Critical Heat Flux Evaluation of a Conceptual Fuel Bundle Design with the ASSERT Subchannel Code

R.F. Dam, K.F. Hau, J. Vecchiarelli, N. Lee
AECL Mississauga

Abstract

An assessment of a new 61 element conceptual fuel bundle design has been conducted for EPDC (Electric Power Development Company) in the conceptual design study of a Highly Advanced Core (HAC) CANDU[1] plant. Given the conceptual nature of the fuel design, the subchannel code ASSERT-IV, with a CHF model developed based on Stern experiments[1], was used to assess the bundle performance. The study included the effects on CHF of axial flux shape, variable radial flux shape, creep, and turbulence enhancement.

To complete the analysis of critical channel power, the cross sectional average code NUCIRC was required. This necessitated the development of a methodology to use ASSERT to provide the necessary corrections for the NUCIRC assessment. Overall, the ASSERT code proved to be a valuable tool in predicting the conceptual bundle design performance. Along the way, several interesting trends were observed which have impacted on the general understanding of the competing effects leading to dryout in a CANDU fuel string. This study also demonstrates the potential value of a subchannel code, such as ASSERT, for assisting in design development of new bundles.

1.0 INTRODUCTION

Prediction of pressure drop and critical heat flux (CHF) in CANDU fuel strings has been a topic of interest for several years for AECL, and owners of CANDU nuclear power stations. This has lead to the development of several models used to predict dryout power on a bundle average basis. In addition, several experiments have been carried out to create a database which can be used to both develop prediction capabilities and validate existing models.

In recent years several additional parameters of interest have become apparent, which require further development of bundle average models. The need to analyze variations in geometry has had significant impact on model development and lead to further experiments. A leading example is the impact of pressure tube creep.

Creep impact on 37 element CANDU fuel strings has been a particular focus point in recent years. However, when considering new bundle designs, the existing cross sectional average models are no longer applicable. The introduction of turbulence enhancement devices, modifications to fueling schemes resulting in changes to axial flux distributions (AFD), slightly enriched fuel or reprocessed fuels resulting in radial (RFD) and axial flux distribution changes, and basic bundle geometry changes (eg. 43 element) has lead to the need to deal with fuel bundle variations at the design stage.

To address this need, the subchannel code ASSERT-IV was developed. The modelling methodology has been focussed on providing a prediction tool for CHF and pressure drop for CANDU fuel strings that is capable of dealing with geometry changes and heat flux changes. The fundamental models for CHF and pressure drop are generic for all designs, requiring only that the specific geometry and heat flux be input. An example of the potential for such a code can be seen by looking at the design assessment carried out by AECL for EPDC of Japan, to evaluate the fuel string design for the Highly Advanced Core CANDU design (HAC).

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[1] CANDU is a registered trademark of AECL

The study was carried out over several years. The first year considered several designs, including two 61 element designs and a 71 element design. The second year of the study focused on one design, which was the HAC 61 MK4 design. The analysis was improved by giving ASSERT the ability to model the variation in the radial flux distribution (RFD) as a function of the axial location in the fuel string. The ASSERT-IV model had also been further developed in a separate program. In conjunction with the latter development, the turbulence enhancement model was also improved.

The objective of the second study was two fold. First, the impact of the variation in the RFD was addressed. The second objective was to evaluate the potential addition of turbulence enhancement appendages to the bundle design. The improved turbulence enhancement model was an important contributor to this analysis

The third year of the study built upon the work from the previous by extending the analysis to crept pressure tubes. For this year, the impact of creep on thermal margins was assessed for the HAC 61 element MK4 design. As a reactor ages, the pressure tubes will creep. The enlargement of the pressure tube causes flow to bypass the fuel bundle, possibly reducing the thermal margin. The unique aspect of this analysis compared to previous CANDU 37 element fuel analysis is that the axial flux is considerably different, the RFD varies significantly throughout the fuel string, and the creep profiles are also different.

This paper deals with the way ASSERT was used to predict CHF characteristics for the conceptual 61 element design. It will hihglighted how the ASSERT code can be used to assist in the design of a new fuel bundle in the conceptual design stage. It also demonstrates the useful insights that can be gained by such a code.

2. MODELLING

2.1 Code

The analysis in this paper makes use of the subchannel code ASSERT–IV [2]. The code version used for this study was ASSERT–IV V2R9 with enhancements as described in references [1] and [3] (geometry based model (GBM) and CHF model including turbulence enhancement), in addition to variable radial flux distribution capabilities.

2.2 Model

The geometry for the ASSERT HAC 61 MK4 is represented in figure 1. The inside diameter of the pressure tube the design is identical to the standard CANDU pressure tube used with the 37 element fuel string. A representative creep profile is illustrated in figure 2. The figure also gives a comparison to an exit skewed creep profile typical of the 37 element fuel string design. A sample AFD is represented in figure 3, compared to an exit skewed cosine profile typical of a 37 element fuel string.

2.3 Critical Heat Flux Modelling

The CHF in a bundle geometry is generally a function of the local mass flux (G), the local quality (X), and the local pressure (P). Based on experiments for a given bundle geometry and power distribution, a correlation or table lookup method can be developed to predict dryout based on the bundle average mass flux, quality, and pressure. However, this method is limited to predictions for one geometry and power distribution. Correction factors can be developed to correct for these effects. Although these corrections are intended to be best estimate, they do not account for the unique CHF trends in a different geometry or power distribution. An example of a simple geometry change that requires a correction factor is the effect of pressure tube creep on CHF.

From a subchannel perspective, a correlation or table lookup approach can be developed in much the same way as would be done for a bundle average approach. Like bundles, subchannels also can have very different geometries. The common practice with subchannel codes is to assume that the subchannels are similar to tubes, for which there is an abundance of experimental dryout information. ASSERT-IV uses a tube lookup table. The table is derived from a dryout heat flux database for vertical, circular, 8 mm, tubes with an uniform axial heat flux distribution [4].

The use of tubes to approximate subchannels introduces the need for correction factors such as:

a) Tube Size

b) Gap Effect

c) Channel Orientation

d) Turbulence Enhancement

e) Boiling Length Average Correction

Considering the fluid conditions, there are two effects that the code must predict. These are the mass flux distribution and the phase distribution. The mass flux distribution is driven by pressure drop considerations while the phase distribution is affected by local mixing and the net movement of void from one area of the bundle to another. The overall effect of flow redistribution and thermal mixing can be considered simply as mixing. With regards to this aspect of the model, the void diffusion model described in reference [1], has been further developed and was used for this analysis.

2.4 Pressure Drop Modelling

The pressure drop model used for the analysis is a fl/d+k model as described in [1]. The Colebrook-White friction factor correlation is used for friction, while the geometry based model described in [1], [3], and [5] is used for the endplate and spacer plane form losses. The GBM calculates the form losses based upon the subchannel blockage or expansion geometry for specific locations in the fuel string.

3.0 APPLICATION

ASSERT can be used like an experiment to model the effect of various parameters. The impact of creep on CHF can easily be determined and the appropriate bundle average correction factor determined by predicting the mass and phase distribution and appropriate turbulence enhancement . The correction factor can be used by bundle average codes such as NUCIRC. In the present example, CHF correction factors, and an estimate of the aligned endplate form losses were used in NUCIRC for critical channel power analysis.

4.0 CASES

4.1 Turbulence Enhancement

To validate the model for prediction of turbulence enhancement, two experiments were simulated. The first was a 43 element bundle with 3 equally spaced spacer planes per bundle. The second experiment was a 37 element bundle with 3 equally spaced spacer planes per bundle. Both of these bundle designs include length over diameter ratios similar to those in the HAC 61 MK4 design, which serves adequately to validate ASSERT for the current study.

The experiments were conducted in refrigerant-12 for a range of inlet subcooling and flowrates. For the current validation exercise, these conditions were translated into the equivalent D_2O conditions.

4.2 Impact of Turbulence Enhancement Devices

Models representing the 61 element geometry with and without turbulence enhancement devices were simulated to determine the bundle average CHF correction factor characteristics. For each ASSERT-

IV model, a case set of 12 cases were run. Three pressures were chosen with the intermediate pressure being based upon the channel dryout pressure. The channel exit pressure was varied between 10 and 11 MPa. The inlet temperature was maintained at the 100% full power value of 265°C. Since this value would be invariant in the CCP analysis, sensitivity was not evaluated. The flowrate covered the range of 14 to 20 kg/s. This encompasses the highest and lowest dryout flow conditions for the HAC core.

4.3 Impact of AFD

The HAC core design includes numerous variations on the AFD. Consequently, several characteristic AFDs were selected to represent the entire core. In addition, one artificial AFD was defined to verify the conclusions from the analysis.

4.4 Impact of RFD

To capture the performance of the HAC fuel string with the actual RFD distribution for each bundle, the actual AFD were used. The interaction of these two heat flux distributions impacts the void distribution within the fuel string and consequently, the dryout location. To determine the CHF correction factor for NUCIRC the methodology focused on determining the channel characteristic. The channel characteristic in this instance is the dryout power as a function of inlet subcooling for different flow rates. The approach was chosen based on the analysis of CHF experiments that determine the dryout power as a function of the inlet subcooling.

The methodology used can be summarized as follows. ASSERT-IV is used to calculate the dryout power for the reference 37 bundle design for a range of pressure, temperature, and flow conditions. The dryout power is also calculated for the same conditions for the new design (ie HAC 61 MK4). The differences in the two bundle characteristics are then simulated with NUCIRC. The NUCIRC CHF correction factor is adjusted until the relative change in dryout power for the two bundles can be predicted by NUCIRC. The tuned correction factor represents the CHF correction factor to be used for the CCP assessment.

4.5 Creep

As with the RFD effect, the impact of creep is also dependent on the AFD and RFD in the channel. Consequently, three channels were chosen to evaluate the impact of creep for the HAC core. The selected channels represented high, medium and low power channels respectively. For each channel, four different creep levels, 1, 2, 3 and 4%, plus the nominal profiles were simulated.

For each creep profile/level, a set of 18 cases were run. The exit pressure was varied between 10 and 11 MPa. The inlet temperature was maintained at the 100% full power value of 265°C. Since this value is invariant in the CCP analysis, sensitivity was not evaluated. The flowrate covered the range of 12 to 22 kg/s.

5.0 RESULTS

5.1 Validation of Turbulence Enhancement

The following table provides the ASSERT-IV predictions of the relative dryout power increase for the CANFLEX bundle with 3 spacer planes relative to the 37 element reference bundle. The results indicate a good comparison at 22 kg/s. There is an underprediction of the experimental results at the 11 kg/s.

Flowrate (kg/s)	Enhanced 43 Element bundle		Enhanced 37 Element Bundle	
	Predicted %	Experiment %	Predicted %	Experiment %
11	5	7.2	3	11.2
22	10.8	11.5	13	15.2

The conclusion is that the turbulence enhancement model is able to capture the overall magnitude of turbulence for the CANFLEX and 37 element bundles with three spacer planes. Since these bundle designs have similar l/d ratios as seen in the 61 MK4 design with turbulence enhancement, ASSERT-IV is considered valid for the current study.

5.2 Impact of Turbulence Enhancement Devices

For the 61 element design without turbulence enhancement devices, a slight dependence is predicted for the relative dryout power (as compared to 37 element fuel) with flowrate. This effect is seen primarily in the lower flow range where local stratification begins to take effect. For the 16 to 22 kg/s range, at pressures of 10.65 MPa (actual boundary condition from NUCIRC), the CHF correction factor is roughly 0.93 for the 61 element design. The correction factor is applied to the 37 element CHF correlation in NUCIRC in order to perform CCP analysis.

The reference 61 element model with turbulence enhancement devices demonstrated a strong tendency toward an increased CHF at the higher mass flows, which results from the mass flux dependency in the turbulence enhancement equation. The CHF enhancement is 25% at a flowrate of 18 kg/s, which corresponds to the expected CCP flowrate for this channel. This level of enhancement is expected based on experimental evidence. It is noted that there is a strong effect of turbulence enhancement with flow. The lower flow cases are expected to be underpredicted based on the validation results, which is conservative. The 25 % enhancement represents a CHF correction factor of 1.18 for the NUCIRC analysis.

5.3 Impact of AFD

It has been noted that the interaction effect of the local RFD and the AFD of the channel will impact on the dryout location and the dryout power. To facilitate the evaluation of this effect, the AFDs of 60 representative channels from the HAC core design, as used in the NUCIRC analysis, were plotted and compared. From this evaluation , 7 basic AFD could be identified.

To evaluate the relative performance of these cases, models were created for each channel type (ie AFD to reflect the channel). The RFDs were assumed to be invariant from channel to channel on a time average basis, since the RFD would be primarily a function of burnup. On a time averaged basis, the burnup would not have a significant variation from channel to channel. For each model, the set of 12 cases described in section 4.2 above were run with ASSERT-IV, and NUCIRC was used to calculate the appropriate CHF correction factor for each case. The resulting correction factors from two channels are plotted in figures 4 and 5. The variation observed at each flowrate is due to pressure variation, with the intermediate point representing the expected exit pressure at dryout.

The results indicate a definite sensitivity to the AFD. Considering the relative performance of each channel and analyzing the corresponding AFD differences, an explanation is evident. The HAC core AFDs tend to be inlet skewed, resulting in improved CHF performance, since the power is reducing relatively parallel to the CHF curve. However, the actual AFD shapes exhibit a slight bimodal power distribution, with the occurrence of a second peak power in the downstream end of the channel. Other shapes show a plateau in the power distribution for the majority of the second half of the channel. The bimodal shapes and those with a significant plateau region show a reduced CHF due to the power shape in the second half of the channel.

To support this understanding, an artificial power distribution was created with a stronger second peak. This distribution is identified as c61. The CHF correction factor for this case is plotted in figure 6. As expected, the CHF performance is further reduced relative to the other channel results. This result confirms that as the power becomes further exit skewed, the CHF performance will deteriorate.

5.4 Creep

For a typical natural uranium fuelled 37 element CANDU bundle in a crept channel, dryout power is reduced when compared against the nominal channel as described in reference 1 (see figure 7). However, under certain conditions the 61 element HAC Mk4 bundle does not show the same behaviour. Instead, at low flows the dryout power can actually increase with increase in levels of creep (see figure 8). This goes counter to that expected given the experience with the 37 element bundle (see figure 7). At higher flows, the HAC 61 bundle behaves like the 37 element bundle in that dryout power decreases with increased levels of creep. Detailed evaluation of the ASSERT results has lead to the following explanation.

When a pressure tube is crept, the flow area of the channel is increased. The fuel bundles would sit in the bottom of the channel with the extra area developing at the upper section of the channel. The lower resistance creates a bypass flow through the top of the channel, diverting flow from the fuel bundle. Therefore, for a given flow, it is expected that the dryout power would be reduced because less fluid is flowing through the bundle to cool the pins. It should be noted that the resistance of the overall fuel string is reduced for a crept channel, therefore, given the same header to header pressure drop, the crept channel flow is higher than the nominal channel flow. This is the case for the 37 element bundle design.

There are essentially two differences between the 37 element and HAC 61 element designs that produce the results seen in figure 8. First of all, the 37 element bundle dryout occurs in/around the central pins as a result of void buildup in the centre subchannels even though the inner pins have low power. The 37 element bundle is well balanced in the sense that worse CHF conditions exist where lower heat flux is applied, allowing dryout to occur in both the inner and outer rings. Conversely, the 61 element design is predicted to have a generally more uniform distribution of fluid conditions. This tends to create the situation where dryout occurs preferentially on the high power pins.

In addition, the differences between the CANDU 6 and HAC creep profile also impact on the way dryout occurs. In the 37 element channel, the maximum creep occurs in the second half of the pressure tube, at approximately the same axial location as dryout, and where the average void fraction is high. Therefore, in a crept channel, at all flowrates, the flow is diverted from the critical region of the bundle when the flow is most needed. In the HAC channel, the maximum creep occurs in the first half of the pressure tube. At high flow, this is of no benefit as the channel dryout occurs just downstream of the peak creep location due to flow reduction in the critical high power pins in the lower half of the bundle. At low flows, the flow redistribution helps prevent dryout at the maximum creep location by putting more low quality fluid in the upper channels where void tends to accumulate at low flows. By allowing the flow to get through the maximum creep location without dryout occurring, the fluid benefits from the tapering of the pressure tube as flow is forced back into the fuel bundle. The initial removal and subsequent re-introduction of fluid back into the bundle produces more uniformly mixed conditions than in the nominal pressure tube, and as a result the channel dryout power is increased.

6.0 DISCUSSION

The simulation of a 61 element bundle is outside the available database for which the current ASSERT model is validated. As described above, the model can be checked on other geometries to verify that the correct trends are observed in the results. Moreover, the analyses of the ASSERT predictions can be verified to follow reasonable thermalhydraulic behaviour. Given this, the analysis for the 61 element design focused on establishing the relative change in CHF as compared to the 37 element design. The NUCIRC models, which are used for licensing analysis, form the basis of the subsequent CCP analyses.

In addition to assessing trends only, and validating for key model parameters, the results are reviewed from the perspective of the thermalhydraulic behaviour predicted by ASSERT. In many cases, the ASSERT predictions follow expected trends and differences are only observed in the details. In all cases, the trends at the local level are reasonable. For trends that do not follow expectations, such as the creep effect for low flows, the explanation needs to be complete. ASSERT has proven in these cases to be a useful means of expanding the understanding of the trends seen in bundle thermalhydraulics. The low flow creep cases make sense in light of the local quality, flow distribution, and peak creep location. An extension of the analysis is to consider the impact of higher creep levels. The improvement of CHF with creep must have a limit in that eventually the creep level will be high enough to cause a reduction in CHF at any flowrate. This trend can be seen in figure 8 by looking at the results for the 4% creep. This curve falls below the 3% creep curve at almost all of the flowrates considered except at 12 kg/s, where 3% and 4% curves are similar in value. This result further verifies that the overall predictions follow reasonable trends.

Even though the model continues to be developed, and there is little experience with the model for predictions outside the validation database, it remains an effective tool for this type of analysis. The example of the 61 element bundle evaluation demonstrates the usefulness of this tool, and points to potential for expanding its application. It should be noted that for the analysis described above, the only changes to the model for each simulation are geometry changes (creep, turbulence enhancement devices) or power distribution changes (AFD) and the fluid conditions (pressure flow, temperature). Consequently, the thermalhydraulics parameters are unchanged for all cases, which has been the intent of the model development.

Given the application to the 61 element bundle as an example, it is suggested that the most effective method of using ASSERT in the future is to obtain a minimal experimental database to be used to validate ASSERT for the new application. ASSERT could then be used as a "black box experiment" to fill in the trends between experimental data points. An example for consideration is to capture the impact of various combinations of creep profiles and AFD profiles associated with the existing 37 element bundle.

Ultimately, for ASSERT to be used for this type of analysis there is a need to quantify the uncertainty on the predictions. This is a task for the future, once the final model development has been completed. There are a number of experiments for different bundle geometries available to establish the capabilities of the model. The key is to ensure that the validation database is continually growing.

7.0 CONCLUSIONS

ASSERT has been used to analyze a new conceptual 61 element bundle design. As part of the design evaluation, the impact of turbulence enhancement devices, AFD effects, and creep effects were considered. The code was validated against turbulence enhancement experiments to demonstrate the codes capabilities prior to assessing the 61 element bundle. The analysis helped to gain insight into the key parameters of the AFD affecting dryout power. In addition, a crept pressure tube geometry had the unexpected effect of increasing CHF for low flow cases. However, the code also showed that this effect would reverse as the creep level was further increased.

The analysis illustrates how ASSERT can be used to evaluate trends in CHF due to parametric changes. This becomes a powerful means of evaluating the impact of both power distribution effects, and geometry effects. It is recommended that ASSERT could be used effectively to compliment experimental data by establishing points between experimental data points to create more complete trends.

ACKNOWLEDGEMENTS

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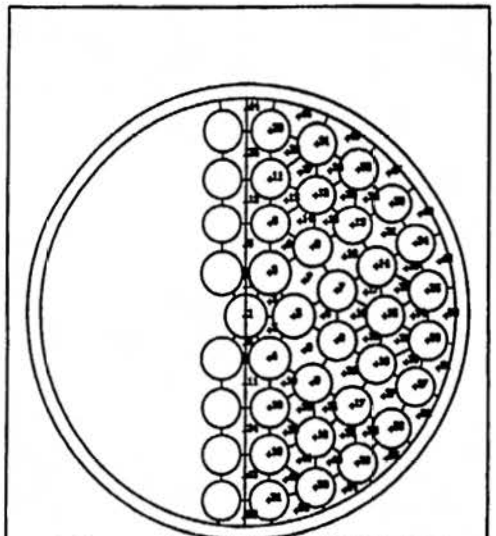

Figure 1: 61 Mk4 ASSERT Model

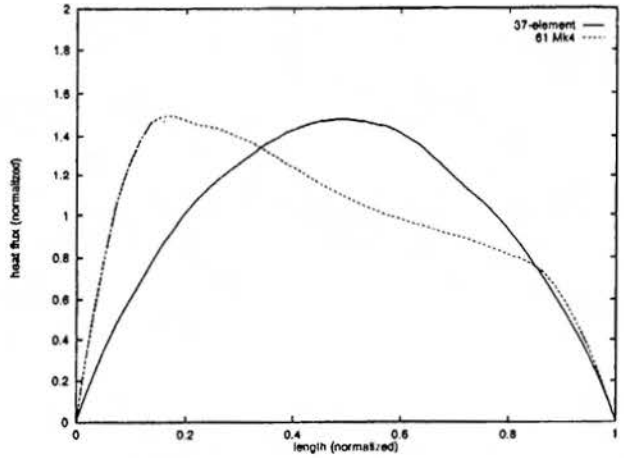

Figure 3: AFD for 37 and 61 Element Fuel Strings

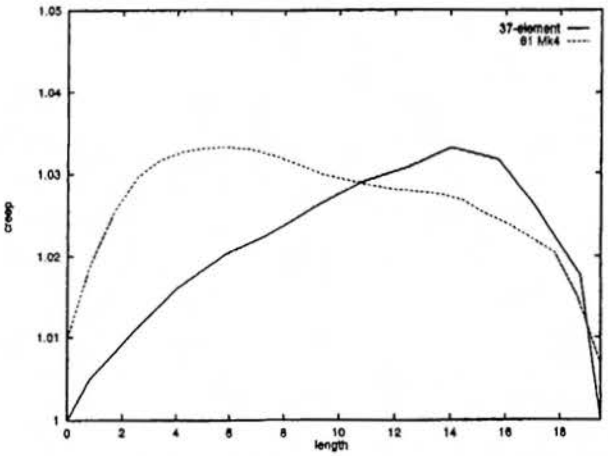

Figure 2: Creep Profiles for 37 and 61 Element Fuel Strings

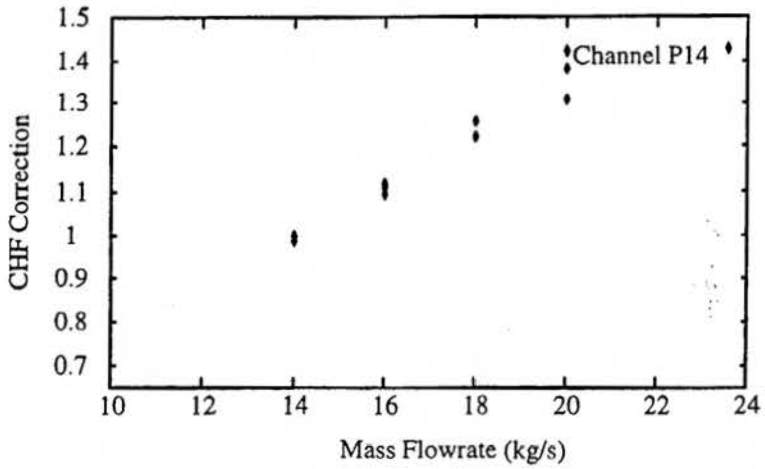

Figure 4: CHF Correction for Channel P14

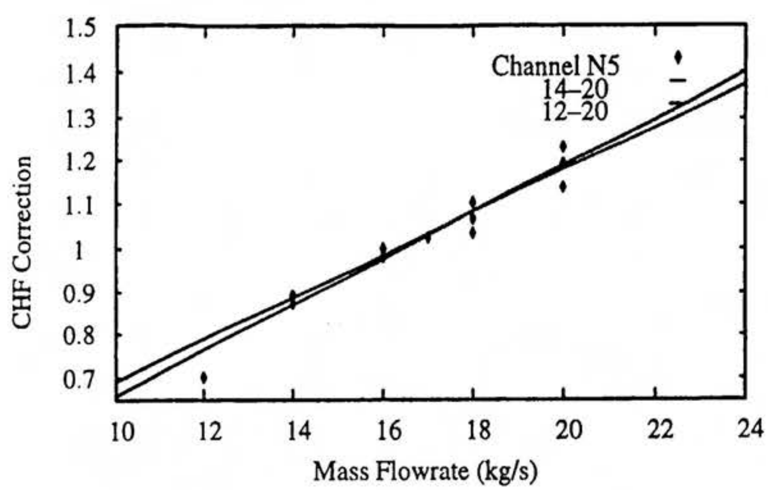

Figure 5: CHF Correction for Channel N5

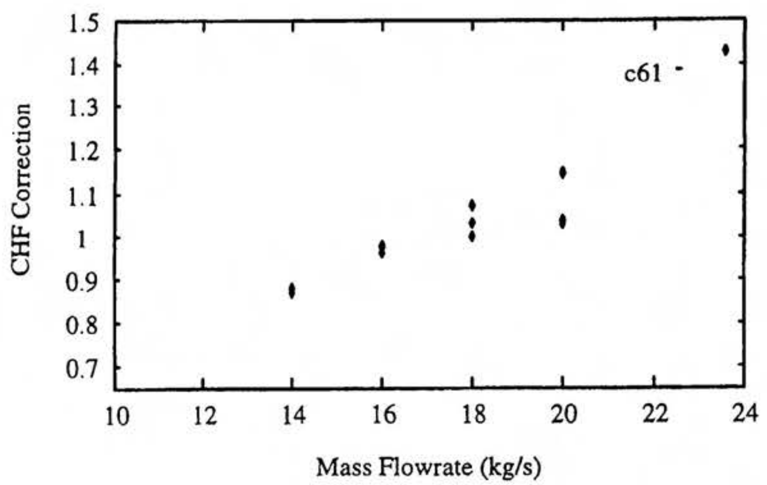

Figure 6: CHF Correction for Artifical AFD c61

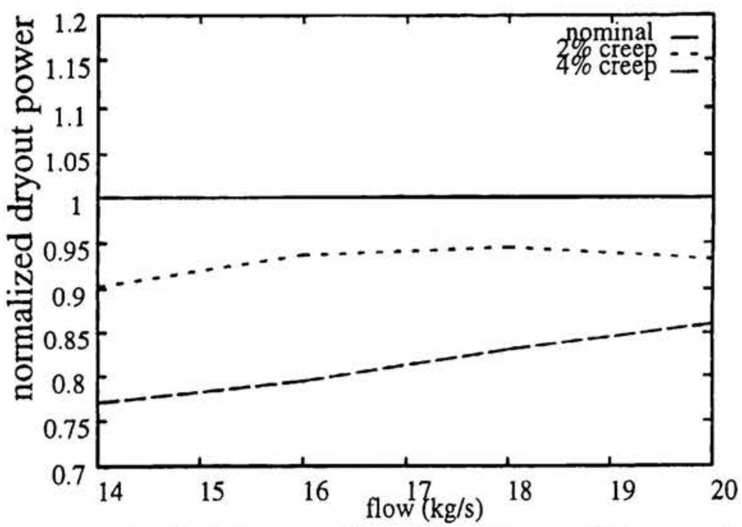

Figure 7: 37 Element Bundle – Dryout Power at Various Creep Levels (10.55 MPa)

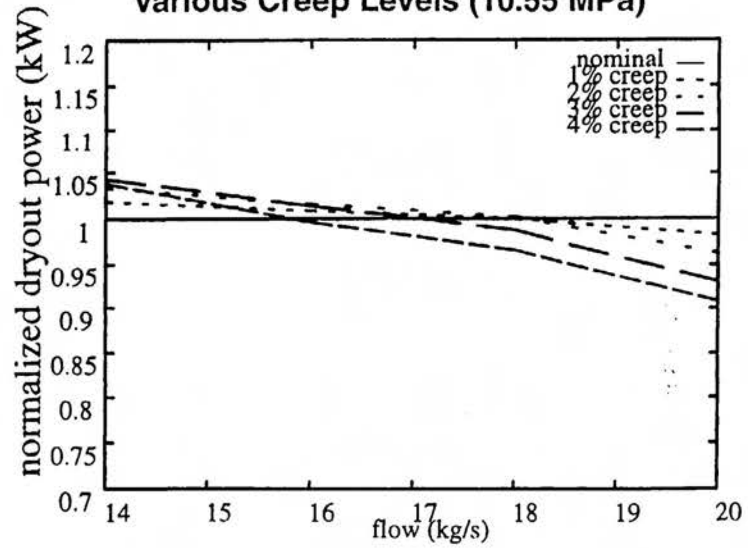

Figure 8: HAC 61 MK4 – Dryout Power for P14 at Various Creep Levels (10.55 MPa)