Presentation and Comparison of Experimental Critical Heat Flux Data at Conditions Prototypical of Light Water Small Modular Reactors

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ABSTRACT

The Critical Heat Flux (CHF) is a two-phase flow phenomenon which rapidly decreases the efficiency of the heat transfer performance at a heated surface. This phenomenon is one of the limiting criteria in the design and operation of light water reactors. Deviations of operating parameters greatly alters the CHF condition and must be experimentally determined for any new parameters such as those proposed in small modular reactors (SMR) (e.g. moderate to high pressure and low mass fluxes). Current open literature provides too little data for functional use at the proposed conditions of prototypical SMRs.

This paper presents a brief summary of CHF data acquired from an experimental facility at the University of Wisconsin - Madison designed and built to study CHF at high pressure and low mass flux ranges in a 2x2 chopped cosine rod bundle prototypical of conceptual SMR designs. The experimental CHF test inlet conditions range from pressures of 8 – 16 MPa, mass fluxes of 500 – 1600 kg/m²s, and inlet water subcooling from 250 – 650 kJ/kg. The experimental data is also compared against several accepted prediction methods whose application ranges are most similar to the test conditions.

KEYWORDS

critical heat flux, small modular reactors, low mass flux

1. INTRODUCTION

In 1937, Thomas B. Drew and Alfred C. Mueller presented a paper at the American Institute of Chemical Engineers meeting in Toronto exploring an interesting link largely dismissed by the scientific base at the time [1]. In this paper, the authors discuss how since man first put a pot of water on a fire it was known that the water would boil and the pot would, relatively, never be much hotter than the liquid inside it. Furthermore, if the temperature of the fire was increased, the violence of boiling would also increase. Although the Leidenfrost effect was known at the time, the authors noted that of all the investigators of heat transfer at the time, only Nukiyama appeared to recognize and investigate the existence of a 'maximum boiling rate' beyond which additional heating through a surface would actually decrease the heat transfer, exactly opposite the traditionally expected behavior. Nukiyama first presented his important findings and the first 'boiling curve' in the Japanese Journal Society of Mechanical Engineers in 1934 (reproduced in English for the first time in 1966 [2]).

More specifically, this boiling limit or Critical Heat Flux (CHF) condition is a two-phase flow phenomenon that is characterized by a flow regime change near a heated wall which rapidly decreases the efficiency of the heat transfer performance at the heater surface. The CHF condition is categorized by a local increase in vapor void fraction which covers the heater surface. The increased vapor void fraction triggers an abrupt and significant decrease in heat transfer rate between the heated surface and the two-phase coolant. The system response to a CHF event depends on the heat source; constant temperature or constant heat flux. The decrease in the heat transfer coefficient of a constant temperature heat source (e.g. steam heating) will cause the heat flux through the system to quickly decrease. A constant heat flux source (e.g. nuclear reactor, Ohmic heating) will have a rapid rise in the heating element wall temperature. The rise in temperature can lead to melting, enhanced chemical attack, and/or other metallurgical changes.

Since the initial recognition of the CHF condition, especially in the design and operation of nuclear reactors, significant resources have been spent establishing the conditions at which heat transfer deterioration is initiated. Decades of experience and thousands of data points have shown that the nature of a CHF condition is highly complex, requiring experimental data for any new parameters (e.g. geometries, testing conditions, materials, etc.) of interest. One developing application of nuclear power for which a dearth of data is available and therefore requires experimental support, rod bundle geometries in particular, is the Small Modular Reactor (SMR).

SMRs have been proposed as an alternative/complimentary solution to traditional power stations in meeting the 21st century world energy needs. In general these 'small' reactors are categorized according to an electrical output of 300 MWe or less and lend themselves to modularity; the ability to fashion factory pre-fabricated components on site. Although numerous designs have been proposed [3], in general the nature of the SMR, with its enhanced focus on passive safety, lends itself to operate at much lower mass fluxes than traditional reactors along with high pressures that are either on par or slightly lower than traditional reactors. As this low mass flux and high pressure operating conditions have been of little interest till recently, there is limited to no data available that satisfies a multiple parameter criteria (i.e. pressure, subcooling, mass flux, non-uniform axial flux, and bundle geometry)

necessary to predict CHF at the conditions expected to be relevant to SMRs. For example, Figure 1 and Figure 2 demonstrate the limited EPRI data [4] for a continuous non-uniform axial flux, square bundle geometry at the conditions covered in this paper. In total, the plot contains 193 data points, of which 149 contain a large unheated guide tube and 4 contain an unheated ‘control’ rod. Of particular note is the absence of data below a mass flux of approximately 1300 kg/m²s.

The remainder of this paper summarizes the experimental facility built at the University of Wisconsin and the gathered experimental data along with comparisons to a few widely accepted prediction methods in an effort to contribute to a public resource for SMR CHF conditions.

Figure 1. EPRI data for non-uniform heat fluxes, $P < 17$ [MPa], and $G < 1700$ [kg/m²s].

Figure 2. EPRI data for non-uniform heat fluxes, $P < 17$ [MPa], and $G < 1700$ [kg/m²s].

2. EXPERIMENTAL FACILITY

2.1 Overview

The University of Wisconsin High Pressure Critical Heat Flux (UW-HPCHF) facility is a vertical forced circulation deionized water loop that passes through a 2x2 equally spaced non-uniformly heated rod

bundle (Figure 3). The flow passes through a variable speed pump (1) to a the test section (4) and a bypass (3) which then recombine before passing through a shell and tube heat exchanger (5 and 6) before repeating. The flow through the test section is measured with an orifice flow meter (2) while the facility pressure is maintained with a reservoir pressurized (7) with an argon cover gas (8) which also acts as the thermal expansion tank. Under the low flows under consideration, the pressure drop is expected to be minimal across the test section. Therefore, the pressure is measured at the inlet of the test section and assumed to be approximately constant throughout the test section.

Figure 3. Basic process flow diagram and 3-D model (pressurizer not shown)

2.2 Test Section

The test section is comprised of four electrically heated elements with a chopped cosine power profile 2 m in heated length (L_{HL}) described by Equation 1 fixed within a square channel. The chopped profile is obtained with a helically cut tube with varying pitch (thinnest in the middle and thicker at the ends) while delivering a maximum per element power of 100 kW. The specific dimensions of the heater elements and square test section are summarized in Table I. The channel wall is comprised of stainless steel 316 while the cladding of the heater elements is Monel K500. The geometry, power shape, and peak-to-average power ratio of the heaters were chosen to be representative of proposed SMR designs. Additional information and discussion of the facility can be found here [5].

$$\frac{q(x)}{q_{avg}} = \theta_0 + \theta_1 \cos \left(2\theta_2 \left[\frac{x}{L_{HL}} - 0.5 \right] \right) \quad (1)$$

Given: $\theta_0 = 0.82$; $\theta_1 = 0.68$; $\theta_2 = 2.44$; q_{avg} is the average heater power; $q(x)$ is the local power

Table I. Summary of test section and heater element dimensions

Parameter	Ratio	Parameter	Size (cm)
Pitch/Diameter	1.33	Diameter	0.95
		Pitch	1.26
h/G	0.75	G (rod-rod gap)	0.31
		h (rod-wall gap)	0.23
$q_{\text{peak}}/q_{\text{avg}}$	1.5	Channel Width	2.67

Due to concerns that boiling and flow induced vibrations would potentially cause the heaters to make contact and significantly alter the geometry, three small and sparsely located grid spacers were applied. The design used in the experiment yields a 16% flow blockage of a length of 2.54 cm per spacer and do not have mixing vanes. The three spacers used in this study were centered at 1.0, 1.5, and ~ 2.0 m as measured from the upstream end of the heated section of the heater elements (Figure 4).

Standard practices of CHF detection employs thermocouples located at various locations either on the outer or inner wall of the heater's cladding [6]. In this study, ten thermocouples per heater are embedded on the inner wall of the cladding in each heater element at different axial and circumferential positions (Figure 4). The positions of the thermocouples were chosen to maximize detection of first CHF occurrence. Additional thermocouples monitored the inlet, outlet, and bulk fluid temperatures within the channel.

Figure 4. (Left) Axial thermocouple location, heater profile, and spacer locations (green markers). (Right) Circumferential thermocouple locations.

2.3 Experimental Procedure

From a steady state condition, the power of the heater elements is increased slowly (~ 1 kW/heater/min). As the power level increases, the system pressure is allowed to rise as the inlet subcooling is controlled. Additionally, the mass flux is adjusted to maintain a constant mass flux or allowed to slightly decrease. The facility is thus brought to a critical condition where a CHF event occurs, recognizable by a significant spike (Figure 5) in one or more of the thermocouples embedded in the heater elements. This procedure is a common method for obtaining experimental CHF data [7].

Figure 5. Characteristic heater element thermocouple response to a CHF event

The ‘trip’ temperature for the system which indicates CHF occurrence is set approximately 150°C above the saturation point (i.e. $\sim 75\text{-}100^{\circ}\text{C}$ above the embedded thermocouple measurements). Once the CHF event is detected, the power is automatically reduced and a steady state condition is established. The process is then repeated. This 150°C threshold, while arbitrary, does not significantly alter the measured CHF point and associated system conditions due to the slow approach to the CHF and magnitude of the temperature excursion. Using this procedure, a total of 96 CHF tests have been performed covering the inlet conditions outlined in Table II. The full test summary can be found in Appendix A and reference [5].

Table II. Summary of inlet conditions of CHF data

Parameter	Range
Inlet Subcooling (kJ/kg) - h_{sub}	250-650
Inlet Pressure (MPa) - P_{in}	8-16
Mass Flux ($\text{kg/m}^2\text{s}$) - G	500-1600

A representative distribution of the maximum error for any give test is presented in Table III. The primary sources of measurement error for these CHF tests are associated with CHF detection based on the thermocouple locations on the heater elements, voltage and current uncertainties of the heaters,

inlet conditions (i.e. temperature and pressure), and mass flux through the test section (depends on multiple parameters). Using manufacture specified uncertainty, geometry tolerances, etc., the error associated with various parameters was calculated using propagation of error. The large error associated with the local CHF is dependent on the spacing between each individual heating element's thermocouples. The estimated heat lost in the test section is limited to a maximum of a few percent.

Table III. Summary of main parameter uncertainty from propagation of error analysis

Parameter	Nominal Value	$\pm \sigma$	Unit	% Error
Inlet Subcooling	409	13	kJ/kg	3.1%
Inlet Pressure	12.1	0.16	MPa	1.3%
Mass Flux	898	17	kg/m ² s	1.9%
Heater Power	56.0	0.79	kW	1.4%
Average Critical Heat Flux	930	16	kW/m ²	1.7%
Local Critical Heat Flux	1250	200	kW/m ²	16%

$$x = f(a, b, c, \dots) ; \%Error = \frac{\sigma_x}{x} \cdot 100 = \frac{\sqrt{\left(\frac{\delta x}{\delta a} \sigma_a\right)^2 + \left(\frac{\delta x}{\delta b} \sigma_b\right)^2 + \left(\frac{\delta x}{\delta c} \sigma_c\right)^2}}{x}$$

3. CRITICAL HEAT FLUX DATA

The following section presents CHF data gathered from the HPCHF facility according to important parameters commonly evaluated in discussions of the CHF from a fixed inlet condition approach. The primary variables under consideration are those summarized in Table II; namely inlet subcooling, inlet pressure, mass flux, and exit quality. For reference, the local and average CHF are defined by Equations 2 and 3 where A_{htd} is the heated area of a heater element, D is the diameter of a heater element and L_{HL} is the heated length, and the average and local heat flux (q''_{avg} and q''_{local}) have been defined with Equation 1. The complete experimental data set is included in Appendix A.

$$q''_{avg} = \frac{q_{avg}}{A_{htd}} ; q''_{local} = \frac{q(x)}{A_{htd}} \quad (2)$$

$$A_{htd} = \pi \times D \times L_{HL} \quad (3)$$

In order to better visualize the conditions covered by the experimental data in context of existing literature Figure 6 and Figure 7 are presented below. These figures are the same EPRI plots presented in the introduction with the addition of this reports experimental data.

Figure 6. Overlay of experimental data and EPRI data for non-uniform heat fluxes, $P < 17$ [MPa], and $G < 1700$ [kg/m²s].

Figure 7. Overlay of experimental data and EPRI data for non-uniform heat fluxes, $P < 17$ [MPa], and $G < 1700$ [kg/m²s].

Figure 8 illustrates the locations and number of CHF occurrences registered at each thermocouple. There are 115 indicated CHF events in the figure out of 96 tests due to simultaneous trip of multiple thermocouples on a few tests (typically between thermocouples at the same axial position). It was anticipated that the most likely axial heights for CHF were to be at thermocouples 3/4, 5/6, and/or 7 based on behavior of a non-uniform power profile. Circumferentially, it was reasoned that rod-rod gaps, rod-wall gaps, and the center channel were to be the most likely locations of CHF given proximity of heaters and flow restrictions. Although rare that multiple thermocouples were tripped that were not at the same vertical location (3 occurrences), when it did occur, the local CHF value was determined from the tripped thermocouple located most upstream (higher local CHF value). This does not significantly impact the results of local CHF presented in Table IV.

With these prior predictions, the map of CHF in Figure 8 seems to match assumptions. The locations of the thermocouples on heaters 3 and 4 are more strategically oriented than of heaters 1 or 2 (i.e. thermocouples are located at both axial and circumferential locations matching the previously mentioned expected CHF locations). Therefore, although the tripped thermocouples are mostly located on heaters 3 and 4, the locations of the thermocouples tripped are in the areas believed to be most conducive for a CHF event and not necessarily indicative of significant deviations of non-uniformity in subchannel properties. Furthermore, as the CHF condition in any given test was approached, typically multiple perturbations in heater thermocouples were observed and a set of four bulk thermocouples, located at the same axial location (1.78 m) and near the wall between each set of heaters, were typically in agreement adding some qualitative support to that conclusion. Therefore, a CHF location map such as Figure 8 appears to not be uncommon or unreasonable given similar maps reported in literature [8] and the previous discussion.

Figure 8. Location of CHF occurrence detected with embedded thermocouples

3.1 Influence of Parameters: Subcooling, Pressure, Mass Flux, and Exit Quality

Within the range of experimental conditions covered in this study, open literature predicts a linear behavior between CHF and inlet subcooling [9]. In other words, the change of the CHF value is directly proportional to the energy required to obtain a saturated condition given all other variables remain constant. Evaluation of the data in this regard demonstrates that the expected trend of a linear increase in the CHF with increasing subcooling is indeed observed (Figure 9 - Left). Note, all lines in Figure 9 and Figure 10 are to assist in trend visualization and are not necessarily an indication of a linear correlation. Furthermore, the portions of data plotted below have been grouped together whose conditions are within $\sim \pm 5\%$ of the specified values in the legend.

Pressure has a complicated effect on the CHF. For a fixed inlet approach, as pressure is increased, the CHF will increase, reach a maximum, and then decrease. Readers are directed to other sources such as [10] for possible explanations of this behavior though in essence it is thought to be highly dependent on

the physical properties of water and their impact on flow behavior. Given that the experimental data of this study lies at higher pressures, CHF is expected to decrease as the pressure increases. Figure 9 (Right) presents the CHF data as a function of the inlet pressure. This figure demonstrates a clear decrease in the CHF with increasing pressure as expected.

Figure 9. (Left) CHF vs. Inlet Subcooling with linearly increasing correlation. (Right) CHF vs. Pressure with clear decrease in CHF with increasing pressure.

Similar to inlet subcooling, the CHF has been shown to increase with increasing mass flux in a quasi linear behavior. This dependency is generally greater at lower flow mass fluxes and diminishes at higher pressures, presumably dependent on the change of flow patterns [11]. Once again for the conditions at which experiments were run, the expected monotonically increasing behavior of mass flux and CHF was observed (Figure 10 - Left). Exit quality conversely has been shown to increase with decreasing mass flux [11] with which this experimental data is in agreement (Figure 10 – Right). Exit quality in the plot is not a measured value, rather it is simple calculation using a heat balance based on the inlet conditions and heater element powers with no energy losses.

Figure 10. (Left) CHF vs. Mass Flux with monotonic increase of the CHF with increasing mass flux. (Right) CHF vs. Exit Quality with decrease in CHF with increase in quality.

3.2 Comparison to CHF Correlations

Chosen for their wide acceptance and validated range of applicability similar to this study, the EPRI correlation (with the non-uniform correction and cold wall factors but not the grid spacer factor) [12], the CISE-GE [13], the W-3 (with the non-uniform correction factor) [14], and the 2006 Groeneveld Look-Up-Table (LUT) (with correction factors 1, 2, 4, and 5) [15] have been selected for comparison to experimental data. It is worth noting that each prediction was evaluated with various combinations of their correction factors, where applicable. The correlations with the specified factors indicated in Table IV produced the most accurate results based on the mean and RMS error of the average CHF.

In addition to the generalized prediction methods, an Artificial Neural Network (ANN) analysis using MATLAB's 'neural net fitting tool' was also employed using a random subset of 70% of the experimental data to 'train' the network. An ANN applies statistical learning algorithms inspired by biological neural networks (i.e. central nervous system). It is ideal for pattern recognition and is an alternative way to tackle complex and ill-defined problems (i.e. CHF appears to be a perfect candidate). For brevity the interested reader is directed to these references [16] [17] [18] [19] for a more thorough discussion of ANN and its successful application to CHF. The error presented in Table IV for ANN represents only the mean/error associated with data not used in training and is less accurate (i.e. more realistic) of the ANN prediction capabilities for this data set. The network used has three inputs: inlet subcooling, inlet pressure, and mass flux; one output: local or average CHF; and one hidden layer with five neurons.

Based on the common approach of channel centered flow geometries in subchannel analysis and its more consistent accuracy (in terms of average critical heat flux), the prediction results were calculated from the channel centered approach (Figure 11 - Left). Using this geometry and the primary inlet conditions, the iterative heat balance method (HBM) [15] was used to determine the predicted location of CHF. The HBM iteratively increases the overall heater power until local heater flux and predicted CHF are within a specified tolerance of one another. The predicted local heat flux is the flux associated with

the convergence location. The average CHF is calculated based on the value of the total heater power at convergence. This process is conceptually captured below with a representative iteration depicted in the right image of Figure 11.

Figure 11. (Left) Channel centered flow geometry marked in red. (Right) Iterative HBM example.

The comparison between the prediction methods and experimental data is shown graphically in Figure 12 with an associated error summary presented in Table IV. In general the EPRI, the CISE-GE, and the W-3 all predict the average CHF reasonably with means relatively near 0% and RMS errors not too divergent from the reported prediction accuracies of approximately 10-20%. The notable difference is tendency of the EPRI and CISE to predict conservative CHF values while the W-3 and 2006 LUT error on the side of being non-conservative (over predicts the CHF). It is noted that each of the correlations have regions of both over and under predicting the CHF which should not be overlooked. Furthermore, the non-conservative 2006 LUT (based on heated 8 mm tubes) performance could be a result of cold wall effects not explicitly handled by a correction factor unlike the EPRI which has an explicit cold wall factor that lowers the predicted CHF by ~5-10% for the conditions considered in this paper.

The performance of the ANN demonstrates the predictability of the facility behavior and helps to substantiate the confidence in the repeatability of the facility at the conditions tested. It is hypothesized that, similar to previous applications of ANN to CHF, this network could be applied in overcoming limitations of the test facility and associated database in order to better understand CHF behavior at SMR conditions.

Although average CHF was relatively well represented, all correlations failed to provide reasonably accurate predictions of local CHF (i.e. CHF location occurrence). This is to be expected since there is significant uncertainty associated with the first occurrence of CHF given the limited number of heater thermocouples (Table III). If the location of CHF could be more precisely determined it is reasonable to suggest that the associated local CHF could be decreased. Therefore, the predicted vs real local CHF value is arguably in better agreement than that indicated in Table IV.

Figure 12. Comparison of average CHF prediction methods to experimental data

Table IV. Summary of local and average CHF prediction vs. experimental error

<i>Channel Centered</i>		Parameter Error [%]			
Method	Factors	$q''_{CHF,avg}$		$q''_{CHF,local}$	
		$\bar{x}$	RMS	$\bar{x}$	RMS
2006 LUT	K1,2,4,5 ON; K3 OFF	23%	30%	-39%	42%
EPRI	Cwall ON; NonUni ON	-5.4%	16%	17%	28%
CISE-GE	-	-3.1%	18%	-27%	32%
W-3	NonUni ON	7.2%	18%	9.5%	41%
ANN	-	-0.01%	2.5%	1.9%	16%

$$\bar{x} = \frac{1}{N} \sum_i^N \epsilon_i ; RMS = \sqrt{\frac{1}{N} \sum_i^N \epsilon_i^2} ; \epsilon = \frac{Predicted - Experiment}{Experiment}$$

The predicted CHF deviation from experimental results (ϵ) for the four primary parameters discussed are shown in Figure 13 and Figure 14. Although some correlations were able to predict the average CHF for these conditions, these figures show a bias of these methods compared to the experimental data. One reason for this bias is the non-complete independence between the inlet parameters (inlet subcooling, pressure, and mass flux) as discussed in Section 2.3. On the other hand, the ANN is presented as a regression model able to predict the average CHF with errors normally distributed around zero (considering only the values not used for training the network). An application of an ANN in this sort of

representation may be better suited to overcome a database's deficiencies and capture truly independent parameter deviations more accurately.

Figure 13. Prediction relative error as a function of (Left) inlet subcooling and (Right) pressure

Figure 14. Prediction relative error as a function of (Left) mass flux and (Right) exit quality

3.3 Scaling Critical Heat Flux Results

Extrapolation of small bundle CHF experiments (e.g., 2x2) to larger commercial bundles (e.g., 17x17) remains an area of open research. This issue is not unique to this experiment as much literature experimental data is performed on scaled down facilities of varying bundle sizes (e.g., 5x5, 3x3) or even single heated elements (e.g., externally heated pipe or single elements enclosed in a non-heated pipe). It is likely that correlations that explicitly consider heated and non-heated parameters (e.g., surface/flow areas and channel geometry) and are created from data sets with different bundle sizes are more

accurate over larger application ranges. For example, the reasonably good prediction by EPRI correlation on this data set may be attributable, in part, to the correlations consideration of cold wall effects and the fact the correlation is based on various sized heating element bundles.

This discussion provides additional motivation to investigate the application of computer learning to the study of CHF. The traditional approach to CHF prediction (i.e., correlation creation) relies on the skill of the scientist to predict the applicable physics and then manipulate the data to determine the weight or importance of the identified physics. This is a difficult task for similar data sets and even more so for more advanced applications. A computer learning approach may potentially enable far more accurate and more diverse prediction capabilities that will be able to address issues such as those of scaling laws discussed here. As such, a detailed study to understand the scaling laws of CHF experiments (e.g., single element $\rightarrow$ 2x2 $\rightarrow$ 5x5 $\rightarrow$ 17x17) is a potential area of further research.

4. CONCLUSIONS

Critical heat flux experiments have been conducted at the low mass flux and moderate to high pressure conditions prototypic of proposed light water SMR designs at the University of Wisconsin High Pressure Critical Heat Flux facility. This study contributes valuable CHF data spanning the conditions indicated in Table II, specifically in a 2x2 bundle configuration, for which minimal public data exists.

An investigation of the primary parameters demonstrated that expected trends in inlet subcooling, pressure, mass flux, and exit quality were observed. Comparison of the experimental data to prediction methods demonstrates the reasonably accurate prediction capabilities of the W-3, CISE-G, and EPRI correlations in regards to the average CHF. It is noted though that all prediction methods evaluated performed unsatisfactorily in regards to local CHF prediction, though a portion of that error is likely associated with the inherent limitation of thermocouple spacing by which local CHF was determined.

Finally, a neural network analysis was also performed on the experimental data which was capable of accurately predicting the experimental data, thereby demonstrating the predictability of the facility's behavior. Given the good performance of the ANN, it is possible that a well-trained ANN can be a useful tool in overcoming experimental and database limitations to expand understanding of CHF and, more generally, thermal hydraulics. A potential application of ANN is expanding the accuracy of predictions between small scale experiments and commercial scale facilities.

ACKNOWLEDGMENTS

This research was performed using funding received from the DOE Office of Nuclear Energy's Nuclear Energy University Programs.

Appendix A: Complete Experimental Data Summary

Test Number	Inlet Subcooling [kJ/kg]	Inlet Pressure [MPa]	Mass Flux [kg/m ² s]	Tripped TC	Local CHF Location [m]	Local Quality [-]	Exit Quality [-]	$q''_{CHF,local}$ [kW/m ²]	$q''_{CHF,avg}$ [kW/m ²]
Test 1	329	10.3	549	Htr 3 TC 6	1.46	0.20	0.31	808	722
Test 2	338	10.4	554	Htr 3 TC 6	1.46	0.20	0.30	818	730
Test 3	346	10.0	728	Htr 3 TC 6	1.46	0.12	0.21	924	825
Test 4	351	10.2	727	Htr 3 TC 6	1.46	0.12	0.21	931	831
Test 5	359	9.5	877	Htr 3 TC 6	1.46	0.09	0.17	1044	932
Test 6	353	9.5	884	Htr 3 TC 6	1.46	0.08	0.16	1027	917
Test 7	407	12.6	586	Htr 3 TC 6	1.46	0.15	0.27	857	765
Test 8	412	12.3	740	Htr 3 TC 5	1.46	0.09	0.19	951	849
Test 9	417	12.4	741	Htr 3 TC 6	1.46	0.09	0.19	968	864
Test 10	405	12.1	889	Htr 3 TC 6	1.46	0.05	0.15	1042	930
Test 11	404	12.1	890	Htr 3 TC 6	1.46	0.05	0.15	1042	930
Test 12	322	13.0	542	Htr 4 TC 4	1.33	0.15	0.31	859	664
Test 13	327	12.9	547	Htr 4 TC 4	1.33	0.15	0.31	875	676
Test 14	319	12.5	702	Htr 3 TC 6	1.46	0.14	0.23	838	747
Test 15	321	12.5	702	Htr 4 TC 4	1.33	0.10	0.23	966	747
Test 16	337	12.2	860	Htr 4 TC 4	1.33	0.05	0.17	1074	831
Test 17	320	12.2	852	Htr 4 TC 4	1.33	0.06	0.18	1053	814
Test 18	413	14.9	584	Htr 4 TC 4	1.33	0.07	0.24	892	689
Test 19*	406	14.9	581	Htr 4 TC 8	1.78	0.21	0.24	417	681
Test 20*	412	14.5	734	Htr 4 TC 7	1.54	0.08	0.16	767	764
Test 21	408	14.5	731	Htr 3 TC 5	1.46	0.05	0.15	838	748
Test 22	426	14.2	892	Htr 3 TC 5	1.46	-0.01	0.09	932	832
Test 23	421	14.2	889	Htr 3 TC 5	1.46	0.00	0.09	927	827
Test 24*	457	16.1	592	Htr 4 TC 8	1.78	0.14	0.18	408	665
Test 25	448	16.1	589	Htr 4 TC 7	1.54	0.08	0.18	656	654
Test 26	459	15.6	745	Htr 3 TC 5	1.46	-0.01	0.10	838	748
Test 27*	460	15.6	746	Htr 4 TC 8	1.78	0.07	0.10	458	748
Test 28	479	15.2	907	Htr 3 TC 5	1.46	-0.08	0.02	913	814
Test 29	462	15.2	899	Htr 3 TC 5	1.46	-0.06	0.03	904	807
Test 30	360	12.6	568	Htr 4 TC 4	1.33	0.13	0.29	923	714
Test 31	343	12.6	555	Htr 4 TC 4	1.33	0.15	0.31	903	698
Test 32*	383	13.5	456	Htr 3 TC 4	1.33	0.19	0.38	858	664
Test 33*	371	14.0	445	Htr 3 TC 4	1.33	0.19	0.39	817	631
Test 34	339	12.2	638	Htr 4 TC 4	1.33	0.12	0.26	966	747
Test 35	335	12.3	635	Htr 3 TC 6	1.46	0.16	0.27	837	747

Test Number	Inlet Subcooling [kJ/kg]	Inlet Pressure [MPa]	Mass Flux [kg/m ² s]	Tripped TC	Local CHF Location [m]	Local Quality [-]	Exit Quality [-]	q ^{''} _{CHF,local} [kW/m ²]	q ^{''} _{CHF,avg} [kW/m ²]
Test 36	324	12.3	628	Htr 3 TC 6	1.46	0.17	0.27	819	730
Test 37*	348	11.9	874	Htr 3 TC 5	1.46	0.08	0.17	967	863
Test 38	349	11.9	876	Htr 3 TC 5	1.46	0.08	0.16	966	862
Test 39	348	11.9	878	Htr 4 TC 4	1.33	0.04	0.16	1117	863
Test 40	395	11.3	1511	Htr 4 TC 4	1.33	-0.07	0.02	1484	1148
Test 41	402	11.2	1523	Htr 3 TC 6	1.46	-0.06	0.00	1247	1113
Test 42	392	11.2	1513	Htr 3 TC 6	1.46	-0.05	0.01	1229	1097
Test 43	390	11.4	1243	Htr 3 TC 5	1.46	-0.02	0.05	1135	1013
Test 44	390	11.5	1241	Htr 3 TC 5	1.46	-0.01	0.06	1154	1030
Test 45	383	11.6	1234	Htr 3 TC 5	1.46	-0.01	0.06	1154	1030
Test 46	508	11.9	605	Htr 4 TC 4	1.33	0.07	0.25	1143	885
Test 47	516	12.0	603	Htr 3 TC 6	1.46	0.12	0.25	996	890
Test 48*	509	11.5	929	Htr 4 TC 4	1.33	-0.05	0.08	1310	1013
Test 49	502	11.5	924	Htr 4 TC 4	1.33	-0.05	0.09	1309	1013
Test 50	393	10.4	555	Htr 3 TC 6	1.46	0.21	0.32	911	814
Test 51	408	10.4	567	Htr 3 TC 6	1.46	0.19	0.31	931	832
Test 52	302	10.3	926	Htr 3 TC 6	1.46	0.10	0.17	991	884
Test 53	302	10.3	927	Htr 3 TC 6	1.46	0.10	0.17	987	881
Test 54	314	10.0	1285	Htr 4 TC 4	1.33	0.00	0.09	1309	1012
Test 55	312	10.0	1282	Htr 4 TC 4	1.33	0.01	0.09	1309	1012
Test 56	327	9.8	1626	Htr 4 TC 4	1.33	-0.03	0.04	1467	1135
Test 57	319	9.9	1617	Htr 4 TC 4	1.33	-0.03	0.05	1463	1131
Test 58	273	10.0	591	Htr 3 TC 6	1.46	0.19	0.29	781	697
Test 59	257	8.7	834	Htr 3 TC 6	1.46	0.15	0.22	967	863
Test 60	253	8.7	832	Htr 3 TC 6	1.46	0.15	0.22	951	849
Test 61	246	8.2	1275	Htr 3 TC 6	1.46	0.09	0.14	1172	1047
Test 62	239	8.2	1273	Htr 3 TC 6	1.46	0.09	0.15	1154	1030
Test 63	258	7.9	1664	Htr 3 TC 6	1.46	0.04	0.09	1323	1181
Test 64	254	7.9	1660	Htr 3 TC 6	1.46	0.04	0.09	1312	1171
Test 65	314	7.8	1664	Htr 3 TC 6	1.46	0.02	0.08	1435	1282
Test 66	314	7.7	1665	Htr 3 TC 6	1.46	0.02	0.07	1425	1273
Test 67	322	7.9	1330	Htr 3 TC 6	1.46	0.05	0.11	1285	1148
Test 68	309	7.9	1320	Htr 3 TC 6	1.46	0.05	0.12	1279	1143
Test 69	323	8.0	958	Htr 3 TC 6	1.46	0.09	0.16	1079	963
Test 70	312	8.0	956	Htr 3 TC 6	1.46	0.10	0.17	1088	972

Test Number	Inlet Subcooling [kJ/kg]	Inlet Pressure [MPa]	Mass Flux [kg/m ² s]	Tripped TC	Local CHF Location [m]	Local Quality [-]	Exit Quality [-]	q ^{''} _{CHF,local} [kW/m ²]	q ^{''} _{CHF,avg} [kW/m ²]
Test 71*	531	14.7	1267	Htr 2 TC 3	1.33	-0.23	-0.13	1180	913
Test 72*	516	14.8	1258	Htr 2 TC 3	1.33	-0.21	-0.11	1194	924
Test 73	618	15.1	1259	Htr 4 TC 6	1.46	-0.29	-0.22	1020	912
Test 74*	504	14.8	1251	Htr 3 TC 3	1.33	-0.22	-0.11	1140	881
Test 75*	497	14.9	1247	Htr 3 TC 3	1.33	-0.20	-0.10	1160	897
Test 76	526	14.5	1591	Htr 4 TC 6	1.46	-0.24	-0.18	1098	980
Test 77	530	14.5	1596	Htr 4 TC 6	1.46	-0.25	-0.18	1097	980
Test 78	584	14.2	1579	Htr 4 TC 6	1.46	-0.28	-0.22	1133	1012
Test 79	582	14.2	1580	Htr 4 TC 6	1.46	-0.28	-0.22	1135	1014
Test 80	479	15.6	917	Htr 3 TC 5	1.46	-0.10	-0.01	876	781
Test 81	471	15.6	912	Htr 3 TC 5	1.46	-0.10	-0.01	856	763
Test 82	468	16.5	615	Htr 4 TC 8	1.78	0.11	0.14	406	663
Test 83*	471	16.5	614	Htr 3 TC 3	1.33	-0.04	0.14	858	663
Test 84	647	15.6	1260	Htr 4 TC 6	1.46	-0.33	-0.26	1022	913
Test 85	647	15.6	1260	Htr 4 TC 6	1.46	-0.33	-0.26	1023	914
Test 86	591	15.9	1243	Htr 4 TC 6	1.46	-0.31	-0.24	931	831
Test 87	590	15.9	1243	Htr 4 TC 6	1.46	-0.30	-0.23	950	848
Test 88	632	16.2	1570	Htr 4 TC 6	1.46	-0.36	-0.29	1173	1047
Test 89	633	16.1	1571	Htr 4 TC 6	1.46	-0.36	-0.29	1173	1047
Test 90	595	16.4	1568	Htr 4 TC 6	1.46	-0.34	-0.26	1135	1013
Test 91	592	16.4	1574	Htr 4 TC 6	1.46	-0.34	-0.27	1117	997
Test 92	500	14.3	937	Htr 3 TC 5	1.46	-0.08	0.01	968	864
Test 93	498	14.3	935	Htr 3 TC 5	1.46	-0.08	0.01	968	864
Test 94	497	14.3	932	Htr 3 TC 5	1.46	-0.05	0.04	1023	914
Test 95	499	14.4	608	Htr 4 TC 4	1.33	0.02	0.20	1011	782
Test 96	495	14.5	609	Htr 4 TC 4	1.33	0.03	0.21	1011	782

* indicates one or more thermocouples exceeded the specified temperature marking a CHF event. See following table.

Additional Tripped Thermocouple Information

Test Number	Tripped TC	Local CHF Location [m]	Local Quality [-]	$q''_{CHF,local}$ [kW/m ²]
Test 19	Htr 4 TC 9	1.78	0.21	417
Test 20	Htr 4 TC 8	1.78	0.13	468
	Htr 4 TC 9	1.78	0.13	468
Test 24	Htr 4 TC 9	1.78	0.14	408
Test 27	Htr 4 TC 9	1.78	0.07	458
Test 32	Htr 3 TC 6	1.46	0.25	744
Test 33	Htr 3 TC 5	1.46	0.25	708
	Htr 3 TC 6	1.46	0.25	708
Test 37	Htr 3 TC 6	1.46	0.08	967
Test 48	Htr 4 TC 6	1.46	-0.02	1134
Test 71	Htr 3 TC 3	1.33	-0.23	1180
	Htr 4 TC 3	1.33	-0.23	1180
Test 72	Htr 3 TC 3	1.33	-0.21	1194
	Htr 4 TC 3	1.33	-0.21	1194
Test 74	Htr 4 TC 3	1.33	-0.22	1140
Test 75	Htr 4 TC 3	1.33	-0.20	1160
Test 83	Htr 3 TC 4	1.33	-0.04	858
	Htr 3 TC 5	1.46	0.02	743
	Htr 3 TC 6	1.46	0.02	743

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