Investigation of Flow Blockage in a Fuel Channel with the ASSERT Subchannel Code

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On behalf of New Brunswick Power, a study was undertaken to determine if safe operation of a CANDU*–6 reactor can be maintained at low reactor powers with the presence of debris in the fuel channels. In particular, the concern was to address if a small blockage due to the presence of debris would cause a significant reduction in dryout powers, and hence, to determine the safe operation power level to maintain dryout margins.

In this work, the NUCIRC[1,2], ASSERT–IV[3], and ASSERT–PV[3] computer codes are used in conjunction with a pool boiling model to determine the safe operation power level which maintains dryout safety margins. NUCIRC is used to provide channel boundary conditions for the ASSERT codes and to select a representative channel for analysis. The pool boiling model is provided as a limiting lower bound analysis.

As expected, the ASSERT results predict higher CHF ratios than the pool boiling model. In general, the ASSERT results show that as the model comes closer to modelling a complete blockage it reduces toward, but does not reach the pool boiling model.

INTRODUCTION

During a recent outage at the Point Lepreau NGS, boiler maintenance work was performed where a temporary boiler nozzle cover remained inside the primary heat transport system. Once the heat transport pumps were started up, the nozzle cover broke free and contacted the primary heat transport main pump. The wooden cover was fragmented into several pieces.

Cleaning of the primary heat transport system recovered most of the foreign material from the primary heat transport system. Regardless, some particles of debris, in this case wood, may have been left in the fuel channels resulting in local blockages. Ultrasonic flow measurements on each feeder were used to test for flow blockage in addition to the primary function of measuring channel flows directly. A 10% flow reduction criteria was used to determine if a channel had been blocked. The size of the blockage which would cause a 10% flow reduction was thus considered a limiting case since any channel with greater flow reductions would be cleaned again.

In order to remove the remaining wood from the fuel channels after the majority of the primary heat transport system is cleaned, it was intended to operate the reactor at low power so that wood disintegration could be aided by a radiation field. The objective of this analysis is to determine the power at which the reactor can safely operate with the remaining wood still in the core to ensure that fuel remains adequately cooled. For this assessment, the target chosen is to ensure that dryout does not occur within an acceptable margin.

The presence of wood in a channel is expected to produce local flow disturbances, although small pieces of wood are not expected to cause any significant problems on their own. However, if the wood is assumed to accumulate at a critical place in the fuel string, the local effects could become significant. Due to the uncertainty of the location of the wood, an objective of this analysis is to define a safe operating envelope under the worst possible scenario of cumulative blockage at a single plane in the fuel string.

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The problem of modelling a significant flow blockage in the fuel string environment is likely best handled through the use of three dimensional finite volume codes (CFD), however this approach is extremely time consuming and costly. A second approach is the use of subchannel codes such as ASSERT. ASSERT however is limited in its ability to capture the local recirculation effects, and cannot model a complete blockage in a given subchannel. The third approach to the problem is to identify a lower bound calculation.

The analysis presented here uses a pool boiling critical heat flux (CHF) correlation to provide a lower bound prediction. The subchannel code ASSERT is used to provide an indication of trends to support that the pool boiling calculation is lower bound in order to assist in justifying the use of a pool boiling model as a lower bound calculation.

METHODOLOGY AND ASSUMPTIONS

The following assumptions have been applied for this analysis:

1) The steady state thermalhydraulics code NUCIRC can provide the best estimate of the system conditions at the time of startup.
2) The blockage is assumed to be entirely in one plane, as opposed to distributed throughout the channel. For a given flow reduction, this is assumed to provide the greatest probability of premature dryout.
3) The effects of inlet subcooling and pressure do not need to be considered. The influence of these terms is considered small within the expected variance of the system conditions.
4) It is assumed that the minimum CHF ratio(CHFR) is an adequate indication of the safety margins. That is, critical channel power calculations are not necessary.
5) The flows of all the channels will be ensured to be within 10% of the nominal flows predicted by NUCIRC. This is done through comparison of NUCIRC predicted flows to ultrasonic measurements.

The approach taken for this analysis is to establish a pool boiling CHF calculation as a lower bound prediction. The subchannel code ASSERT is to be used to provide support for the pool boiling calculation as the lower bound. The methodology can be broken down into three areas:

1) Using NUCIRC to establish boundary conditions for both ASSERT and the pool boiling calculation.
2) Simulating the blocked channel with ASSERT–IV and ASSERT–PV.
3) Use ASSERT–IV and NUCIRC information as boundary conditions for the pool boiling CHF model. Calculating the lower bound CHFR with the pool boiling calculation.

NUCIRC Simulations

ASSERT requires the fuel string exit pressure, inlet temperature, entrance mass flux and the channel power to perform its simulations. The pool boiling calculation requires the fuel string coolant conditions, taken at the exit of the fuel string to be conservative. A NUCIRC circuit simulation is performed using recent pre–outage lock–on models for Pt. Lepreau. The model is adjusted to account for outage maintenance such as boiler cleaning. From this model, the appropriate header to header boundary conditions can be established to perform individual channel analysis.

At this stage an appropriate channel is chosen on which to perform the analysis. A high flow channel will not require as large a blockage, but will have a higher heat flux. A low flow channel would require a larger blockage to reach the 10% flow reduction, but it has a lower heat flux. Although the pool boiling calculation is channel independent, we desire the ASSERT calculation to be more representative of channel behaviour relative to the pool boiling calculation. Consequently, a single channel from the central core region, channel O14, was selected based on its high power and intermediate flow range.

In NUCIRC, blockage is simulated by a form loss applied to the fuel string entrance, which is adjusted until a 10% flow reduction occurs in the channel. In an uncrept channel, this loss factor represents a blockage in any location that can cause a reduction in flow by 10%.

The NUCIRC simulations indicate that an increase of 8.5 in the fuel string entrance loss factor is required to reduce the flow for channel O14 by 10%. It is noted that a lower flow channel would have a higher loss factor (approximately 50 for a low flow channel), but would also have lower channel powers.

Simulation of the Blockage with ASSERT

Figure 3.1 represents the subchannel model used for the ASSERT simulations. The full bundle model is chosen since the blockage may not be radially uniform in nature. The full channel model requires 60 subchannels with 37 rods.

The blockage is introduced as an additional type of loss plane, that was located at the same location as either a spacer plane or endplate, i.e. likely locations of CHF occurrence. In ASSERT, the loss factors within a node are treated as if they are additive. Consequently, placing the blockage geometry at the same location as an endplate or spacer plane causes the loss factor calculated from the blockage to simply be added to the loss factors for the node.

The blockage is input as a form loss factor representing an area reduction in each subchannel. The blockage is assumed to be uniform in each of the affect subchannels. The thick edged orifice equation in ASSERT–IV, which comes from reference [6], is selected to model the effect of the blockage. The blockage area ratio is adjusted until the bundle average loss factor increase, relative to the unblocked loss factor at the plane, matched the loss factor predicted by NUCIRC to produce a 10% reduction in flow.

The ASSERT blockage model requires approximately a 62% area blockage to be uniformly applied to all 60 subchannels to get the loss factor to increase at the blockage plane by a factor of 8.5.

There are two versions of ASSERT, namely ASSERT–IV(Version 2 Revision 9) and ASSERT–PV(Version 2 Revision 7), which have different advantages and disadvantages for this application. ASSERT–IV has been undergoing development to have a single fuel string model to simulate all nominal channel conditions and variations in geometry, such as diametral creep, for the onset of dryout. The models have been under development for two years and recent results have been favourable in comparison to the Stern Laboratories crept channel experiments [4].

ASSERT–IV has a geometry based loss factor model. This model uses input geometry to calculate loss factors at various locations such as endplates and spacer planes. This model has also had good success as noted in reference [4]. The disadvantage of ASSERT–IV is that its numerical scheme has difficulty with significant local blockages.

ASSERT–PV is much better suited to handling both local and larger blockages. It has most of the same models available in ASSERT–IV. However, version 2 revision 7 does not yet have the models that were developed in ASSERT–IV based on the Stern Laboratories experiments.[4] In addition, neither ASSERT–IV nor ASSERT–PV can model a complete blockage of a subchannel without specific coding changes.

It should be noted that a local 100% blockage of a subchannel does not mean that a form loss factor equivalent to 100% flow area blockage should be introduced into ASSERT, since the subchannel is nodalized. ASSERT would interpret a 100% blockage to be applied to the entire length of the node and flow redistribution effects would not be properly accounted for unless the node was the same size as the blockage. The node size used in our simulations is 8 cm. Increasing the number of nodes and reducing the node size is possible in ASSERT but not necessary in this analysis.

The approach taken for this analysis is to use ASSERT–IV for a limited number of cases for comparison. There are similar blockage models created for ASSERT–PV, which uses the geometry based loss factor results from ASSERT–IV. Then two additional models are created,each successively closer to simulating a complete blockage in a fraction of subchannels.

A total of four ASSERT–blockage models are created. The first two are the unblocked channel, and the uniformly blocked channel models. These two blockage models are used in both ASSERT–IV and ASSERT–PV. The third model is radially non–uniform and applies the blockage over 78% of the flow area and the fourth applies the blockage over 65% of the flow area. These two models are only applied in ASSERT–PV.

The tube lookup table is the selected model for CHF prediction for both ASSERT–IV and ASSERT–PV. The heat transfer, friction factor, and thermal mixing models are selected to be comparable to those of the ASSERT–IV model. The nodalization is identical to the ASSERT–IV model.

The ASSERT single channel geometry simulation cases studied are summarized in Table 1.

Pool Boiling CHF model

The pool boiling CHF model is considered the lower bound limit analysis since a blockage in a channel will cause a local stagnation zone or pool. The following assumptions are applied to the pool boiling model:

1) Adequate cooling is maintained by flow induced recirculation caused by the highly turbulent nature of the flow. This ensures the local pool boiling region remains subcooled and reasonably small, i.e. local in nature and void does not accumulate.

2) The heat flux varies with axial position and radial position in the channel. Pool boiling is assumed to occur at the dryout location but with the heat flux corresponding to the maximum radial heat flux and maximum axial heat flux.

3) The fluid conditions; i.e. pressure, temperature, and void fraction, are assumed equivalent to the exit conditions in ASSERT–IV predictions as this location has the highest temperature and void fraction in the channel and the lowest pressure, all of which reduces CHF and ensures conservatism

4) The model is assumed acceptable for subcooled conditions when no void fraction is present. This is to ensure conservativeness in the analysis due to the high sensitivity in the void fraction correction.

5) The correction factor for a horizontal 37 rod bundle is taken from the Compendium of Thermalhydraulic Correlations and Fluid Properties [7]. This factor is assumed to be accurate, however caution is suggested since significant variation in this factor cannot be confirmed or denied.

The pool boiling model is based on saturated pool boiling [8] with modifications for subcooling [9] and void fraction[10].

The critical heat flux under saturated pool boiling is as follows[8]:

$$CHF_{sat} = kH_{fg}\left[\sigma g \rho_g^2 (\rho_f - \rho_g)\right]^{\frac{1}{4}} \tag{1}$$

CHF_{sat} – Saturated Critical Heat Flux for Pool Boiling [W/m^2]
ρ_f – Fluid Density [kg/s]
ρ_g – Vapour Density [kg/s]
σ – Surface Tension [N/m]
H_{fg} – Heat of Vapourization [J/kg]
g – Gravitational Acceleration [m/s^2]
k – Geometric Constant

The effect of subcooling on the CHF pool boiling can be determined using the following equation[9]:

$$\frac{CHF_{sub}}{CHF_{sat}} = 1.0 + 0.1\left[\frac{c_{p_l}(T_{sat} - T_b)}{H_{fg}}\right]\left[\frac{\rho_f}{\rho_g}\right]^{\frac{3}{4}} \qquad (2)$$

CHF_{sub} – Subcooled Critical Heat Flux for Pool Boiling [W/m^2]
C_{p_l} – Specific Heat Capacity [J/kg–K]
T_{sat} – Saturation Temperature [K]
T_b – Bulk Fluid Temperature [K]

Using Griffith's modification, the effect of void fraction can be included as follows[10]:

$$\frac{CHF_{\alpha}}{CHF_{sat}} = 1.0 - \alpha \qquad (3)$$

CHF_{α} – Voided Critical Heat Flux for Pool Boiling [W/m^2]

All thermalhydraulic parameters are chosen as the exit conditions of the ASSERT–IV calculations. The geometric constant is set to 0.053 for a horizontal tube bundle[7] according to Palen's calculation method[11]. The geometric constant is known to vary from 0.149 from a horizontal surface to 0.118 for pool boiling on the outside of a tube, to 0.053 for a horizontal tube bundle.

RESULTS

The main trend in the ASSERT results(minimum CHF ratio vs. power) is that at 10 kg/s, there is little difference between any of the ASSERT–PV blockage models. At 20 kg/s the 65% flow area blockage begins to show some difference and at 30 kg/s the difference is more significant. This trend suggests that the flow can partly refill the blocked subchannels due to a smaller recirculation zone at lower flows.

Examination of the rest of the results does not support the idea of axial location moving upstream as the number of subchannels with blockage decreases. The results suggest that the flow redistribution is affecting local conditions. Further investigation would be required to detail this phenomena, however, as the overall trend is very weak, further investigation is useful only for academic purposes.

For a flow of 10.0 kg/s, no void fraction is observed anywhere in the channel for channel powers less than 1187 kW or 20% of O14 channel power. At 30% of O14 channel power, a void fraction of 2.7% is predicted. Void fraction increases sharply with power after this point.

Considering the details of the ASSERT–PV solution, the reduction in CHF at the 65% flow area blockage is primarily due to a large flow redistribution downstream of the blockage. This flow redistribution becomes more significant at 30 kg/s, because the lateral pressure drop due to the blockage increases with the increase in flowrate. In addition, the impact on the upstream pressure drop due to the blockage will not be uniform as a function of flow. At higher flow, the effective loss factor will increase due to these effects, causing a more significant pressure variation at high flows.

Figures 2 through 5 plot the worst case ASSERT–IV and ASSERT–PV results along with the pool boiling results. The pool boiling curve is broken into three curves. The saturated pool boiling CHF result assumes that the fluid is at saturated conditions. The subcooled boiling correction curve includes the effect of the coolant subcooling. Finally, the void corrected curve applies a correction for the void fraction in the fuel string.

Table 2 shows the minimum CHFR values obtained for the pool boiling CHF model and the ASSERT–IV blocked and unblocked channel models.

Figure 2 shows the results for 10.0 kg/s. ASSERT–PV predicts higher CHF ratios than ASSERT–IV, and ASSERT–IV predicts higher CHF ratios than the pool boiling model. For example, at 10% of O14 channel power, ASSERT–PV predicts a CHF ratio of approximately 55, ASSERT–IV predicts a CHF ratio of approximately 37, and the pool boiling model predicts a CHF ratio of 13.4. Differences in ASSERT–IV and ASSERT–PV are due to corrections for local stratification in the ASSERT–IV CHF model[4].

Figure 3 shows the results for 20.0 kg/s. Now the CHF ratios of ASSERT–IV and ASSERT–PV are much closer in agreement. The ASSERT–PV predictions for MCHFR peak at 100 due to a data output limit in the ASSERT–PV code.

Figure 4 shows the results for 30.0 kg/s. The ASSERT–IV and ASSERT–PV predictions again show improved agreement for similar test cases, but the effect of radially–asymmetric blockage is significant.

Figure 5 shows the same results as Figure 4 except the axis are modified to improve clarity at high powers and low CHF ratios. The pool boiling model shows the influence of adding void fraction, with a significant reduction in CHF ratio beyond 30% of O14 channel power. The subcooling effect is also shown where the CHF ratio increases as subcooling increases. The ASSERT calculations and the pool boiling model are close in agreement near 50% of O14 channel power.

As expected, the ASSERT results fall above the pool boiling curves. The curves approach each other as the power exceeds 50%fp. The difference between the curves becomes more significant as the flowrate is increased as would be expected. The pool boiling curve is somewhat insensitive to the flowrate since the fuel string exit conditions do not change significantly. However, the pool boiling curve is affected by the channel heat flux. The plots give the actual power as opposed to %fp since the actual power determines the magnitude of the CHFR.

The large differences in the CHF ratio between ASSERT and the pool boiling models at low power is due to the flow effects and the subcooling effect. At higher powers, the heat fluxes are significantly higher, and the flow and subcooling effects are not as strong. The accuracy of the saturated CHF pool boiling model(i.e. quality=0) at high channel powers is poor due to the high void fraction present in the flow channel. Accounting for the presence of the void fraction, significantly reduces the CHF ratio. Thus, even though the ASSERT results approach the saturated CHF pool boiling model, the void corrected CHF pool boiling model is significantly lower as expected.

In general, the ASSERT results show that as the model comes closer to modelling a complete blockage it reduces toward, but does not reach the pool boiling curve. Assuming the conditions of the pool boiling curve apply, it appears to be lower bound for the cases considered.

The results previously shown are for the axial and radial location where the highest heat flux occurs in channel O14. For channel O14, this position occurs in bundle 6. The effect of the axial heat flux profile can be further investigated by examining the highest heat flux locations in bundles 1 and 3. Figure 6 shows the minimum CHF ratio vs. channel power for axial positions of bundle 1, bundle 3, and bundle 6. Only the saturated CHF pool boiling model is shown. Bundle 3 shows higher CHF ratios than bundle 6 and bundle 1 shows significantly higher CHF ratios than bundle 3. Since inspection of the fuel channels have suggested that most of the wood remaining after cleaning will be distributed in the first few bundles of the channel, then this analysis shows that conservatism has been maintained. Note that these calculations still assume the same exit fluid conditions.

As the CHF ratio limit is a function of the actual reactor power, the CHF limit will vary from channel to channel. Channels with lower channel powers than O14 will have higher CHF ratios for a given reactor power while some of the inner core channels with channel powers higher than O14 will have slightly lower CHF ratios for a given reactor power as predicted by the pool boiling model. However, these higher power channels will also have higher flows, hence an increase in the CHF ratio due to better cooling; an effect not included in the pool boiling model.

The results are valid provided that the assumption of adequate cooling of the local stagnation zone is established. This cannot be done directly with the present analysis. The uncertainty is largest if a large blockage, as assumed for this analysis, occurs on the top half of the channel where void can be trapped. This void must be removed by the flow induced recirculation effects, i.e. turbulence. To enhance the cooling capability, the channel should not be allowed to see any boiling. This removes the possibility of void being contributed by the main flow of the channel. For 10 kg/s in channel O14, this corresponds to 1800 kW.

The recirculation zone is likely to lose energy to the main flow, but it may not be maintained at the average flow conditions. The zone can heat up somewhat, creating its own equivalent void condition, which is corrected with a liquid holdup term$(1-\alpha)$ in the void corrected CHF pool boiling correlation. The only way to ensure cooling is to define an adequate CHFR limit that will provide margin to ensure that the heat removal capability can match the heat input from the local rods.

The following approach is suggested. It is assumed that a conservative CCP ratio of approximately 1.5 is maintained at full power. In single phase, CHFR and CCP ratio have the same relationship, therefore assume a CHFR of 1.5. Then, the void correction indicates a strong sensitivity to the void in the local fluid in a stagnation situation. Since a void fraction of 80% is achieved at relatively low quality (30%), this is a reasonable base for a correction to the CHFR (ie. 5). Finally, the geometric constant, used in the pool boiling CHF correlation can have a significant degree of uncertainty (50%). The combined CHFR limit from this approach is 15. From Figure 6, this corresponds to approximately 600 kW assuming the heat flux associated with bundle 6. This increases to approximately 770 kW for the heat flux associated with bundle 3.

CONCLUDING REMARKS

Modelling of significant blockages and the effect of wood in the subchannel for dryout considerations has been completed. The pool boiling model has been confirmed as the limiting case at low channel powers assuming that the pool boiling region is local and well cooled. The ASSERT analysis shows support for the pool boiling model as a lower bound calculation.

Maintaining the minimum CHF ratio to maintain the normal operating margins, the required minimum CHF ratio is 1.5. Adjusting the safe limit for the CHF ratio to account for uncertainties in the model and the possible presence of void fraction increases this value to approximately 15. Based on this CHF ratio, a typical central channel can be operated at a minimum of 600 kW.

Modelling the channel by ASSERT predicts a CHF ratio of 35. Channels with lower powers will have higher CHF ratios predicted by the pool boiling model. Channels with higher powers will have slightly lower CHF ratios but the channel mass flow rate will be higher and the increase in flow rate will have a significant increase on the CHF ratio as predicted by ASSERT.

Since a high degree of conservatism has been maintained throughout the analysis, it is expected that the actual CHF ratio will be much higher since the blockage will be distributed and not entirely at one plane. As well, pool boiling is not expected to occur, except in a very localized manner. Cleaning results suggested the wood was well distributed throughout the first few bundles and no compromise of the assumptions was apparent.

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TABLE 1: TEST PARAMETERS FOR ASSERT FLOW BLOCKAGE SIMULATIONS

Channel Flow [kg/s]	0 to 30 kg/s
Channel Power [%FP]	0 to 100%FP with ASSERT–IV and 0 to 50%FP with ASSERT–PV; where 100%FP in Channel O14 is considered to be 5.935 MW
Blockage Size	62% Area Reduction in 60 subchannels, 69% Area Reduction in 45 subchannels, 78% Area Reduction in 39 subchannels NOTE: Cross–sectional averaged area reduction is the same for all three cases (62%)
Blockage Location	Minimum CHFR location, upstream 1/2 bundle, downstream 1/2 bundle

TABLE 2: COMPARISON OF MINIMUM CHF RATIOS FOR POOL BOILING AND ASSERT MODELS

Channel Power [kW] (%O14 Power)	Saturated Pool Boiling CHF Ratio	Subcooled Pool Boiling CHF Ratio	Voided Pool Boiling CHF Ratio	ASSERT–IV Creep, No–Blockage	ASSERT–IV Creep, Uniform Blockage
110.35 (3%)	72.41	81.62	72.41	192.99	120.76
220.16 (6%)	36.29	40.49	36.29	94.93	59.35
593.89 (10%)	13.45	14.81	13.45	55.55	34.83
1186.98 (20%)	6.73	7.15	6.73	25.40	15.59
1781.66 (30%)	4.49	4.76	4.36		8.91
2375.55 (40%)	3.36	3.57	2.67		4.45
2967.98 (50%)	2.69	2.69	1.69	6.29	2.86
4572.93 (77%)	1.75	1.75	1.10		1.14
5938.87 (100%)	1.35	1.35	0.85		

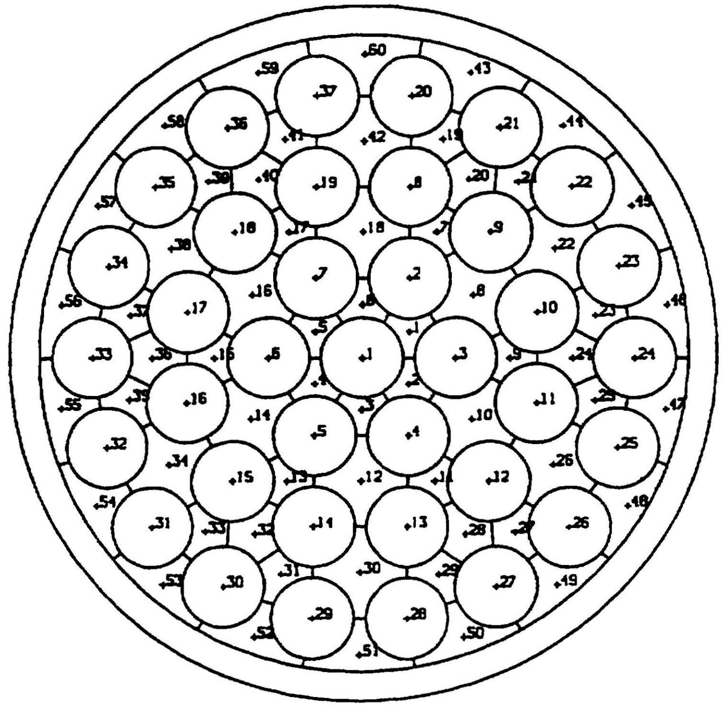

FIGURE 1: 60 SUBCHANNEL MODEL OF 37 ROD BUNDLE IN A CREPT FLOW CHANNEL

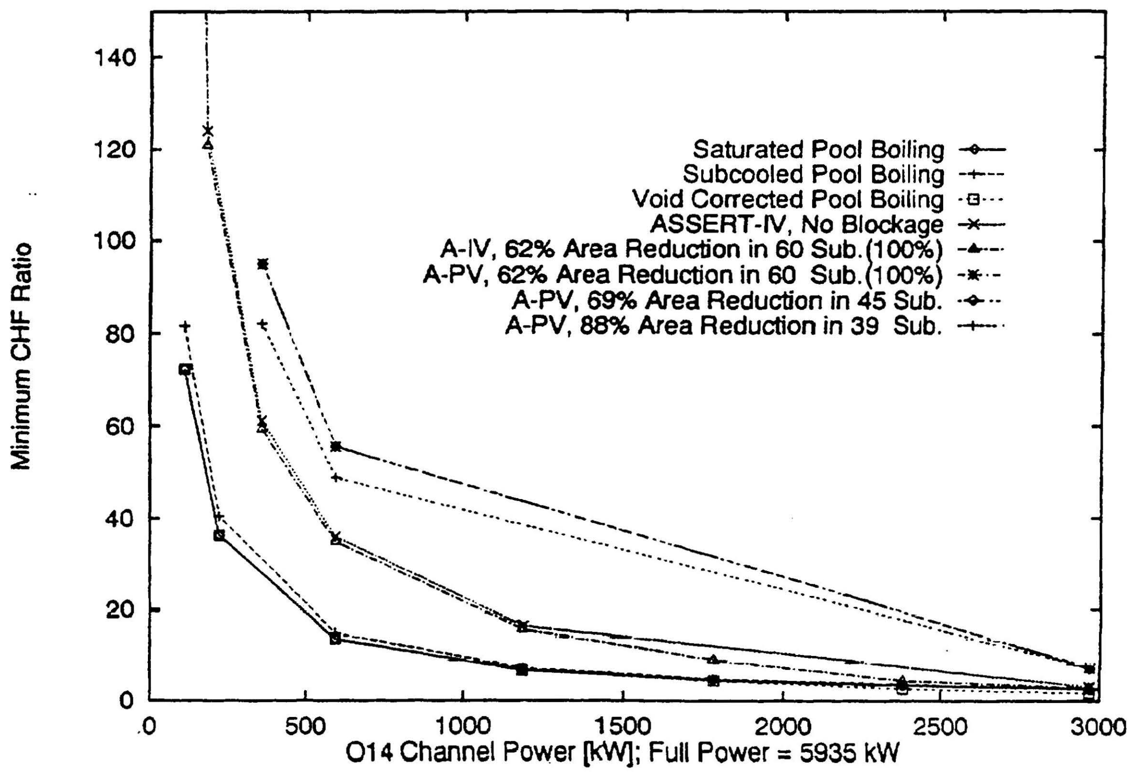

FIGURE 2: MCHFR VS. POWER FOR CREPT CHANNEL O14; 10.0 KG/S

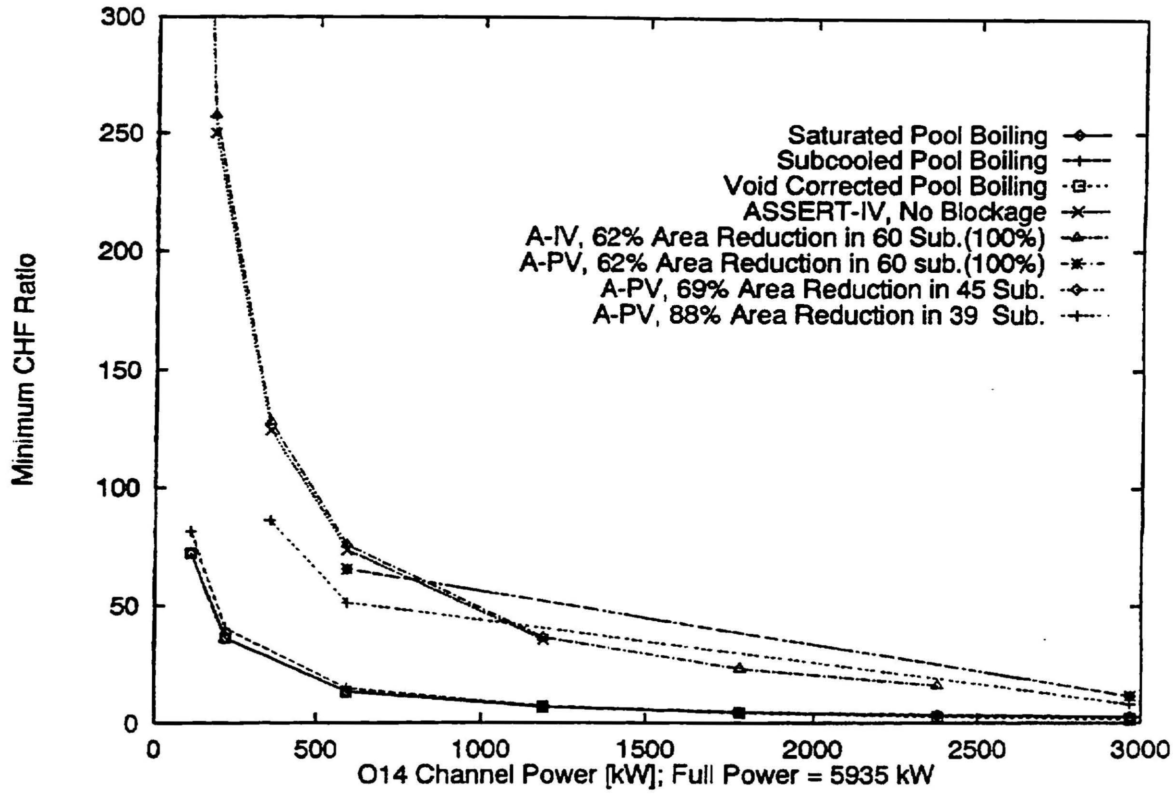

FIGURE 3: MCHFR VS. POWER FOR CREPT CHANNEL O14; 20.0 KG/S

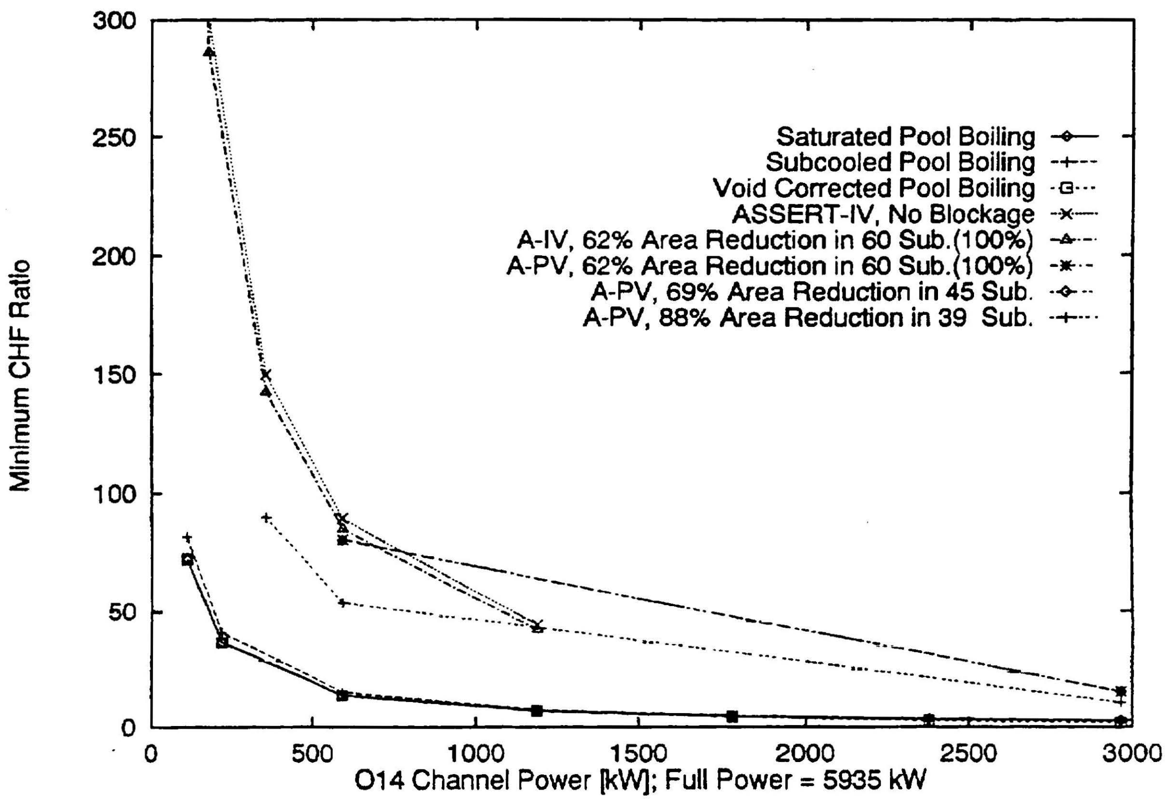

FIGURE 4: MCHFR VS. POWER FOR CREPT CHANNEL O14; 30.0 KG/S

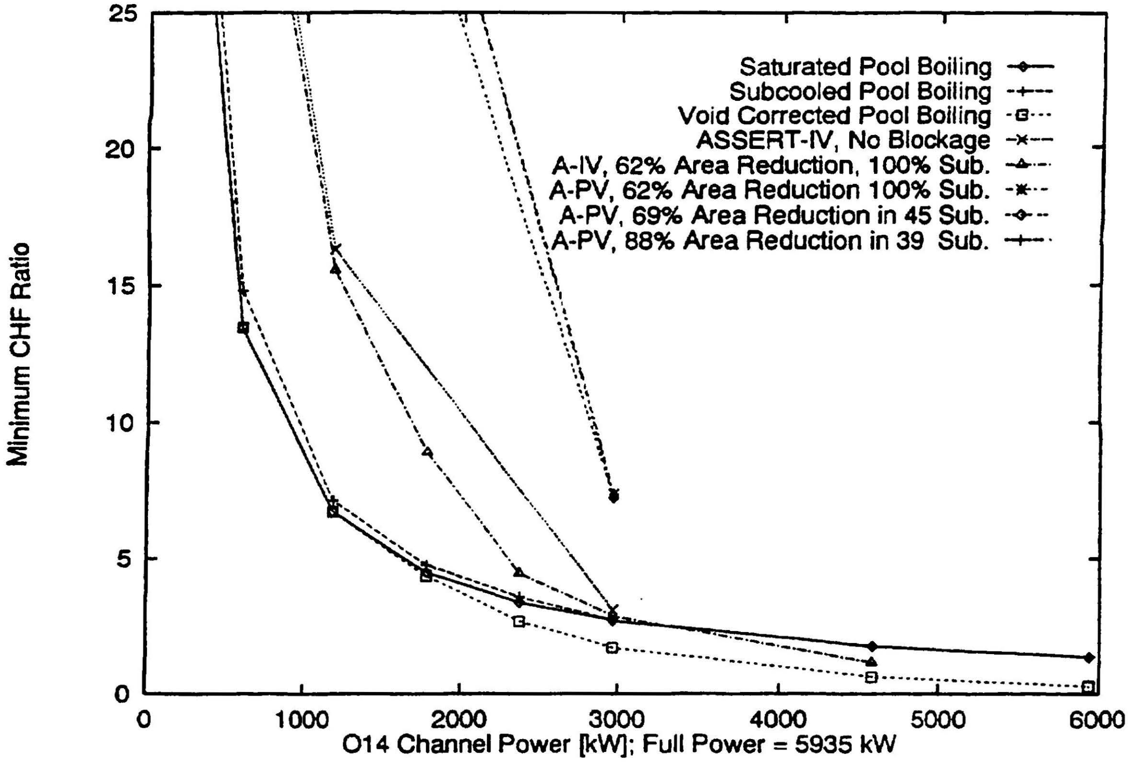

FIGURE 5: MCHFR VS. POWER FOR CREPT CHANNEL O14; 10.0 KG/S

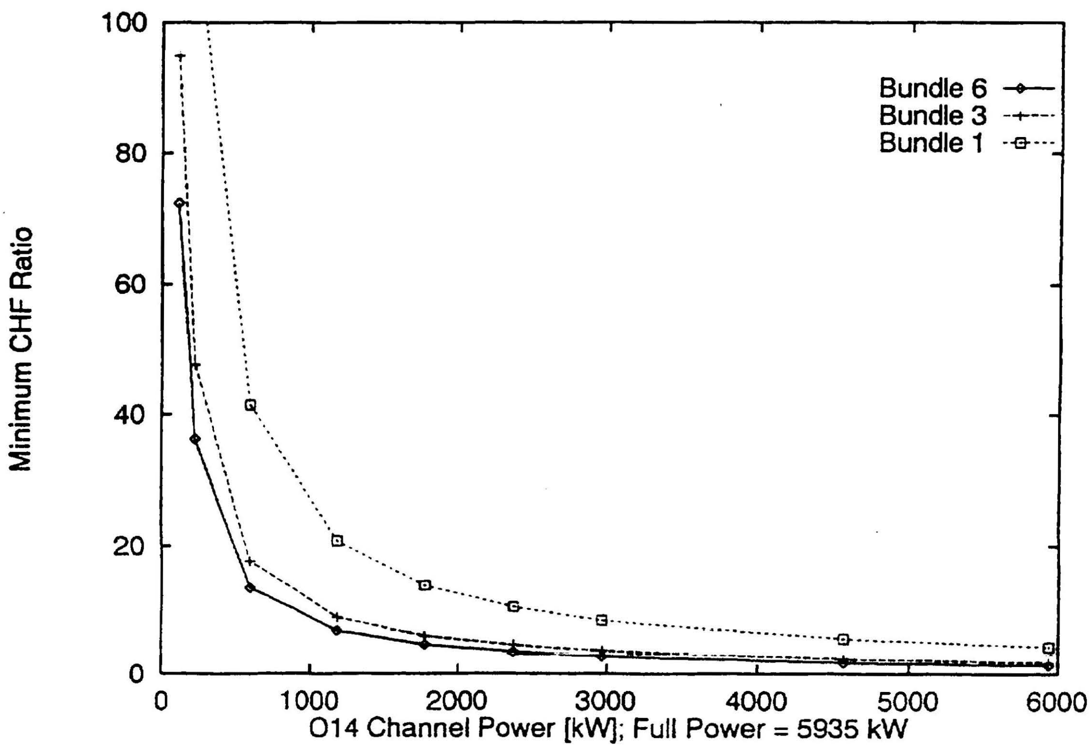

FIGURE 6: MCHFR VS. POWER FOR CHANNEL O14; SATURATED POOL BOILING MODEL; EFFECT OF AXIAL LOCATION