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BENCHMARK TESTING THE ODEN CHF LOOP TO COLUMBIA UNIVERSITY HTRF

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Abstract

Westinghouse has designed and built ODEN, a new Critical Heat Flux (CHF) test loop for PWR applications. It is located at the Westinghouse Thermal-Hydraulic Test Facility in Västerås, Sweden. ODEN can accommodate full length (4.3 m) bundles, up to 6x6 rod arrays, up to 16 MW power, and accurately cover a wide range of PWR thermal-hydraulic conditions. Benchmark qualification CHF tests at ODEN were recently performed. Results indicate good agreement between CHF data from ODEN and data from HTRF. Repeatability (ODEN – ODEN) was also good. This paper presents the details of the comparative tests and the resulting data analyses.

Introduction

It is well known that Critical Heat Flux (CHF), sometimes loosely referred to as DNB (Departure from Nucleate Boiling), is an important parameter in the design and operation of nuclear fuel and nuclear plants. From 1963 until 2003, all the CHF test data which formed the basis for Westinghouse CHF correlations licensed in the US were obtained from the Heat Transfer Research Facility (HTRF) of Columbia University in New York City. In response to HTRF's permanent closure in 2003, Westinghouse built its own new CHF test facility, ODEN, as a replacement to (and improvement upon) the former HTRF. Loop installation was completed in 2006, shakedown testing in 2009, and qualification / benchmark testing versus HTRF was completed in 2010. ODEN is named for the "most furious" Nordic mythological god, and is co-located with the FRIGG loop at the Westinghouse Thermal-Hydraulic Test facility in Västerås, Sweden. These loops share common infrastructure. ODEN will be used for PWR applications (DNB and mixing tests). FRIGG (the mythological "wife" to ODEN) will continue to be used for BWR applications, such as critical power / dryout testing. This paper will describe the ODEN qualification tests which repeated a Westinghouse non-uniform 5x5 CHF test performed under PWR conditions at HTRF. The objectives were to benchmark the two facilities by demonstrating an acceptable comparison of the data, as well as to demonstrate acceptable repeatability within ODEN itself. Two short and one long CHF tests were run at ODEN. The third is compared to a reference HTRF test.

1. Description of ODEN test loop

Section 1.1 presents an overview of the ODEN loop arrangement and design capabilities. Section 1.2 discusses the measurement and control of key parameters.

1.1 Configuration and capability

As shown in Figure 1, ODEN consists of two independently operated sub-loops; one for the test section (right-hand side) where heat is added, the other for heat removal through a bank of heat exchangers (left-hand side). The sub-loops share a common suction to two pumps but each pump discharges to its respective sub-loop. In contrast, HTRF pumps shared a common discharge to both sub-loops. With a dedicated pump to the Test Section, the ODEN configuration reduces the risk of starving the Test Section of flow in the event of a rapid increase in two-phase pressure drop (such as during low flow/ low pressure operation).

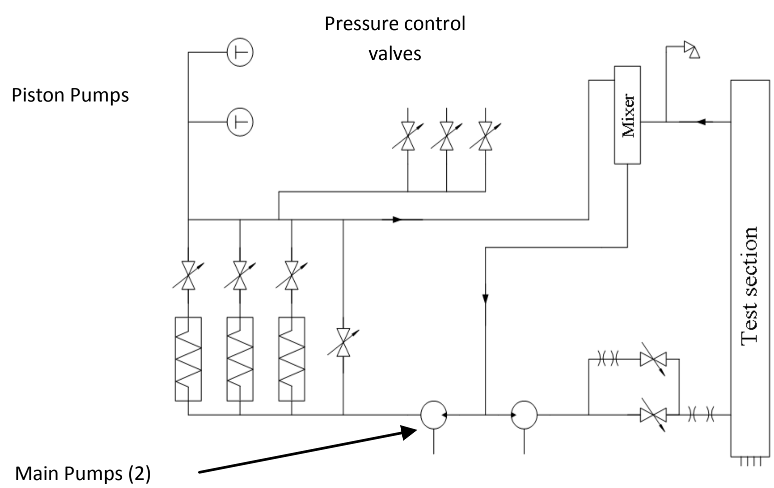

Figure 1 Schematic of ODEN Loop

Like HTRF, the ODEN pressure vessel is designed to accommodate full length test bundles containing 4x4, 5x5, 6x6, and various hex arrays of directly heated rods. Heated lengths can reach up to 4.3 m. ODEN is designed for 200 bar, 366 ^{o}C, and flows to the test section of 0.7 to 22 kg/s. Power to the test section is based on a 400 max VDC (rectified AC) and 44 max kA electrical supply system. Depending on the actual rod bundle resistance, 15-16 MW is realizable at the test section when the heat exchangers are fully configured. HTRF had similar design range of pressure, temperature, and flow, though slightly lower power capability (12-14 MW).

Due to the use of directly heated rods (i.e., Joulean), water quality is carefully controlled with respect to conductivity level. In addition, oxygen content is restricted to reduce risk of corrosion.

1.2 Measurement and control

All parameters which impact the safety-related data from testing are calibrated with traceability to Swedish national standards (SP Technical Research Institute of Sweden). These include inlet and outlet temperature, flow, pressure, and power (voltage, current). For extra assurance, each of these primary measurement channels has a calibrated and redundant measurement channel.

- Temperature – the bundle inlet and outlet is measured using several high precision resistance temperature detectors (RTD). The inlet temperature is regulated automatically (and manually) via control of flow through the heat exchangers.

- Flow – the bundle inlet flow is calculated based on pressure drop across dual inline orifices contained within special flow metering sections which were installed per ISO 5167 and ASME-MFE-14M-2001. One of two pipe diameters can be selected based on the range of flow being tested. An independent on-site check of the ODEN flow measurement system was performed by the SP Technical Research Institute and confirmed excellent agreement. Flow is regulated by control valves.

- Pressure – is measured with capacitance manometers. Pressure control is based on a bleed and feed approach, whereby pressure is reduced via water release and increased via make-up piston pumps. Pressure can be controlled either automatically or manually.

- Power – current is measured via Hall Effect sensors; voltage is measured across the positive and negative bus, and across the bundle heated length. Special rods equipped with voltage taps at the beginning and end of heated length enable a direct power measurement of the heated length. The true time varying power is calculated by computer.

The data acquisition system (DAS) consists of a system of multiple computers which handle the scan, monitor, display, and record functions for test section and loop measurements. The DAS can accommodate up to 288 heater rod TCs, 49 sub-channel TCs (for mixing tests), plus 128 other channels. The scanning rate is 25 Hz. Data is recorded in 25 Hz and 5 Hz modes (averages of 25 Hz data). Transient and steady state data can be remotely accessed online. CHF detection is accomplished by visual observation of the temperature vs. time behavior of the TCs contained in the heater rods. (See Section 3 for more detail). All transient TC traces are displayed on digital plots and selected analog chart recorders.

2. Test configurations

A reference Westinghouse non-uniform CHF test performed at HTRF was selected as the benchmark for the ODEN qualification tests. The bundle configuration consisted of a 5x5 typical cell rod array with non-uniform (cosine) power shape and 4.3 m heated length. The bundle contained 8 Westinghouse mixing vane grids and 9 simple support grids. The axial configuration is shown in Figure 2.

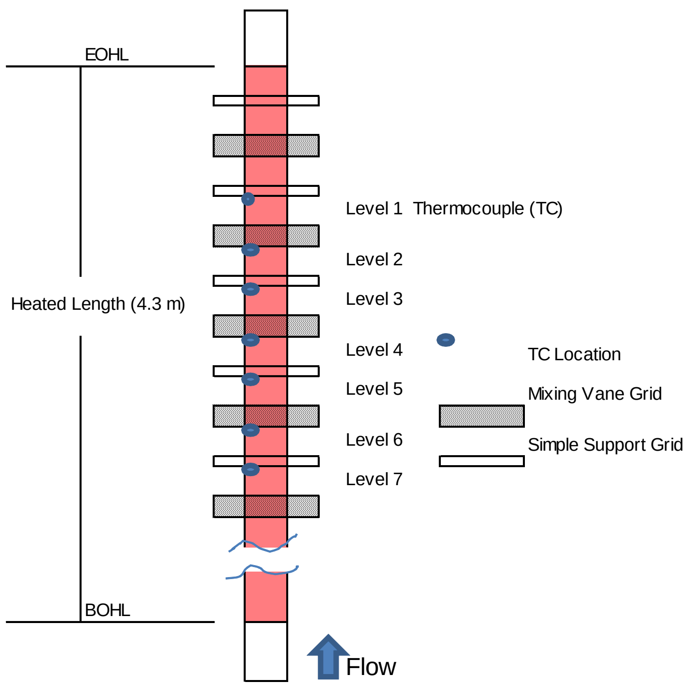

Figure 2 Axial geometry

Each ODEN qualification test was based on the same HTRF reference geometry. For the ODEN tests, new heater rods were fabricated based on original HTRF drawings and resulted in essentially identical radial and axial power profiles. As with the HTRF reference test, the outer 16 (cold) rods contained 5 thermocouples; the inner 9 (hot) rods contained 7 TCs each. TCs were positioned just upstream of the 3^{rd} – 9^{th} grids upstream of EOHL. Table 1 summarizes the comparison between the HTRF and ODEN test configurations.

	Test Facility			
	HTRF	**ODEN**		
Test #	Reference	Test 1	Test 2	Test 3
Rod array	5x5			
Cell type	Typical			
Heated Length	4.267 m			
Axial power shape	1.5 cosine			
Radial power ratio (hot/cold)	0.826	0.822	0.826	0.827
Heater Rod Diameter	9.5 mm			
Pitch between rods	12.6 mm			
Test section side	65.0 mm			

Table 1: Test configurations at HTRF and ODEN

3. Test Conditions and Procedure

The procedure for performing a given CHF "run" was the same for ODEN as for HTRF. First, the desired steady state condition at the test section was established with respect to flow, exit pressure, and inlet temperature. The initial power applied to the test bundle was about 20 percent below that corresponding to the expected CHF power level at that condition. Once the setpoint was established the CHF condition was approached in the quasi-steady state manner illustrated by Figure 3. While flow and pressure were held constant, and with inlet temperature held constant via heat exchanger control, the bundle power was slowly and manually increased in small increments (≤ 30 kW) until a temperature excursion was observed in one (or more) TCs in the heater rods. Since the bundle was in a critical condition at that moment, power was typically reduced by ~ 20 percent to avoid rod burnout. CHF was recorded as the condition at maximum power immediately prior to this power reduction. The power reduction was usually a manual operation, though two independent power trip protection systems (digital and analog) could automatically shut off bundle power if any heater rod TC temperature exceeded a settable threshold (typically 500 - 550 ^{o}C).

In the case of a classic DNB event (heat flux driven CHF), the response of the TC is generally quite fast. Thus the decision to reduce power is based primarily on behavior of the temperature-time slope. In the case of classic dryout (quality driven CHF), the response is much slower. In this case the decision to reduce power is based primarily on consistent temperature rise after a change in slope. Engineering judgment is used in either case.

During the testing phase, the raw data was examined regularly for reasonable behavior to insure consistent bundle integrity and reliable test operation. Such checks included daily repeat tests of single phase bundle pressure drop, loop energy balances, and a standard CHF condition.

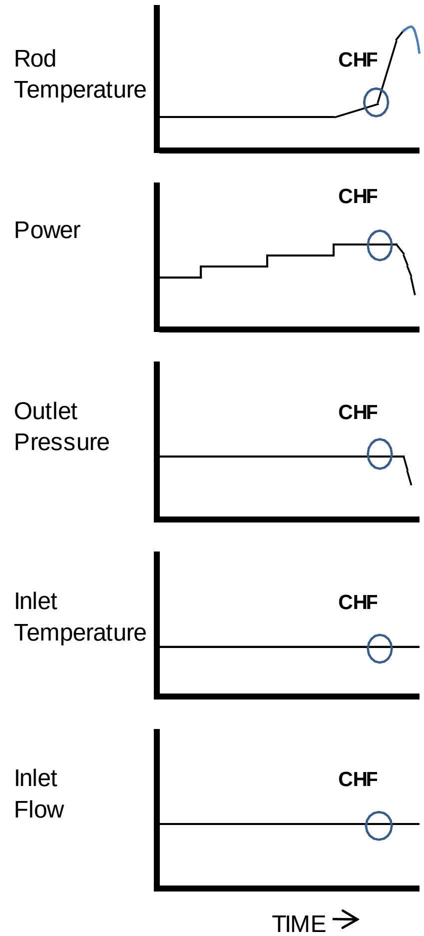

Figure 3 Example approach to CHF

Three ODEN qualification tests were conducted. Tests #1 and #2 were stopped prematurely due to equipment problems after a total of only 17 CHF points were acquired. However, Test #3 obtained 119 CHF points over 77 unique conditions. Due to the limited number of data in Tests #1 and #2, Test #3 was chosen for direct comparison to HTRF. The common pairs between Tests #1 - #3 were used for a rough estimation of *between setup* repeatability (though more test data will be needed for a more comprehensive evaluation).

There were 75 conditions in common between ODEN Test #3 and the HTRF reference test. The range of common test conditions included:

- Pressure 10.3 to 16.5 MPa
- Mass Velocity 1356 to 4949 kg/m^2 s
- Mass Flow Rate 3.3 to 12.1 kg/s
- Inlet Temperature 192 to 324 ^oC
- Power 2.2 to 6.3 MW (0.7 to 2.0 MW/m^2)

Table 3 shows the distribution of common CHF data when grouped by nominal mass velocity and pressure.

	Pressure (MPa)				
G (kg/m^2 s)	10.3	12.4	14.5	16.5	**TOTAL**
1356	3	3	4	4	14
2034	3	4	4	5	16
2712	4	4	5	5	18
3390	5	4	4	5	18
4068	1	2	3	2	8
4949				1	1
TOTAL	16	17	20	22	**75**

Table 3 Distribution of common CHF conditions

In order to enhance the direct comparison of ODEN and HTRF heat flux data, the target condition of each run in the ODEN tests was set to the actual measured condition of the corresponding run in the HTRF reference test. In addition, challenging tolerance criteria were defined for an acceptable *matched condition*. The tolerances and actual differences in condition (based on absolute value) are shown in Table 4. The tolerance criteria were met for all data with respect to Tinlet, flow, and for most pressures. The slight differences in pressure among some points were judged to be acceptable since the effect of pressure on CHF is quite small over the tested range.

			Actual	
Parameter		Tolerance	Average	Std dev
Tinlet	ºC	≤ 1.4	0.3	0.3
Flow	kg/s	≤ 0.16	0.03	0.02
Pressure	MPa	≤ 0.17	0.05	0.04

Table 4 Differences between actual (ODEN) vs. target (HTRF) conditions

Two special matrices were performed in Test #3 to evaluate repeatability within a given test setup. The first matrix (Method A), consisted of a set of “focused repeats” in which several CHF runs were *focused* on just four conditions. The purpose was to acquire a statistically significant number of independent matched pairs. Table 5 shows the number of data in each group of focused repeats:

One Tinlet per group

G (kg/m^2 s)	Pressure (MPa)				
	10.3	12.4	14.5	16.5	**TOTAL**
1356			3		3
2034			4	7	11
2712		4			4
3390					
4068					
4949					
TOTAL		4	7	7	**18**

Table 5 Number of *Focused Repeat* CHF points, test #3 (method A)

The second matrix (Method B), evaluated the response of 24 matched pairs over a nearly balanced 3x3x3 matrix of pressure, inlet temperature, and flow. The purpose was to estimate the within setup repeatability as a function of condition. Table 6 shows the number of paired CHF conditions:

One Tinlet per group

G (kg/m^2 s)	Pressure (MPa)				
	10.3	12.4	14.5	16.5	**TOTAL**
1356					0
2034		2	2	2	6
2712		3	3	3	9
3390		3	3	3	9
4068					0
4949					0
TOTAL	0	8	8	8	**24**

Table 6 Number of CHF pairs, test #3 (method B)

4. Data Reduction

The validity of the CHF data was assessed by checking the linearity of CHF power vs. inlet temperature (at constant flow and pressure). Non-linear behavior could indicate a potential abnormality warranting further investigation (and potential outlier). In addition, the control parameters were evaluated for stability and consistency of the primary and redundant measurements. The final 75 conditions are reported in Table 3.

5. Data analysis

The CHF data were analyzed by direct comparison of the raw measurements.

Raw data evaluations sought to investigate the *within setup* repeatability (Methods A and B) based on heated length power at CHF. The *between setup* repeatability (between tests) and *between facility* repeatability (ODEN to HTRF) were checked using hot rod average heat flux (q"h) as the basis instead of raw bundle power in order to account for the slight differences between the bundle radial power distributions.

(1) $$q''h = PF_{MAX} * (\text{Power at CHF}) / (\text{Heated Area}) \; ; \; MW/m^2$$

where PF_{MAX} = max radial power factor

DEL_{21} was the metric used for comparing between any two CHF runs. When using q"h as the basis, DEL_{21} between runs 2 and 1 can be expressed as:

(2) $$DEL_{21} = (q''h_2 - q''h_1) / [0.5(q''h_2 + q''h_1)]$$

Use of the DEL parameter tends to equalize small differences in test conditions by normalizing to the average.

6. Results – ODEN to ODEN Repeatability

Repeatability within a given setup, as well as between setups is addressed next.

6.1 Within setup repeatability

Results for ODEN to ODEN *within setup* repeatability are presented for Test #3 since it had the most number of data. This evaluation was based on the raw bundle CHF power for ODEN data repeated over the 24 conditions shown in Table 6 and within the repeat tolerances of Table 4. (Note that, since the radial power distribution is the same, a comparison based on q"h would have given the same result). A plot of the original versus repeated CHF points is shown in Figure 4. Linear regression reveals excellent agreement ($R^2 > 99\%$).

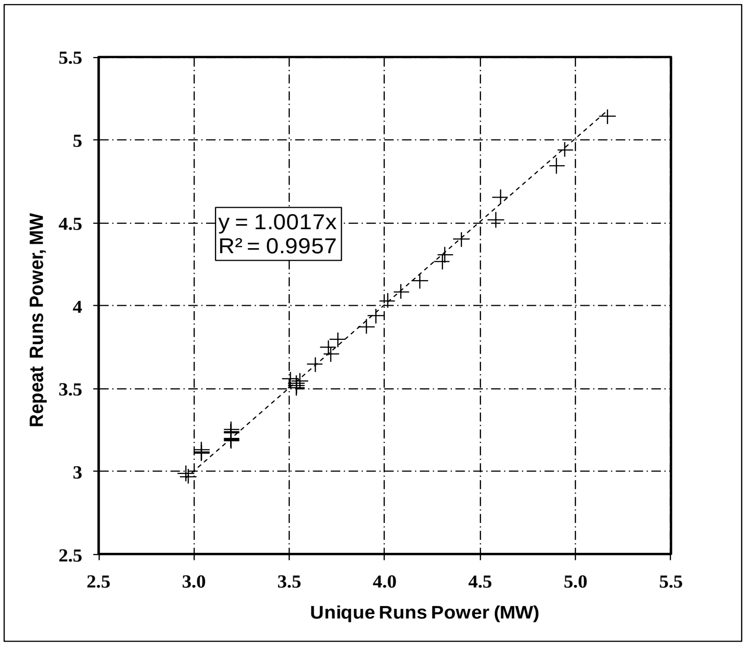

Figure 4 ODEN within setup repeatability (power, MW)

Using a statistical approach, the *mean* of the DEL_{21} distribution (i.e., 24 paired differences) when stated with 95% confidence limits was 0.1% ± 0.3%, or *statistically zero.*

The repeatability of an individual CHF point within the same setup was estimated at a 95% confidence level as approximately two standard deviations of the DEL_{21} distribution (or T times the standard deviation, s, for normally distributed samples). When taking both Methods A and B into account, the within setup repeatability of an individual point was found to be ~ 2% in power. This result is consistent with HTRF historical data.

6.2 Between setup repeatability

Due to the limited number (5) of CHF data in Test #2, ODEN to ODEN *between setup* repeatability was estimated based on comparison of Test #3 (119 points) and Test #1 (12 points). Using a statistical approach similar to that presented in section 6.1, the between setup repeatability for an individual point was approximately 4 % to 5% (based on q"h). Though consistent with historical HTRF data, very few conditions could be considered. Therefore, the between setup repeatability is stated only as a rough estimate.

6.3 ODEN vs. HTRF

A raw data comparison was made in terms of q"h for the ODEN Test #3 and HTRF reference test data corresponding to the 75 conditions of Table 3. The ODEN and HTRF test control parameters for each condition were within the tolerances given in Table 4. Figure 5 shows the results. A high degree of correlation (R^2 > 98.5%) was observed.

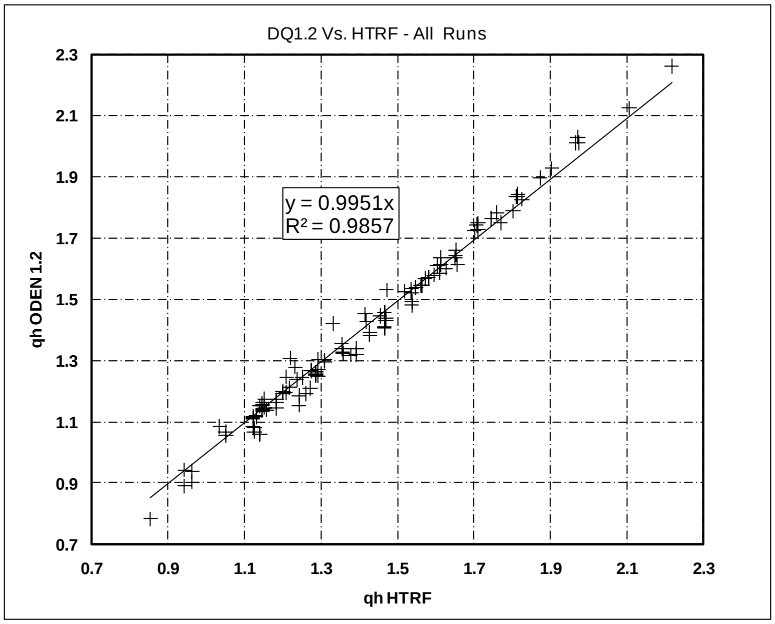

Figure 5 – ODEN vs. HTRF CHF (hot rod average heat flux, MW/m^2)

Again employing the statistical approach explained previously, the *mean* of the DEL_{21} distribution (i.e., 75 paired differences between ODEN and HTRF) when stated with 95% confidence limits was found to be -0.6% ± 0.7%, or *statistically zero.* With 95% confidence, the repeatability in terms of q"h of an *individual* CHF point obtained at ODEN was found to be within 5.9% of the corresponding CHF point obtained at HTRF.

7. Conclusions

Recently completed benchmark testing has shown that the Westinghouse ODEN CHF Loop has replicated well the CHF power for the same bundle geometry and conditions at Columbia University's Heat Transfer Research Facility (HTRF). ODEN to ODEN repeatability was also very good. The new ODEN CHF Loop will provide both Westinghouse and external users with a new capability for CHF testing of new or modified fuel designs in the future.

8. References

[1] ISO 5167-2:2003, “Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full.”

[2] ASME-MFE-14M-2001, “Measurement of Fluid Flow Using Small Bore Precision Orifice Meters”

9. Acknowledgements

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