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CORETRAN/VIPRE ASSEMBLY CRITICAL POWER ASSESSMENT AGAINST NUPEC BWR EXPERIMENTS

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This study has been performed, in the framework of the STARS project, to assess CORETRAN-01/VIPRE-02 code capability to predict critical heat flux conditions for BWR fuel assemblies. The assessment is based on comparisons of the code results with the NUPEC steady-state critical power measurements on full-scale assemblies tested under a range of flow conditions. Two assembly types were considered, the standard BWR 8x8 and the so-called “high-burnup” assembly, similar to GE-10. Code modelling options that have a significant impact on the results have been identified, along with code limitations.

Introduction

The critical heat flux (CHF) is one of the major limiting factors for reactor cores. Safety regulations require that the occurrence of this phenomenon should be precluded under incidental conditions (Class I and II events according to the ANS classification of plant conditions). Due to the complexity of the CHF phenomenon, the evaluation of CHF conditions remains essentially empirical, and a two-step approach is used. First, the fuel assemblies are tested in experimental loops to determine CHF conditions under a range of operating conditions (flow, pressure, inlet subcooling), and the results are then synthesised in various forms, which can be either a semi-empirical model, a look-up table, or a purely statistical formulation. Secondly, safety evaluations for CHF occurrence are performed with thermal-hydraulic codes which include one or several of such formulations.

In the STARS project, CORETRAN-01/VIPRE-02 is the code package used for such an application. CORETRAN-01 [1] couples the neutronic code ARROTTA with the thermal-hydraulic code VIPRE-02 for detailed three-dimensional steady-state and transient reactor core analysis. However, VIPRE-02 [2] has been the object of only a few validation studies, and none on the CHF predictive capability. These assessments consist of a numerical benchmark study for the method of characteristics [3], a lateral mixing study based on experiments with Refrigerant-114 [4], and more recently, a limited testing of the one-dimensional void model [5]. Steps toward filling this lacuna have been undertaken within the framework of the STARS project by assessing the void prediction at the bundle and subchannel level [6,7], and through the present CHF study.

The assessment material used here are steady-state measurements of the critical power for two full-scale BWR assemblies tested under a range of pressures, flow rates, and inlet subcoolings. These measurements [8, 9] are part of an extensive experimental program, undertaken by NUPEC (Nuclear Power Energy Corporation) to demonstrate the reliability of newer assembly designs, in particular, the so-called "High-burnup" assembly (comparable to the GE-10 design from General Electric), for the replacement of the standard BWR 8x8 assemblies.

The NUPEC critical power experiments

Critical heat flux (CHF) experiments were performed on full-scale assemblies operated over a range of flow rates (20% to 120% of nominal flow rate), pressures (55 bars to 85 bars), and subcoolings (25 kJ/kg to 125 kJ/kg). The Inconel rods were heated by conduction from an internal electrical heater which provided a chopped-cosine axial power distribution with a peaking factor of 1.55. The radial power distribution, prototypical of BWR fuel assemblies, is shown in Fig. 1. Thermocouples were mounted on the high-power rods facing subchannels with the lowest thermal margin.

The CHF tests were conducted by setting the bundle flow rate, inlet subcooling and system pressure at the required values, and then by increasing the bundle power stepwise until the critical heat flux condition is reached. This condition is considered to have occurred when the wall temperature increased by ~14 K above the highest achievable stable wall temperature. This criterion was used because the wall temperature was not excursive in the vicinity of CHF conditions but exhibited fluctuations of increasing magnitude as the power was increased, and therefore, the critical power could not be pinpointed. Hence, the range of 14 K represents the (transitional) unstable heat transfer region prior to stable dryout. The power was then reduced for the next test.

CORETRAN-01/VIPRE-02 subchannel modelling

The CORETRAN-01/VIPRE-02 *subchannel* models used in the present study have already been described in the previous validation work [6, 7], and therefore are only briefly described here. The radial nodalization is shown for the so-called "High-burnup" assembly Fig. 1, where the radial power distribution is also indicated. Axially, the assembly was divided in 24 nodes in order to match the given experimental heat flux profile. The boundary conditions are a uniform inlet mass flux and enthalpy at the bottom nodes, and uniform pressure for the top nodes. Since these tests are steady-state tests, a heat flux boundary conditions was used (as opposed to a power boundary condition which would then require the modelling of the heat conduction in the rods). Given these model features, several selections, among the code options, have to be made.

First, an appropriate CHF correlation has to be selected. This choice is based on several considerations: the range of applicability of the correlation, asymptotic trends, type of correlation (design or best-fit correlation), size of the experimental data base used to develop the correlation, and consistency between the methodology to develop the correlation and the code application.

Based on the criteria listed above, the EPRI-Columbia CHF correlation [10] was determined to be the most suitable, and was therefore selected. In particular, this correlation is the only one that is based from a *subchannel* methodology, i.e., where the CHF correlation was derived from parameters determined from subchannel analyse.

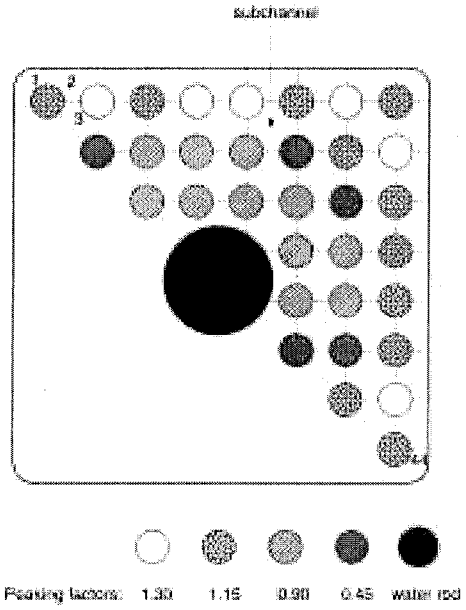

Fig. 1: Radial nodalization for the NUPEC "High-burnup" assembly

The code used for that task was COBRA-IIIC developed by BATELLE [11], and since VIPRE-02 derives from the COBRA series of codes, there is a particularly good consistency between these two codes. The remaining code modelling options [13] have been the object of sensitivity tests, as shown below. Some results obtained with other CHF correlations are also included to give an indication of the expected discrepancy.

The one-dimensional model for BWR fuel assemblies is also used to predict CHF conditions. In this approach, cross-sectional bundle-averaged parameters are used, as opposed to local parameters in subchannel analysis. In other words, in the 1-D models, the relevant parameters are radially homogenised. In order to yield accurate CHF predictions, the one-dimensional approach relies on the proper formulation of the bundle radial heterogeneity factors to compensate and these simplifications. These factors have to be determined from experiments and for each assembly type and local peaking factor distribution. However, these accurate one-dimensional CHF correlations are proprietary (e.g., GEXL from General Electric [12]). Consequently, the 1-D treatment without proper corrections to take into account the radial heterogeneities, is bound to decrease the reliability of the results, while not including them can only yield non-conservative results. Figure 3 illustrates such a difference.

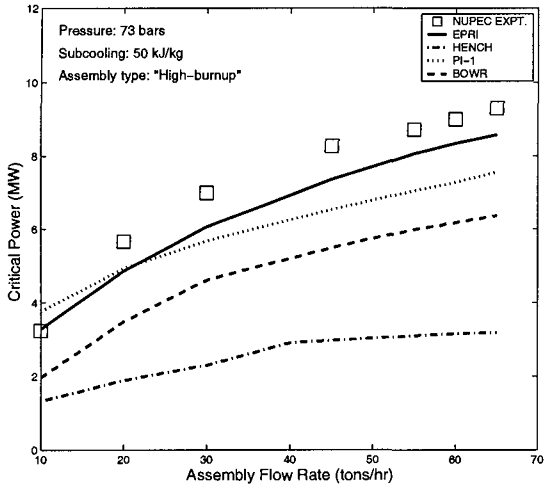

Fig. 2: Comparison between experimental and calculated data for a range of correlation.

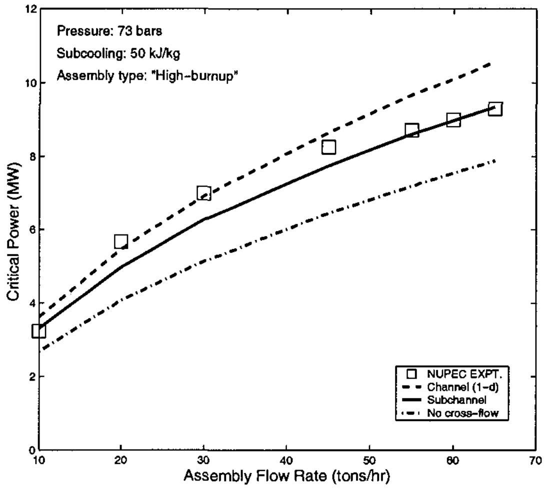

Fig. 3: Comparison between experimental and calculated data: Limiting models (spacer correction included with Ks=2.0).

Closed-channel modelling can be useful to obtain, in a subchannel model, conservative estimate of the critical power. This can readily be done by suppressing the crossflow via a code option to treat all the subchannel in the 1-D mode only (i.e., the cross-flow is then neglected in the flow and energy equations). This configuration gives a higher nodal coolant enthalpies since it conserves the radial peaking factors while isolating the adjacent channels. Figure 2 gives an indication of the degree of conservatism for such configuration.

Comparison between experimental and predicted CPR: base-case results

Given the several modelling options in the code, the approach was to obtain first results from a base set of options, consistent with the EPRI-Columbia methodology, and then perform sensitivity tests to identify the most important options. The so-called "High-burnup" assembly data have been used to establish the base case.

The effect of the flow rate, shown in Fig. 3, is relatively well predicted by the code for flow rates ranging from 20% to 120% of the nominal flow rate, i.e., from 10 tons/hr to 65 tons/hr (or from 300 kg/(m2.sec) to 1970 kg/(m2.sec)). However, the CPR is underpredicted by up to 12% in the intermediate flow rate region. The experimental and calculated critical power increases linearly with the inlet subcooling. (Fig. 4). Although the two slopes are slightly different, a better match the nominal conditions (i.e., at a subcooling of 50 kJ/kg) would reduce the under-prediction at the 25 kJ/kg subcooling case to the level of the experimental error. The decrease of the critical power with the increased system pressure (Fig. 5) is reproduced by the code, but with a weaker effect. The measured decrease in CPR is ~0.4%/bar, while the code predicts ~0.6%/bar. Thus, while the code prediction is good at 75 bars, it is conservative at lower pressures by about 5% at 50 bars.

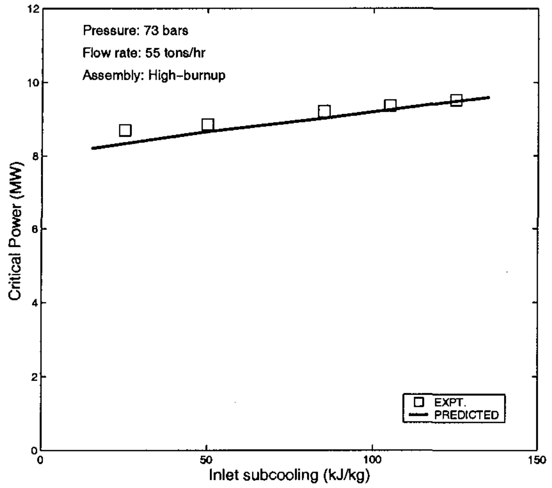

Fig. 4: Comparison between experimental and calculated data:
Effect of subcooling

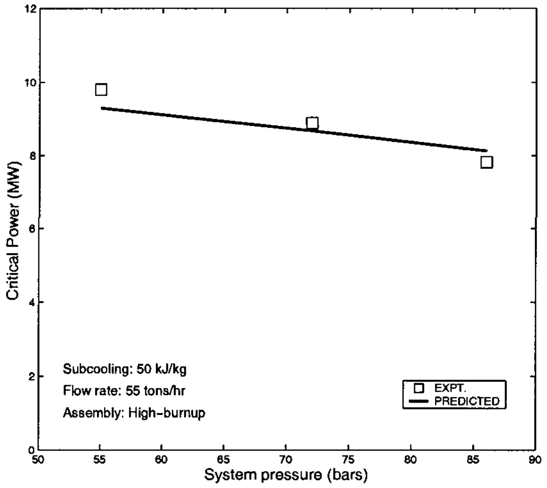

Fig. 5: Comparison between experimental and calculated data:
Effect of system pressure.

Sensitivity tests

The effect of the *mixing model* is shown in Figure 6, where β=0 correspond to the supression of the turbulent lateral mixing, and β=0.05 corresponds to the upper range value. For consistency with the EPRI-Columbia CHF methodology, the value β=0.02 has been selected and is used throughout the study. (This value is also compatible with the experimentally-determined value of 0.019 used in the Westinghouse mixing technology studies, based on measurements on enthalpy mixing between adjacent subchannels).

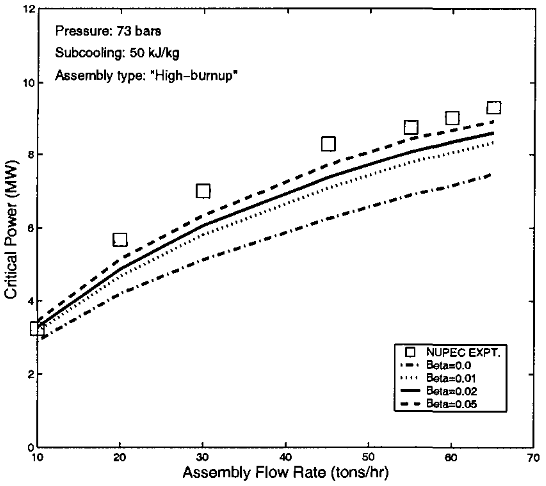

Fig. 6: Comparison between experimental and calculated data:
Effect of mixing coefficient.

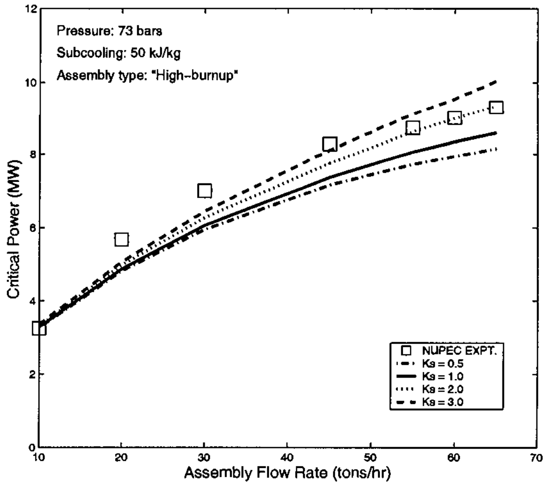

Fig. 7: Comparison between experimental and calculated data:
Effect of spacer grids.

In the EPRI-Columbia CHF correlation, a purely empirical correction factor is used to take into account the *spacer grid* effect. Since the transverse momentum exchange due to the spacers depends on the intensity of spacer-induced turbulence, itself gauged by the axial pressure drop, the grid form loss coefficient was used to characterise this effect, and the correction was optimized as follows,

$$Fs=1.3 - 0.3\,Ks$$

where Ks is the spacer grid form loss coefficient. For the standard grids, Ks being approximately equal to one, the correction was normalized such that Fs=1.0 for these grids. Figure 7 shows the impact of the spacer grid correction on the critical power. Based on this information, and the spacers form loss coefficients in the NUPEC experiments not being known, the value Ks=2.0 is used as a reference value for the rest of the study, if not mentioned otherwise. This value, somewhat arbitrary, is representative of the higher-range value for the grid loss form coefficients.

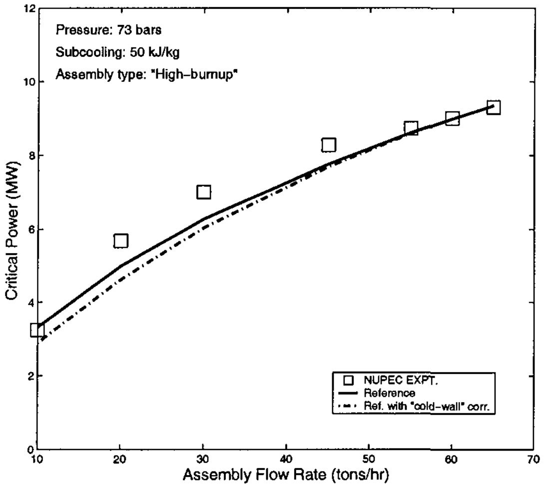

Fig. 8: Comparison between experimental and calculated data: Sensitivity to the "cold-wall" correction.

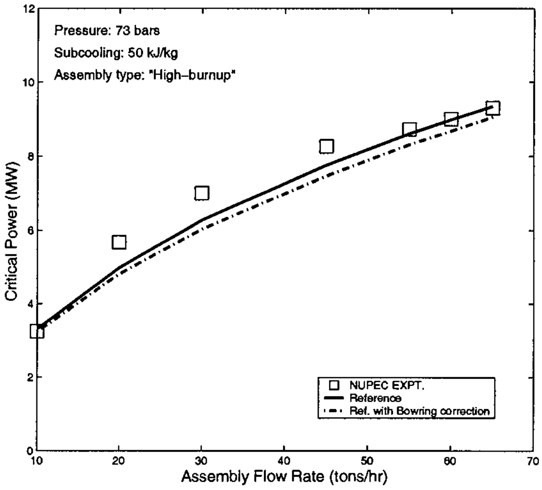

Fig. 9: Comparison between experimental and calculated data: Correction for non-uniform axial power distribution.

The *"cold-wall"* correction aims at taking into account the observed lower CHF values for channels with unheated, or so-called "cold" walls, in a "matrix" channel (subchannels delineated by several heater rods). The effect, attributed to a reduced participation in the heat transfer process of the liquid flowing along the unheated wall, is incorporated in the CHF correlation by an empirical correction. Figure 8 shows the impact of such correction: it can also be seen that while the effect is negligible at nominal conditions, it become increasingly noticeable towards the low-flow region.

The effect of the *non-uniform* axial power shape is incorporated in the CHF correlation by the following correction factor Cnu

$$Cnu=1 + (Y -1)/(1 + G)$$

where

$Y=[\int q(z)\,dz]/(z\,q(z))$

This effect, amounting to a reduction of ~3.5% at nominal conditions, as shown in Fig. 9, tends towards zero at low flow rates - this is not expected. (The use of this correction is also not recommended in the code.)

The reported estimated accuracy of the experimental flow conditions is as follows:

Pressure : 1 %
Flow rate : 1 %
Power : 1 %
Inlet fluid temperature : 1.5 K

The impact of these compounded uncertainties on the CPR values were less than 2%.

Discussion

Several points need to be made as to the outcome of this assessment. First, satisfactory predictions of the NUPEC experimental critical bundle power are obtained, provided that, among the several CHF correlations available in the code, the EPRI-Columbia CHF correlation is used, and so consistently with the methodology used to develop the correlation. The requirements to satisfy this consistency include a (channel-centered) subchannel configuration and the use of the same code sub-models (e.g., the lateral turbulent mixing), and this is met due to the code modelling flexibility.

For best-estimate calculations, several sources of uncertainty remain, given a consistent use of a CHF correlation. One source of uncertainty is the role of the spacer grids. The basic purpose of the spacers is to maintain the relative positions of the fuel rods throughout the core length. Generally, the spacers increase the flow resistance and turbulence, and therefore contribute to the reduction of the lateral enthalpy imbalance between subchannels. Some spacer grids are designed specifically as turbulence promoters to enhances thermal mixing and therefore increase the CHF limit. Thus, in the low-quality region, bubble condensation is promoted and CHF increased by improving single-phase heat transfer and by delaying bubble coalescence. However, in the annular-flow regime, the spacers role is more complex as it affects the (droplet) entrainement in several ways (thinning of the liquid film, collection of droplets and runoff, inter-channel mixing,...) [14]. Developing a spacer model from first principle is very difficult and would require detailed investigations of the flow field in the vicinity of the spacers. For practical purposes, semi-empirical approaches have been applied in three-field codes such as in the General Electric proprietary code COBRAG [14] and the commercial Studsvik/ScanPower code RAMONA-5 [15]. However, this approach cannot be applied to two-field codes like VIPRE-02.

In the case of EPRI-Columbia CHF correlation, the spacer correction does not distinguish between the two fundamentally different mechanisms. The correction uses the spacer form loss coefficient (i.e., the local pressure drop) as the figure of merit for turbulence enhancement, and therefore should be applicable to DNB-type CHF only. Using the newer BWR assembly spacer form loss coefficients will reduce the calculated CHF since these values typically range between 0.4 and 1.0 (a value of 1.0 corresponds roughly to the "standard" spacer grid). Hence, the spacer correction should include a quality (or void) dependency. Furthermore, spacer correction should also includes the total number of spacers and/or their axial spacing (i.e., grid span).

Although the current study showed VIPRE-02 reliability in predicting the NUPEC steady-state BWR data, CHF for several flow conditions remained to be assessed. These include the conditions for (i) low flows (at high and low pressures), (ii) oscillating flows including the role of the heater thermal response. It may be worth recalling that the lowest mass flux for the EPRI-Columbia validity is 0.20 Mlb/hf-ft2 (or 270 kg/m2.sec) which corresponds also to the lowest mass flux used in the present NUPEC experiment (10 tons/hr or ~300 kg/m2.sec). Extrapolation of the EPRI-Columbia correlation towards to the low-flow region is expected to be non-conservative. It has also been reported that turbulence-enhancement spacers do not have any impact at low flows and can even decrease the CHF under such flow conditions [16].

Finally, another item, not considered to the author's knowledge, is the effect of corrosion and crud deposists on the critical heat flux [17]. This concerns primarily the high-burnup fuels for which thick corrosion layers have been observed and have been spurring the development of new corrosion-resistant cladding materials. This difficulty is compounded with the fact that water chemistry has to be suitable for a variety of cladding materials. Not only can corrosion introduce uncertainties as large as, if not larger than those which have already been recognised for other effects (such as rod bow, inlet flow maldistribution, ...), the trend may also not be the same for DNB and dry-out. Moreover, crud increases the core pressure drop and therefore impact on the core inlet flow maldistribution. (The effect of crud layer on the thermal resistance has been considered in the Westinghouse proprietary fuel rod design code PAD [18].)

Concluding remarks

In the framework of the STARS project, an assessment of the critical heat flux (CHF) predictive capability has been undertaken for the CORETRAN-01/VIPRE-02 code. This has been performed by comparing the code predictions with experimental data obtained from the NUPEC full-scale fuel assemblies, tested under a range of steady-state flow conditions pertaining to BWRs.

The first outcome of the study is that the code gives good CHF predictions provided that consistency is preserved when applying a particular CHF correlation. Consistency includes not only the validity range of the flow parameters and fuel assembly type, but also the methodology used in developing the correlation itself. Among the several correlations available in the code, the EPRI-Columbia CHF correlation, which is the only one based on subchannel analysis, was found to fulfil this requirement best. Sensitivity tests, performed to identify the incidence of code modelling options on the results, showed the importance the spacer grids and the cross-flow mixing. Accurate CHF predictions (say within an error band less than ~20%) would require a better modelling of the role of the spacers, including the spacer pitch.

It is also worth mentioning that the effect of corrosion and crud deposits as an additional source of uncertainty are not taken into account in current CHF correlations. This effect is believed to be, at least, as important as other recognised effects. This is relevant primarily for high-burnup fuels for which high levels of corrosion and associated crud deposits have been observed.

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