, which allows an operator to change the loop pressure in a short time. Dissolved non-condensable gas was eliminated prior to the data collection so as to avoid its effect on CHF. The concentration of dissolved oxygen is monitored and maintained below a predetermined threshold during data collection.

2.3. Heater rods

The heater rods simulating fuel rods used at SL are “indirect heaters” which have an insulated helical filament inside the rods and the electric current is applied to the filament. The insulated filament is covered with coaxial metal tubes called the sheath and the clad. On the other hand, the previous tests in

HTRF and KATHY adopted “direct heaters” where the electric current is directly applied to the outer wall of the heaters. As such, the axial power shape of indirect heaters is achieved by varying the filament pitch and corresponding width. The thermocouples of the indirect heaters are embedded in grooves cut on the sheath and covered with the clad. One of the advantages of indirect heaters is that electrical discharge between grid spacers and heater rods is prevented, which significantly reduce the damage on heater rods and grid spacers.

2.4. **Power supply**

Heater rods are connected to power supplies to electrically heat the rod bundle. In SL, heater rods are divided into several power zones, and each zone is connected to separate power supplies, which creates another advantage specific to the indirect heaters: The applied voltage can be easily changed to achieve zone by zone power distribution. The voltage polarity is also reversed for some of the power zones in order to essentially cancel the magnetic forces on the heater rods.

3. TEST CONFIGURATION AND CONDITION

3.1. **Test configuration**

The CHF tests were conducted using two types of 5x5 rod bundles. The typical cell test bundle consists of 25 heater rods, and the thimble cell test bundle consists of 24 heater rods and one unheated rod at the center simulating guide thimble. The summary of test bundle geometry is shown in Table II. The both test bundles are designed so that identical configuration is achieved with HTRF and KATHY tests. The axial arrangement of grid spacers and thermocouples is presented in Figure 2. In between the mixing vane grids, simple support grids are used to support the heater rods while they are designed so as to minimize the perturbation of the local flow. The thermocouples are attached near the lower edge of the grid spacers where DNB is expected to occur.

Table II Test bundle geometries

Heater Rod Diameter	9.5mm
Unheated Rod Outer Diameter	12.2mm
Rod Pitch	12.6mm
Active Heated Length	3658mm
Number of Mixing Vane Grid Spacers	9
Type of Mixing Vane Grid Spacers	Z3
Axial Grid Spacing	453.6mm
Axial Power Shape	Cosine
Axial Power Peaking	1.54
Radial Power Peaking (Central to Peripheral)	1.18
Number of Heater Rods	Typical cell test: 25 Thimble cell test: 24
Number of Unheated Rod	Typical cell test: 0 Thimble cell test: 1

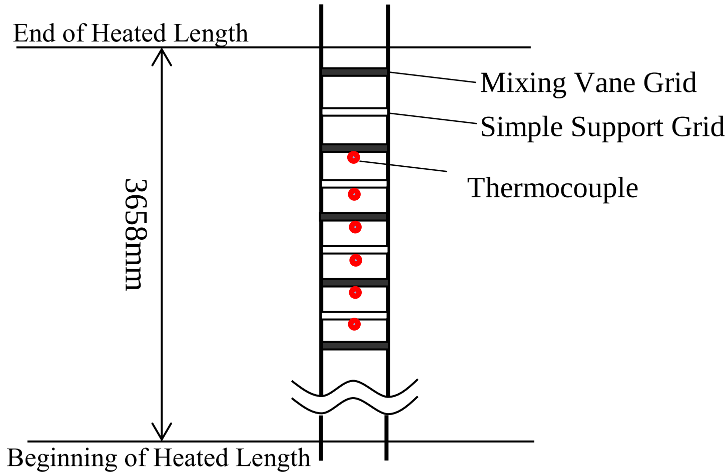


Figure 2 Axial geometry of test section

3.2. **Test condition**

The parameter ranges, which are determined so as to cover the conditions which appear in normal operation and anticipated operational occurrences for typical PWRs, are shown below:

- Pressure 9.8 to 16.6MPa
- Inlet mass flux 5 to 17 $x10^6$ $kg/hr/m^2$
- Inlet temperature 176 to 330 °C
- Bundle power Up to 6.4 MW

Number of data points for each mass flux/pressure condition is shown in Table III and Table IV for typical cell test and thimble cell test, respectively. For each combination of mass flux and pressure, CHF data were collected at various inlet temperatures. The target coolant condition for each data point is determined to reproduce the coolant condition in the previous tests at HTRF and KATHY.

Table III Number of data points for each mass flux/pressure condition (typical cell test)

		Inlet Mass Flux (10^6 $kg/hr/m^2$)					Total
		5	8	11	14	17	
Pressure (MPa)	9.8	6	5	6	6	5	28
	12.3	6	4	7	4	3	24
	14.7	7	5	8	6	3	29
	16.6	4	4	8	6	3	25
Total		23	18	29	22	14	106

Table IV Number of data points for each mass flux/pressure condition (thimble cell test)

		Inlet Mass Flux (10^6 kg/hr/m^2)					Total
		5	8	11	14	17	
Pressure (MPa)	9.8	4	4	4	5	4	21
	12.3	3	3	5	4	4	19
	14.7	3	6	7	5	3	24
	16.6	3	4	6	6	4	23
Total		13	17	22	20	15	87

3.3. **Test procedure**

The measurement begins with a target loop condition including system pressure, inlet mass flux and inlet temperature and with a lower power than expected CHF. The power is gradually increased while maintaining the loop condition until one of the thermocouples inside the heater rods detect increase in the heater rod temperature corresponding to a DNB occurrence. The tolerances for the loop conditions for each parameter are ±0.05kg/s for flow, ±0.5°C for temperature and ±100kPa for pressure. After the DNB occurrence, the power is decreased to protect the test bundle from damage. The measured data are recorded at a frequency of 10 Hz in a data server from the initial condition to the end of power decrease. A schematic drawing of the test parameter behavior is shown in Figure 3. The criterion of temperature increase, ΔT, at which DNB occurrence is judged is selected so that ΔT is small enough to avoid heater rod damage and large enough to avoid noise for measurement of temperature. For a comparison purpose, the same criterion is applied to the data obtained in HTRF and KATHY.

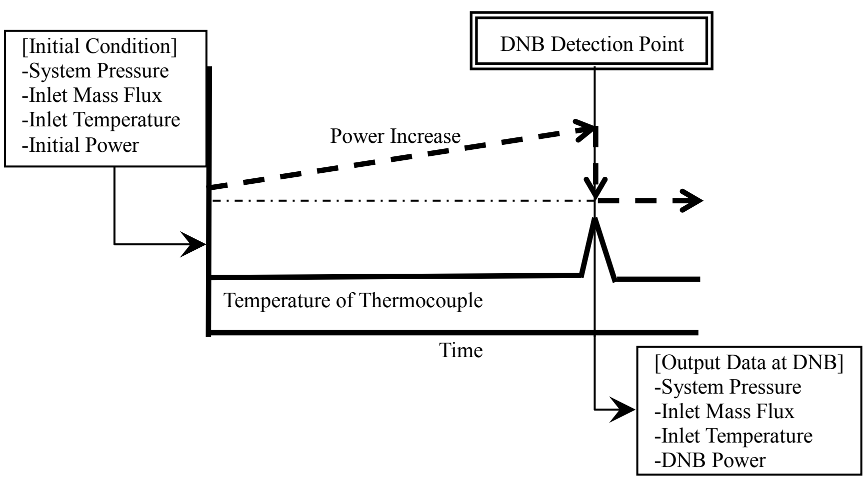


Figure 3 Schematic drawing of test parameter behavior

4. RESULTS

4.1. Repeatability during testing

During the tests, repeatability of the test data was periodically checked by repeating the measurement at the same test condition so that inconsistency between data points due to unexpected test bundle damage can be detected. Figure 4 shows the distribution of bundle-average heat flux normalized by the mean value of all the repeatability test runs. The measured heat fluxes are distributed within the range of ±2%, which are comparable to the data obtained in KATHY. It was also confirmed that no systematic bias in the repeatability test data was observed, which ensures data consistency throughout the tests.

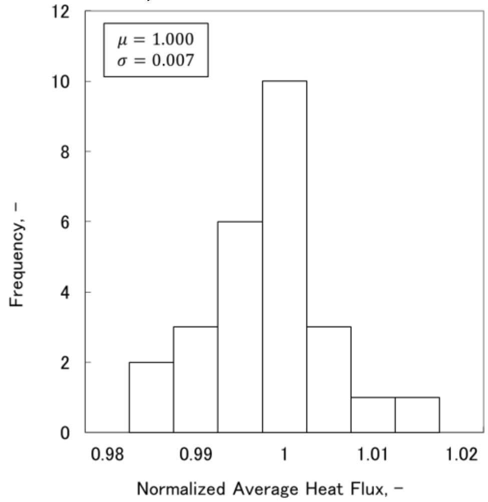
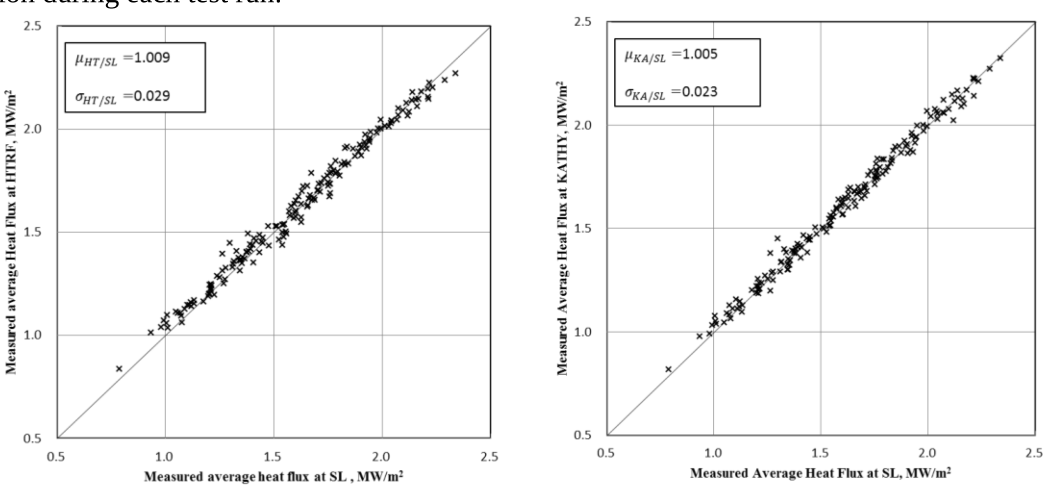


Figure 4 Repeatability Test Result

4.2. Comparison of measured heat flux between three test facilities

The measured bundle-average heat fluxes corresponding to DNB occurrence are compared between SL and HTRF in Figure 5 (a) and between SL and KATHY in Figure 5 (b), respectively. The agreement between three facilities is excellent, for the mean value of heat flux ratio indicates less than 1% difference even with the data scattering due to the nature of DNB phenomenon as well as small variation of test condition during each test run.



(a) SL vs. HTRF (b) SL vs. KATHY

Figure 5 Comparison of measured average heat flux between three test facilities

4.3. **Comparison between three test facilities via subchannel analysis**

The Measured-to-Predicted critical heat flux ratio, *M/P* is defined as the ratio of the measured local heat flux corresponding to DNB occurrence to the predicted critical heat flux using a subchannel analysis code and a CHF correlation. By using *M/P*, the variation of test condition during each test run is compensated and more precise representation of the loop-to-loop data variation can be obtained.

The *M/P* statistics are compared between SL, HTRF and KATHY in Table V. While the total number of data points for each of typical cell test and thimble cell test is 193 without the repeatability test data as presented in Table III and Table IV, some data points at lower mass flux condition were excluded from the statistics because those data points resulted in high local quality outside of the applicable range of the CHF correlation. It is confirmed that the mean value of *M/P* for SL data agrees in less than 1% with HTRF and KATHY. The standard deviation of *M/P* for SL is equivalent to one for HTRF and KATHY.

Table V Comparison of *M/P* between three facilities

	SL	HTRF	KATHY
Number of Data Points	173		
Mean of *M/P**	1	0.998	1.009
Standard Deviation of *M/P**	0.066	0.061	0.063

* All the values are normalized by mean of *M/P* at SL.

The analysis of variance (ANOVA) was performed to confirm that statistically significant difference was not observed in the M/P distributions from the three facilities. Prior to the ANOVA, the normality of each distribution was confirmed by D' test as shown in Table VI, where the D' statistics from three facilities are within the acceptance range with the significance level of 5%.

The result of ANOVA is presented in Table VII, where F statistic falls below the test statistic with the significance level of 5%. This indicates that the difference in *M/P* distributions from the three facilities is statistically insignificant.

Table VI Normality test results

	SL	HTRF	KATHY
D' statistics	644.95	632.71	639.10
Lower bound (D')*	630.05		
Upper bound (D')*	650.21		

* These bounds are based on the significance level of 5%.

Table VII ANOVA test result

F statistic	1.578
Test statistic*	3.013

* The statistics is based on the significance level of 5%.

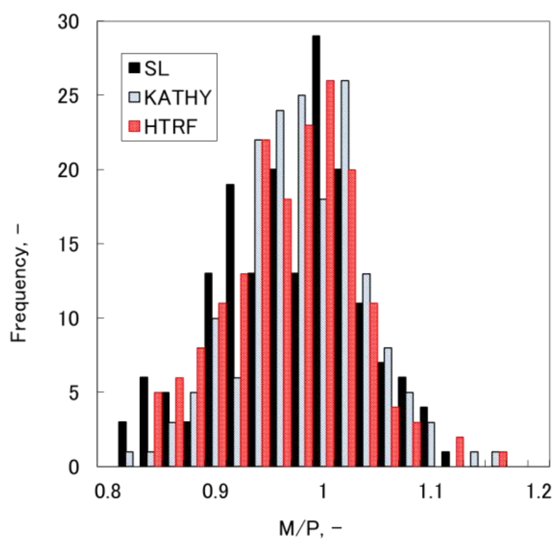


Figure 6 *M/P* distribution

5. CONCLUSIONS

A series of CHF tests was performed using the test facility in SL for 5x5 rod bundles simulating typical PWR fuel with 12-ft heated length, and the results were compared against the data obtained in HTRF and KATHY with the rod bundles of the same design. The repeatability result confirms that the variation of test data was within a reasonable range and that consistent data were obtained throughout the tests. The comparison of CHF data between three facilities shows excellent agreement, and *M/P* statistics show that the agreement in the mean values between three facilities is less than 1 % with the same level of standard deviation. As a result, it is concluded that the data obtained in the test facility at SL has the same level of credibility compared to the other test facilities used for collecting licensing basis CHF data.

6. REFERENCES

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