

QUANTIFICATION OF UNCERTAINTIES ASSOCIATED WITH USING 28-ELEMENT BLA CHF CORRELATION

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Abstract

This paper addresses concerns regarding the use of the 28-element Bundle Boiling Length-Averaged (BLA) Critical Heat Flux (CHF) correlation in safety analysis outside the range of conditions of the Stern Labs (SL) 28-element bundle CHF tests whose data are used to derive the correlation. An approach has been developed to address the concerns and is based on the capability of the subchannel ASSERT code Critical Heat Flux (CHF) models, namely the Table Look-up method and mechanistic dryout model, to represent the underlying physical phenomena. The approach has been applied and the results demonstrated the appropriateness of the continued use of the BLA CHF correlation and also established the basis for assessing the uncertainty allowances associated with its use for other applications.

Introduction

Several concerns have been raised by the Canadian Nuclear Safety Commission (CNSC) regarding the use of the 28-element Bundle Boiling Length-Averaged (BLA) CHF correlation in safety analysis. The main concern is the use of the BLA CHF correlation without adequately accounting for prediction uncertainties, primarily for axial flux profiles other than the flat cosine profile that is used in the Stern Labs 28-element bundle CHF tests whose data are used to derive the correlation. CNSC staff also expressed concerns about uncertainty allowances in the BLA CHF correlation when predicting dryout powers for: 1) different pressure tube axial creep profiles and at different creep levels, 2) different radial flux profiles, and 3) conditions applicable to various thermalhydraulic boundary conditions corresponding to specific accident sequences such as the small break Loss of Coolant Accident (SBLOCA) and the Loss of Flow (LOF) accident. This paper summarizes work done to address these concerns.

1. Approach Outline

The axial flux shapes encountered during postulated Slow Loss of Regulation (SLOR) accidents cannot be covered by a single tested flux shape. Due to cost and schedule considerations for additional tests, a practical approach based on an engineering judgment was developed to quantify additional prediction uncertainties for using 28-el fuel BLA CHF correlation for non-tested configurations. The approach consists of the following steps:

- Validate the ASSERT code [1] against the 28-element CHF data. This task will demonstrate the capability of ASSERT for predicting the dryout power for the 28-element bundles.

- Use the ASSERT code to predict dryout powers for other flux shapes.
- Use the BLA and the Local Conditions (LC) CHF correlations to predict dryout powers for other flux shapes.
- Show the consistency in trends between ASSERT predictions and BLA CHF correlation predictions for dryout powers of other flux shapes
- Use ASSERT predictions as the basis for the method to quantify additional prediction uncertainties associated with the use of the BLA CHF correlation for axial flux profiles other than the flat cosine used in the SL tests. This is done as follows:
 - Categorize the axial flux profiles as discussed according to the symmetry index and peak index.
 - For each category or group of power profiles, the difference between the BLA CHF correlation prediction and ASSERT (mechanistic and table look-up) predictions will be the estimate for "average bias". The variation in the bias will be estimated by the standard deviation.
 - To identify the additional prediction uncertainty for a given power profile, the symmetry and peak indexes for that profile are calculated, a category is assigned, and the associated bias and variance is determined.

2. ASSERT Validation Against 28-element Fuel Bundle Dryout Data

ASSERT-PV V3R1-IST has been validated against SL measurements. The emphasis was on validating the code for the following parameters:

- Dryout Power,
- Axial dryout location,
- First fuel element to experience dryout,
- Dryout angle,
- Dryout quality, and
- Sensitivity of the dryout prediction to the number of the axial nodes.

Two options were used to predict the CHF in ASSERT: the table look-up (TLU) method and the mechanistic annular film dryout model.

The experimental data used in this validation exercise were obtained from the documented results of the Stern Labs 28-Element Pickering-style CANDU fuel bundle tests. The axial power shape is the flat cosine shape shown in Figure 3. Two different PT geometries were used in the SL tests: one with a uniform diameter PT corresponding to the as-new dimensions and the other with an axially non-uniform diameter variation having a maximum 3.3% diametral creep.

ASSERT predictions of dryout powers have been compared to experimental data. For both the TLU method and mechanistic model, the mean errors and standard deviations of the predictions are relatively small as shown in for the thermalhydraulic boundary conditions relevant to Neutron Over Power (NOP) analysis and for the two uncrept and one crept data series. The Table Look-Up method in ASSERT underpredicts the test data with a systematic bias of 1.4%. The mechanistic ASSERT model overpredicts the test data with a systematic bias of 2.1%. For both approaches, the standard deviation is about 2%.

ASSERT predictions of axial dryout locations and rods in dryout have also been compared to experimental results. Using the TLU CHF Method, ASSERT accurately predicts the axial dryout location within 25 cm in 93.8% (all within 50 cm) of the cases and the rod location correctly in 62.5% of the cases. In addition, nearly 50% of the ASSERT predicted dryout angle were within $\pm 30^\circ$ of the measured angle value. For dryout quality, the average difference between the quality predicted by the TLU model of ASSERT and the measured dryout quality is 0.001.

Using the Mechanistic CHF Model, ASSERT predicted dryout location within 25 cm in 42.8% of the cases, and within 50 cm in 98.4% of the cases, dryout to occur in rod elements the outer ring. In addition, nearly 25% of the ASSERT predicted dryout angle were within $\pm 30^\circ$ of the measured angle value. For the dryout quality, the average difference between the quality predicted by the ASSERT mechanistic model and the measured dryout quality is 0.017.

For both the Table Look-up and the mechanistic model, ASSERT predictions achieved spatial convergence and are not sensitive to axial nodalization.

The good agreement between ASSERT predictions and the experimental data demonstrates the capability of ASSERT models to represent the underlying physical phenomena and predict reasonably well the dryout powers for power shapes other than the one used for the tested configuration, i.e. the flat cosine power shape.

3. Axial Heat Power Shapes Identification and Categorization

Axial power profiles during the SBLOCA and SLOR transients were identified and examined. Representative flux shapes from the recent SBLOCA analysis for the Pickering Nuclear Generating Station (PNGS). Aged and un-aged conditions were collected and examined. The axial power profiles at the time of the break (i.e. steady-state profiles) were found to be very close to the axial power profiles at the time of dryout for typical SBLOCA break sizes as shown in Figures 1 and 2. Since the flat cosine profile is representative of the steady-state profiles in the adjusted core region with the high power channels, especially for Pickering B, the impact of flux profiles on the accuracy of the BLA CHF correlation is insignificant under SBLOCA conditions, which bounds the LOF accident conditions.

A large number of distorted power configurations (“power shapes”), representing potential operating configurations during a SLOR accident, have been examined. Nine axial power profiles shown in Figure 3 were selected from representative high-power central channels and peripheral channels and can be characterized as:

- The power shape for the nominal, steady-state core in the central, adjusted core region.
- A double-humped (“M”) profile.
- A centrally flat and broad profile.
- A centrally peaked profile.
- An upstream-skewed profile.
- A downstream-skewed profile.

- The steady-state axial profile for a channel outside the adjusted zone, which is not subject to contouring by adjusters.

The nominally adjusted and centrally broad profiles are very close to the flat cosine profile tested at Stern Labs (SL) and therefore their impact on dryout power is expected to be minor. On the other hand, the nominally un-adjusted, double-humped, downstream and upstream skewed profiles deviate appreciably from the flat cosine, with the potential for impact on Onset of Dryout Power (ODP).

Generally there are two broad categories of profiles: one for use in LOF, SBLOCA and nominal NOP, and the other for non-standard NOP cases. The first category includes the flat-cosine like profiles (adjusted zone) and the cosine like profiles (unadjusted zone). A scheme was developed to further categorize the selected profiles according to the symmetry and peak of the shape. Five groups of profiles, three symmetric and two asymmetric, were identified. The symmetric groups are represented by the cosine, flat cosine, and double humped profiles whereas the asymmetric groups are represented by the upstream skewed and downstream skewed profiles. Figure 3 shows the selected profiles and Table 1 identifies the profile groups.

4. ASSERT and CHF Correlation Predictions of Dryout

The effects due to axial power profile, PT creep profile, and radial power profile have been assessed by comparing the predictions of two validated ASSERT models, the BLA and LC CHF correlations against their own predictions for the flat cosine power profile and the results are summarized in Table 2. This comparison was performed for thermalhydraulic conditions of interest to NOP analysis. The comparison showed that the effects due to PT creep profile and radial flux profile on dryout power predictions are insignificant. For the axial power profile, the comparison between ASSERT and correlations predictions showed minor differences, as expected, for the flat-cosine like profiles. For the non-standard axial power profiles, the comparison showed the following:

- The largest decrease in ASSERT predicted ODP was found with the use of the PB – Down-stream Skewed (narrow) profile, as the average ODP decreased by up to 10.9% compared to the flat cosine. On the other hand, the greatest increase in ASSERT predicted ODP was found with the use of the PB – Up-stream skewed profile, as the average ODP increased by up to 8.8%.
- Consistent trends between the ASSERT code and the BLA correlation predictions.
- The BLA predicted ODPs are generally lower than the ASSERT predictions. The BLA captured the trend and predicted an increase in ODPs for the upstream skewed power profile. The difference in ODP is noticeably large for non-standard power shapes: the downstream skewed power shape, the nominal cosine shape, and the M-shape.
- The LC predicted ODPs are generally lower than the ASSERT predictions. The difference in dryout power is noticeably large for non-standard power shapes: the downstream skewed power shape, the upstream skewed power shape, the nominal cosine shape, and the M-shape.
- The differences in predicted dryout powers between the BLA and LC correlations are generally small (less than 3% was found with the use of the double-humped power

shape), with the notable exception for the upstream-skewed power profile where the BLA correlation predicted an increase of 7% in ODP whereas the LC correlation predicted a 1% decrease.

The results demonstrated the appropriateness of the BLA CHF correlation for use in applications involving axial power shapes that are similar to the axial flux shape used in the SL tested configuration and also established the basis for assessing the uncertainty allowances associated with its use for applications involving axial power profiles representative of conditions of interest to the NOP analysis.

5. Additional Prediction Uncertainty Associated with the use of the BLA CHF Correlation

5.1 Additional Uncertainty Due to Axial Power Shape Profile

The additional uncertainty associated with the use of the BLA CHF correlation for profiles other than the one used in the SL tested configuration has been evaluated by the calculating the average difference (bias) between the ASSERT predictions and BLA predictions. The standard deviation of the differences in the predicted ODP values, over the thermalhydraulic conditions of interest for Slow Loss of Regulation (NOP) accidents, has been calculated for each group of profiles as summarized in Table 3.

As expected the bias for the flat cosine group of power shapes is very small, with a conservative value of 0.4%. The bias for the asymmetric group of non-standard upstream skewed profiles is also a small conservative value of 1.1%. Larger conservative biases are associated with the use of the other groups of non-standard profiles as follows: 7.8% for the downstream skewed; 6.8% for the double-humped; and 8.3% for the cosine. The associated standard deviations are as follows: 3.1% for the flat cosine; 4.5% for the downstream skewed; 5.3% for the double-humped; 2.5% for the upstream skewed; and 3.5% for the cosine.

5.2 Additional Uncertainty Due to Pressure Tube (PT) Creep Profile

A comparative analysis of the ASSERT predictions and the predictions of the BLA and local conditions CHF correlations to assess the effect of PT creep profile on dryout powers has been performed. Four PT creep profiles were considered and shown in Figure 4: 1) Profile 1 for Pickering A Channel K05 (outside adjusted zone); 2) Profile 2 for Pickering A Channel L14 (inside adjusted zone); 3) Profile 3 for Pickering B Channel N04 (outside adjusted zone); and 4) Profile 4 for Pickering B Channel O08 (inside adjusted zone).

Comparing ASSERT predictions to those of the BLA CHF correlation for PT creep profiles 1 to 3, the BLA CHF correlation tends to predict slightly higher dryout powers than ASSERT. Only for the PT creep profile 4, the BLA CHF correlation predicts lower dryout powers than ASSERT.

At the peak diametral creep of 3.3%, the largest difference in dryout powers between the ASSERT mechanistic model and the BLA CHF correlation is 1.99%. For the peak diametral creep of 3.3%, the largest difference in dryout powers of 1.52% has been observed between the ASSERT TLU method and the BLA CHF correlation.

The difference in dryout power predictions between the BLA CHF correlation and ASSERT is within the uncertainty of the BLA CHF correlation. Similarly, the difference in dryout powers predictions between the LC CHF correlation and ASSERT is within the uncertainty of the Local CHF correlation. Therefore, No additional uncertainty is assigned.

5.3 Additional Uncertainty Due to Radial Power Profile

An assessment using validated ASSERT models to assess the impact of the radial power profile on dryout power has been performed. The overall predicted results and mean errors are given in Table 4 and Table 5. The results show that the effect of the slight increase in the radial power peaking factor for the outer ring had a minimal effect on dryout powers as the predicted dryout powers decreased by an average of 0.1% to 0.4%.

Since Table 4 and Table 5 show that the effect of radial power profile has insignificant impact on the BLA CHF prediction, no additional uncertainty is assigned.

6. Summary and Conclusion

A new approach has been developed to assess the additional prediction uncertainty associated with the use of the 28-element bundle BLA CHF correlation in safety analysis outside the range of conditions of the SL 28-element bundle CHF tests whose data are used to derive the correlation. The approach is based on the capability of the subchannel ASSERT code models, namely the Table Look-up method and mechanistic dryout model, to represent the underlying physical phenomena. The approach has been applied and the additional prediction uncertainties to account for the effects of axial power profile, radial power profile and pressure tube creep have been estimated.

7. References

- [1] V.F. Rao and N. Hammouda, "Recent Developments in ASSERT-PV Code for Subchannel Thermalhydraulics", CNS 8th International Conference on CANDU Fuel, Honey Harbour, Ontario, Sep 21-24, 2003.

Table 1: Power Profile Groups

Groups	Symmetry Index*		Peak Index**		Power Shapes
Group 1		1.01		0.11	PA-1: Nominal adjusted/Centrally broad
	1.03	1.05	0.01	-0.02	PB-1: Nominal adjusted
		1.04		-0.06	PB-3: Centrally broad
Group 2		0.67			PA-2: Downstream skewed
	0.67	0.61	n/a		PB-5: Downstream skewed (N)
		0.73			PB-6: Downstream skewed (B)
Group 3	1.02	1.02	-0.33	-0.33	PB-2: Double-humped “M”
Group 4	1.66	1.66	n/a		PB-4: Upstream skewed
Group 5	1.00	1.00	0.24	0.24	PB-7: Nominal unadjusted

* The symmetry index is calculated by dividing the integrated power from bundles 1 to 6 over the power from bundles 7 to 12.

** The peak index is calculated by dividing the difference between the power at the centre of the channel (i.e. average of bundles 6 and 7) and at the fourth bundle (i.e. average of bundles 3 and 4) over the power at the centre.

Table 2: Mean Predicted Differences in Dryout Powers For Different Axial Power Profiles
(Comparison against Flat Cosine Profile Predictions)

	PA – Central. Broad	PA - DSS	PB – Nom. Adj.	PB - Double Humped	PB – Central. Broad	PB - USS	PB - DSS narrow	PB - DSS broad	PB - Nom Unadj.
¹ Table Look Up Method (%)	-0.6	-7.3	-1.0	-3.6	-1.8	8.8	-10.9	-7.5	-4.2
² Mechanistic Model (%)	-1.3	-6.8	-0.9	-1.2	-1.2	5.4	-8.4	-5.8	-4.0
³ BLA CHF Correlation (%)	-1.9	-14.4	0.5	-8.0	0.2	7.2	-17.2	-10.3	-11.0
⁴ LC CHF Correlation (%)	-1.3	-16.7	0.1	-10.6	-1.1	-1.3	-18.8	-11.2	-13.0

¹ Standard deviation range: 0.3% to 1.4%

² Standard deviation range: 0.2% to 1.0%

³ Standard deviation range: 0.5% to 3.0%

⁴ Standard deviation range: 0.3% to 2.1%

**Table 3: Additional Prediction Uncertainty Associated with the Use of BLA Due to
 Different Axial Power Profiles**
 (BLA Predictions Compared against ASSERT Predictions)

	Estimated Average Bias (%)	Estimated Average Standard Deviation (%)
Group 1: Flat Cosine (Nominal Adjusted; Centrally Broad)	-0.4	3.1
Group 2: Downstream Skewed	-7.8	4.5
Group 3: Double Humped “M”	-6.8	5.3
Group 4: Upstream Skewed	-1.1	2.5
Group 5: Cosine (Nominal Un-adjusted)	-8.3	3.5

Table 4 TLU Method - Summary of Differences between ASSERT predictions using SL Radial Power Profile and Upper Bounding Radial Power Profiles

		Original RPP 0.780/0.902/1.104	Modified RPP 0.7842/0.8837/1.1121	Difference between Biases (in absolute %)
R1 and R2 only	Mean Bias (%)	-2.11	-2.5	-0.39
	Std. Deviation (%)	2.45	2.48	0.03
C1 only	Mean Bias (%)	-0.58	-0.89	-0.31
	Std. Deviation (%)	1.42	1.42	0
All Points in Conditions of Interest	Mean Bias (%)	-1.39	-1.75	-0.36
	Std. Deviation (%)	2.16	2.19	0.03

Table 5 Mechanistic Model - Summary of Differences between ASSERT predictions using SL Radial Power Profile and Upper Bounding Radial Power Profiles

		Original RPP 0.780/0.902/1.104	Modified RPP 0.7842/0.8837/1.1121	Difference between Biases (in absolute %)
R1 and R2 only	Mean Bias (%)	1.92	1.64	-0.27
	Std. Deviation (%)	2.17	2.17	0.13
C1 only	Mean Bias (%)	2.32	2.12	-0.2
	Std. Deviation (%)	1.15	1.13	0.08
All Points in Conditions of Interest	Mean Bias (%)	2.11	1.86	-0.24
	Std. Deviation (%)	1.77	1.77	0.12

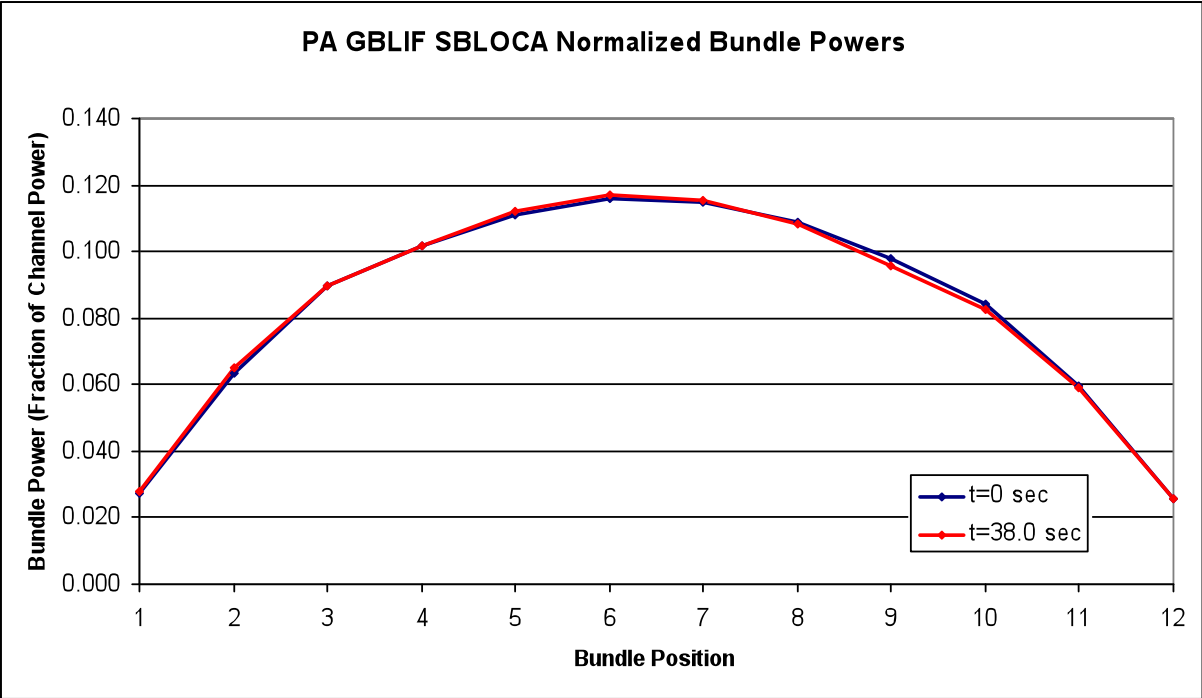


Figure 1 PA GBLIF Break Channel R10 Normalized Bundle Powers, Unaged Conditions

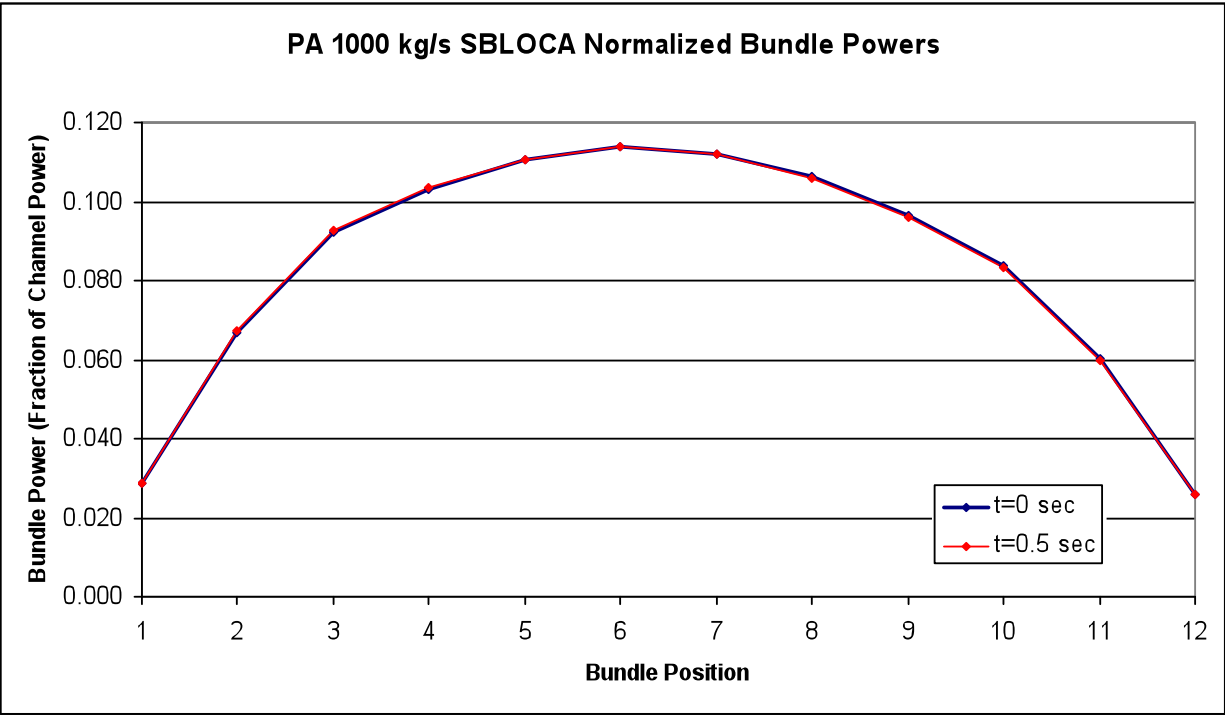


Figure 1 PA 1000 kg/s Break Channel G10 Normalized Bundle Powers, Unaged Conditions

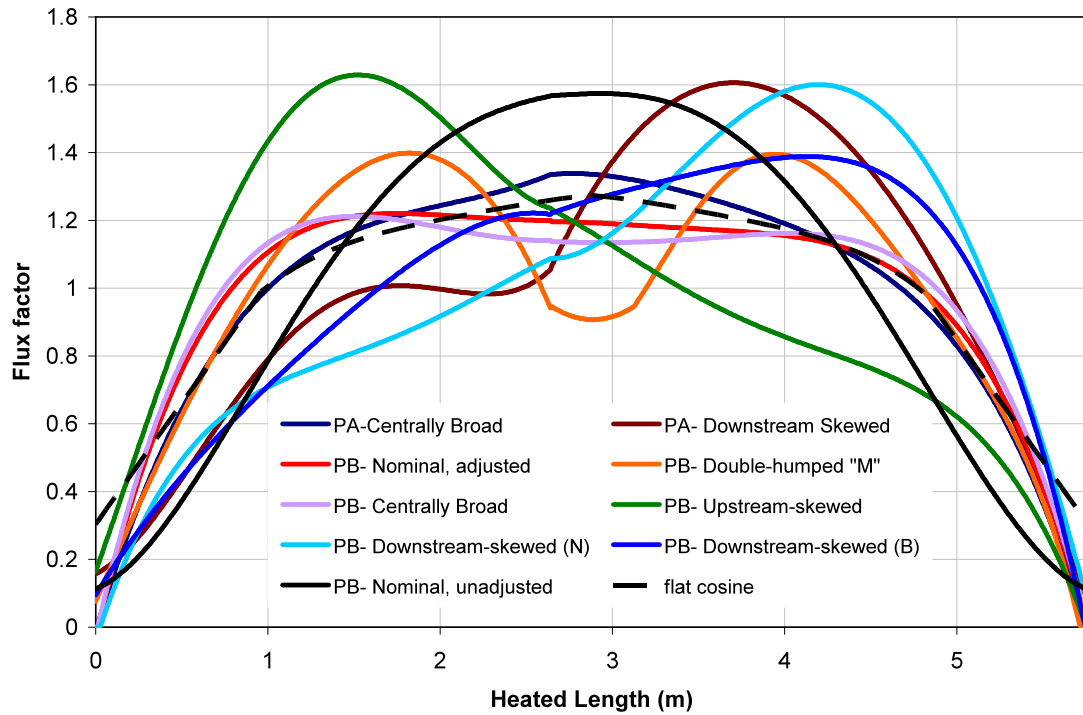


Figure 3: Axial Power Shapes Selected for the Assessment

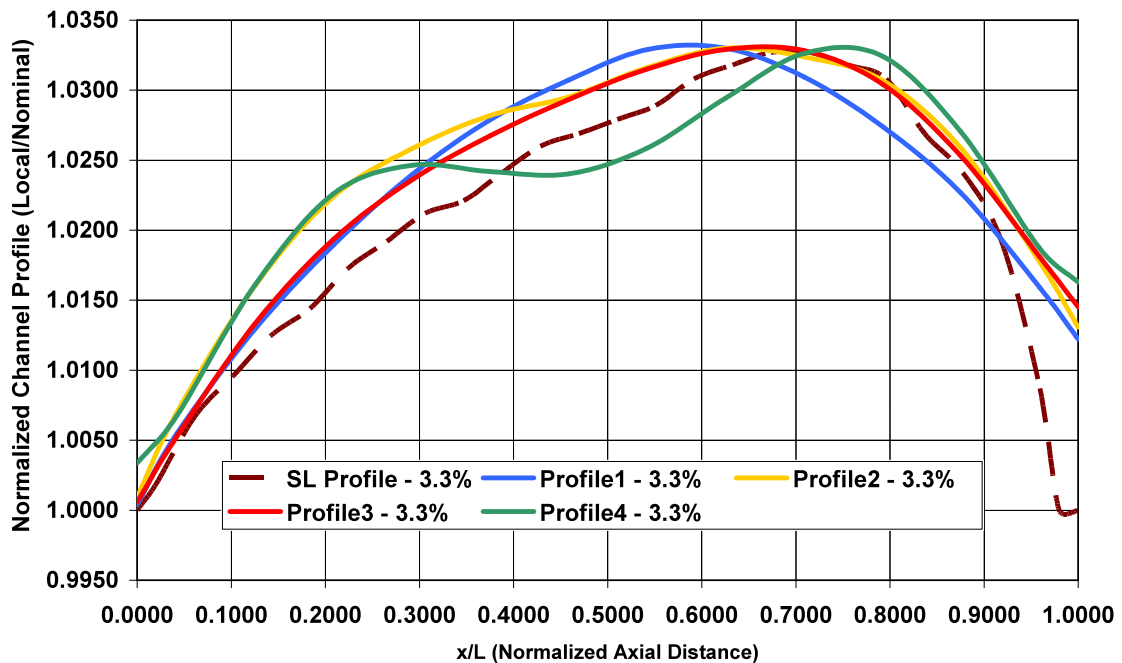


Figure4: PT Creep Profiles at 3.3% Maximum Creep Level for Pickering A and B