13th International Conference on CANDU Fuel
Holiday-Inn Waterfront Hotel
Kingston, Ontario, Canada, 2016 August 15-18

REPEATABILITY OF FULL SCALE 37M CRITICAL HEAT FLUX EXPERIMENTS PERFORMED AT STERN LABORATORIES INC.

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ABSTRACT

In 2015, a series of critical heat flux (CHF) experiments was performed in the Stern Laboratories test facility to repeat many of the test conditions performed previously in 2008 and 2011 with the full scale 37M fuel simulation.

The data are self-consistent, repeatable and follow established trends with sub-cooling, flow rate, pressure and diametrical pressure tube creep. A quantitative analysis comparing the dryout power values for the 2008, 2011 and 2015 campaigns yields a one-sigma standard deviation of +/- 1.3%.

This paper presents a summary of the results and comparison study.

1. Introduction

A full-scale fuel simulation replicating the 37-element CANDU fuel used in the Bruce/ Darlington Nuclear Power Stations was fabricated and tested in the Stern Laboratories experimental facilities commencing in 1992. The many series of CHF experiments that were performed from 1992 through 1998 are referred to as the original series (37O) and included experiments with pressure tubes having maximum diametral creep of 0%, 3.3% and 5.1%.

In 2008, the original design (37O) fuel simulation was cleaned and rebuilt except the original centre element was replaced by a smaller 11.5 mm diameter centre element to replicate a new fuel design (37M). CHF experiments were performed for the 37M design with pressure tubes having maximum diametral creep of 3.3% (37M-C1) first and then 5.1% (37M-C2). The fuel simulation was cleaned and reassembled and then experiments were performed with the un-crept pressure tube (37M-R1).

In 2009, the fuel simulation was cleaned and rebuilt with the original centre element to replicate the 37O fuel design and CHF experiments (37R series) were performed to duplicate the original experiments with the 5.1% crept pressure tube. The fuel simulation was then cleaned, reassembled and experiments were performed with the 3.3% crept pressure tube.

In 2011, the fuel simulation was cleaned but also underwent a significant rebuild with twenty new downstream elements installed. A series of 37M experiments was performed with the 3.3% crept pressure tube (37M-C3). The fuel simulation was then cleaned and reassembled, and a series of experiments was performed with the 5.1% crept pressure tube (37M-C4).

In 2015, the fuel simulation was cleaned, thermocouple carriers were replaced in several elements and the element strings in two key positions #20 and #26 were switched with #28 and #30. A series of CHF experiments was performed in the 3.3% crept pressure tube (37M-C5) and reported separately [1].

A summary of the various series of CHF experiments performed for the 37M fuel simulation is given in Table 1. It should be noted that the fuel simulation has been used extensively for many experiments and has undergone many cleanings, repairs and rebuilds that have resulted in subtle variations in the geometry within the acceptable manufacturing tolerances.

This paper presents a summary of the many CHF experiments performed for the 37M fuel design over several years. It includes a discussion of the consistency, repeatability and reproducibility of the experiments by examining the dryout power data for the 3.3% crept pressure tube which is considered the most relevant for comparison purposes.

Table 1: Summary of 37M CHF Experiments

Series	Date	No. of Tests	Flow Liner	Initial Conditions
37M-C1	March 2008	~ 120 CHF	3.3% crept	Cleaned, minor repairs, new centre element, new endplates
37M-C2	April 2008	~ 120 CHF	5.1% crept	Same as 37M-C1
37M-R1	October 2008	~ 100 CHF, 11 PDO	Un-crept	Cleaned, minor repairs
37M-C3	March 2011	50 CHF, 4 PDO	3.3% crept	Cleaned, significant rebuild (20 new element strings)
37M-C4	October 2011	~ 65 CHF, 6 PDO, 5 Transient tests	5.1% crept	Cleaned, some repairs
37M-C5	May 2015	~ 120 CHF, 6 PDO	3.3% crept	Cleaned, repairs, some TC carriers replaced, elements 20 & 26 switched with 28 & 30, Some pull-rods removed

2. Brief desecription of 37M fuel simulation

The full-scale 37M fuel simulation was designed and fabricated to simulate as closely as possible a string of 12 fully aligned 37M bundles in a Bruce/Darlington fuel channel and includes endplates, bearing pads and inter-element spacers. Each of the 37 element strings consist of nickel alloy (mainly Inconel 718) tubes, 480 mm heated length, joined by nickel-201 spool pieces to form a 12-segment, 6 metre long bundle string with monel clad copper extensions. The extensions at each end have the same overall diameter as the heater tubes and serve as the power connectors. The 37M design was the same as the original 37O, or later the 37R, designs except for the smaller OD centre element. A cross-section of the fuel simulation is shown in Figure 1. The axial heat flux profile of the fuel simulation and the axial variations of the inside diameter of the crept pressure tubes are shown in Figure 2.

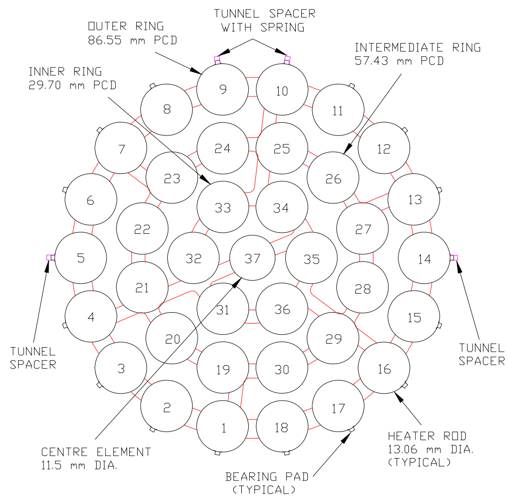

Figure 1: Fuel Simulation Cross-Section

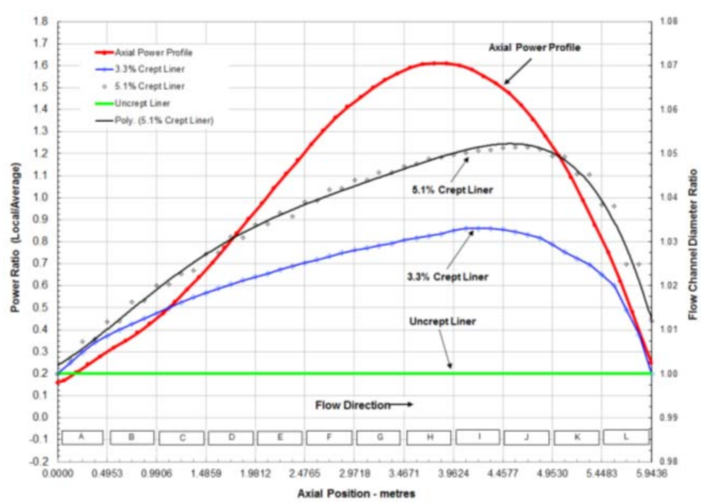

Figure 2: Axial Profiles

3. Summary of CHF results for the 3.3% crept experiments

Three series of experiments were performed using the 37M fuel simualtion with the 3.3% crept pressure tube. (37M-C1 series in March 2008, 37M-C3 series in March 2011 and 37M-C5 in May 2015). The fuel simulation was cleaned, assembled and installed in the test facility to the same specifications for each series. Between series, the fuel simualtion was disassmbled for cleaning, twenty downstream elements were replaced prior to the C3 series and two elements in key positions (#20 and #26) were switched (with #28 and #30) as well as several thermocouple carriers were replaced prior to the C5 series. These three series with the 3.3% crept pressure tube are nominally the same and their use for assessing the consistency, repeatability and reproducibilty of the 37M dryout power data is considered appropriate based on the amount of data (3 series, ~290 data points, over 7 year period) for a statisical study.

The 37M dryout power data for each mass flow are shown plotted in Figures 3 to 5 in terms of the Normalized Dryout Power versus Deviation of Inlet Temperature From Maximum at Outlet Pressures of 9, 10 and 11 MPa. Linear best fit lines for each flow are included in the plots. On average, the dryout power results for the 2011-37M-C3 series are approximately 3% higher than the 2008-37M-C1 series (2.9% for the 3.3% crept and 3.1% for the 5.1% crept). The dryout power results for the 2015-37M-C5 series are consistent with both the 2008 and 2011 series.

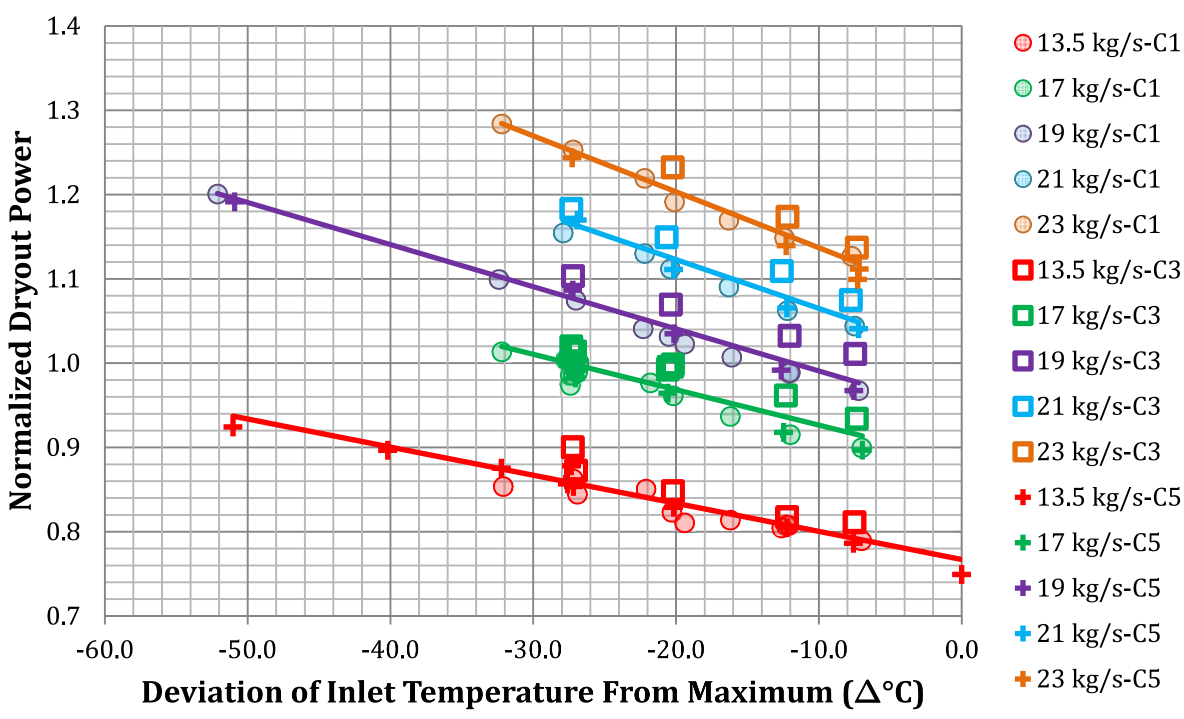

Figure 3: 37M CHF Data at 9 MPa (3.3% Crept)

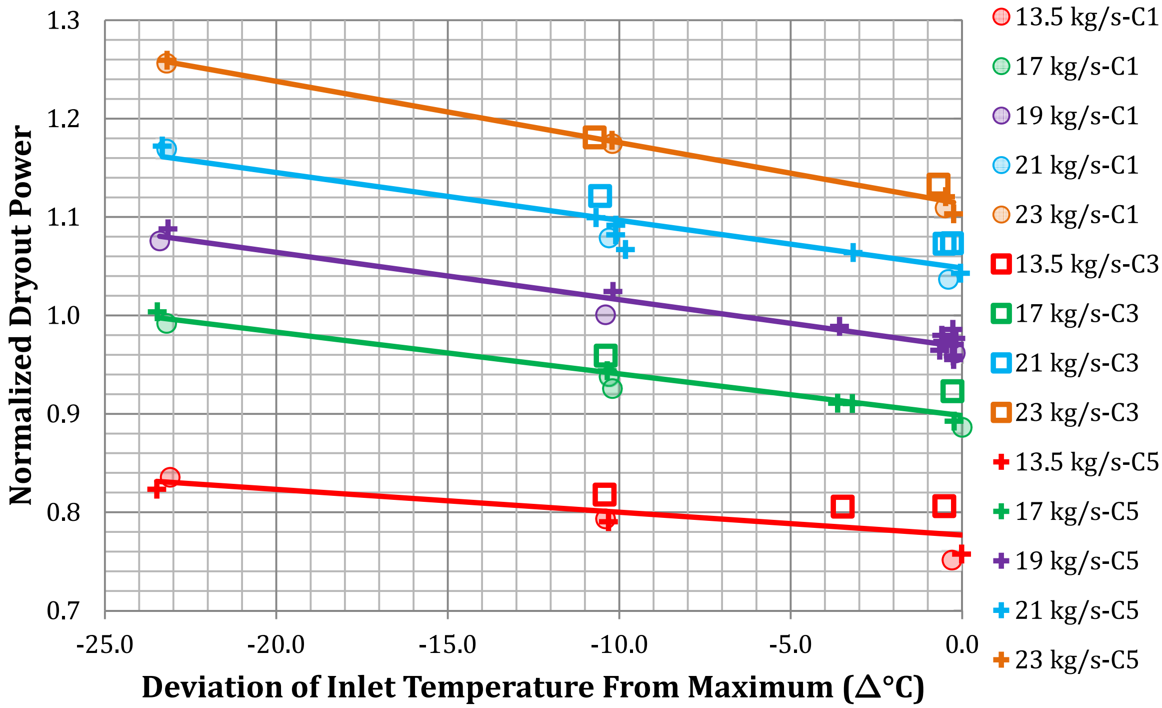

Figure 4: 37M CHF Data at 10 MPa (3.3% Crept)

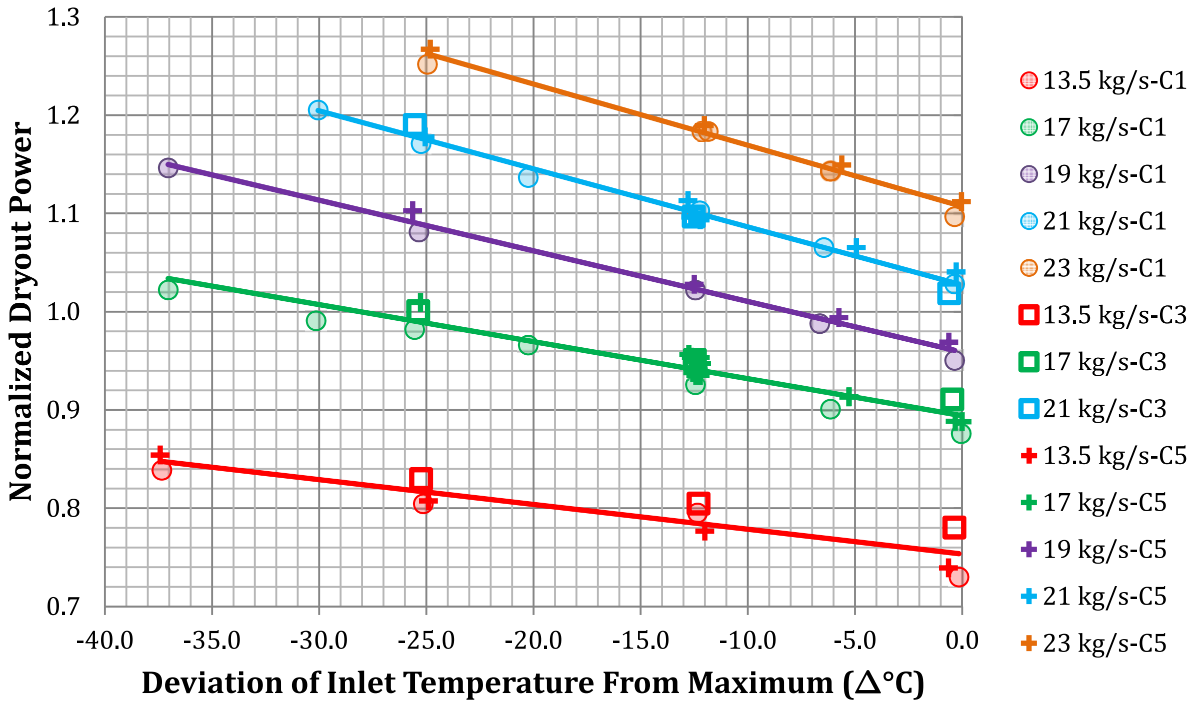

Figure 5: 37M CHF Data at 11 MPa (3.3% Crept)

The dryout power data for these three series (C1, C3 and C5) acquired under similar test conditions (data clusters) were compared to assess the repeatability and reproducibilty of the experiments. The data cluster averages and the deviations were computed, and the cluster deviations were plotted along with a normal distribution curve, as shown in Figure 6. The figure shows good agreement of the computed data against the normal distribution curve with a standard deviation of ±1.3% (1σ).

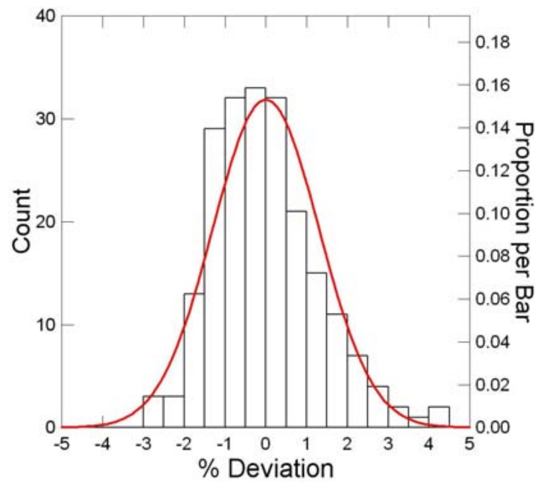

Figure 6: Deviations of the Dryout Power Between Series for Similar Conditions

During a series, repeat CHF tests were performed each test day at several standard conditions to monitor the state of the fuel simulation and assess any degradation in performance, generally due to crud buildup on the surface of the fuel elements. As shown in Figures 7 and 8 below for the 37M-C1 and 37M-C5 series, there was generally a gradual reduction in dryout power over the duration of a test series of about 2 to 3%. This degradation is typical for all series with some variability depending on various factors.

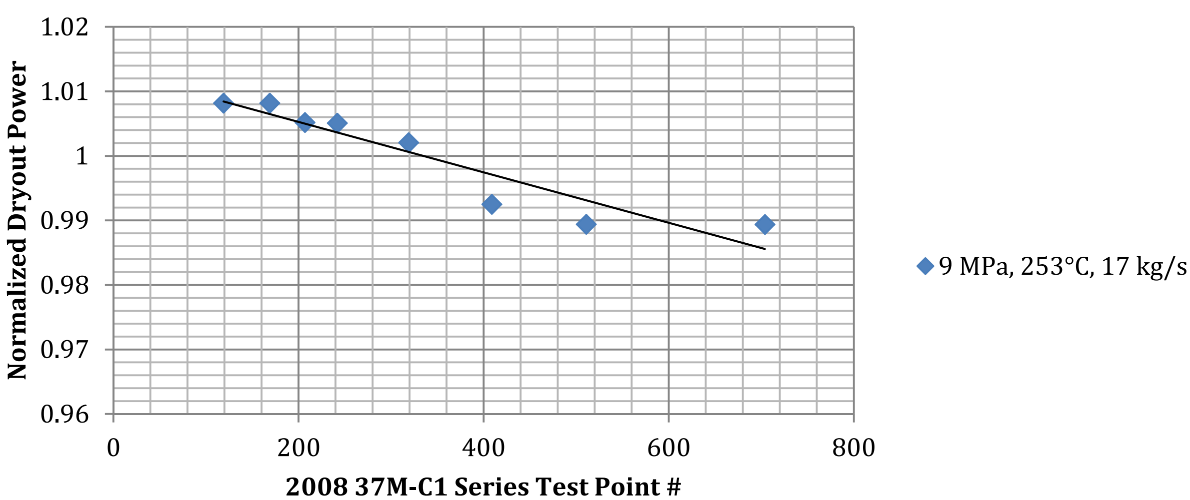

Figure 7: Daily CHF Repeat for 37M-C1 Series

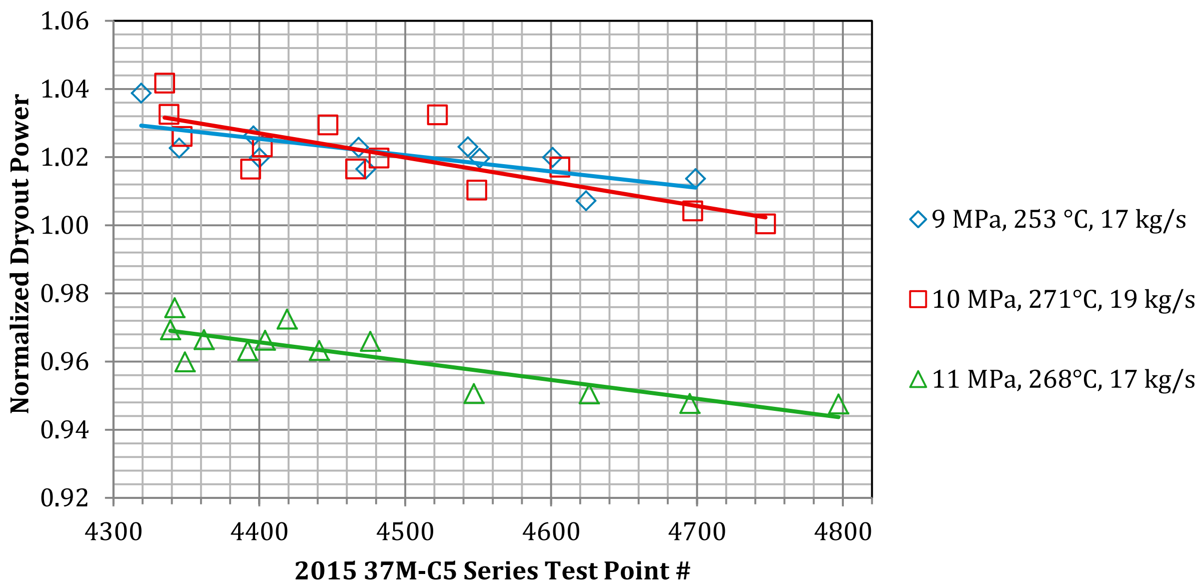

Figure 8: Daily CHF Repeat for 37M-C5 Series

The primary locations where initial dryout occurred have been summarized in Table 2 for each of the three test series. Initial dryout occurred at element positions #2, #20, #26 and/or #35 for the vast majority of tests, and when combined account for 78.8% to 98.0% of the initial occurrences, depending on the series. The downstream element string #2 was replaced prior to the C3 series and element string #20 was switched with #26 prior to the C5 series, indicating that the occurrence of CHF was dependent on the element position and not the element itself. The location of CHF was reasonably consistent and did not change significantly between test series.

Table 2: Summary of Primary Initial CHF Locations

Thermocouple	37M-C1 (2008)	37M-C3 (2011)	37M-C5 (2015)
2I	0%	18.4%	0%
2J	14.4%	6.1%	0.6%
2K	0%	8.2%	25.0%
20J	11.1%	10.2%	4.3%
20K	28.9%	42.9%	51.2%
26I	0%	10.2%	0.6%
35J	24.4%	2.0%	11.6%
Sum	78.8%	98.0%	93.3%

4. Conclusions

For the experiments performed with the 37M fuel simulation in the 3.3% crept pressure tube over a period of several years, the dryout power data for the three test series (37M-C1, 37M-C3 and 37M-C5) are consistent based on a quantitative comparison of the data acquired at similar test conditions. Analysis of the results from all three series combined show that the dryout power data are repeatable and reproducible to within ±1.3% (1σ).

Initial dryout occurs predominantly at key element positions even if elements are replaced or switched with another element string, indicating CHF is position dependant and not overly sensitive to the properties of individual elements.

There is a gradual degradation of the fuel simulation CHF performance during a test series, most lkely due to a gradual buildup of crud (mixture of iron and aluminum oxides) on the surfaces of the heated elements. This degradation contributes to the variability of the data. The crud buildup is specific to the SL test loop and not observed in reactors, therefore the experimental results may be conservative compared to real fuel.

5. References

[1] R.A, Fortman, "Repeat Critical Heat Flux and Post-Dryout Experiments Using the Modified 37-Element Fuel Simulation in Water", SL-272/COG-15-2060, November, 2015.