Critical Heat Flux Correlations

Boiling crisis occurs when the surface heat flux is increased beyond the critical point on the boiling curve. In Light Water Reactors the dominant critical heat flux mechanisms are departure from nucleate boiling (DNB) in the subcooled or low quality regions, or dryout in high quality regions. The behavior of boiling crisis is dependent on local fluid conditions. In the subcooled or low quality regions, critical heat flux occurs at a relatively high heat flux and may be associated with the cloud of bubbles at the rod surface inhibiting the liquid return. Under these conditions, the temperature excursion at the heated surface can be severe. In the high quality regions, critical heat flux occurs at lower heat fluxes. The flow pattern is usually annular and the heated surface covered by a liquid film. When the evaporation rate is high enough, a dry patch can occur in the liquid layer. Since the vapor velocity is high, post critical heat flux heat transfer is better than in the low quality cases and the temperature excursion at the heated surface less severe.

Though attempts have been made to develop mechanistic or phenomenological models for predicting critical heat flux, these have generally met with only limited success. As a result, reactor design is traditionally accomplished through the use of empirical, dimensional correlations that have undergone extensive experimental testing. As the mechanisms governing critical heat flux are significantly different, the correlations and models used to predict critical heat flux are significantly different also. The specific correlation employed by an individual reactor vendor is generally proprietary, however representative critical heat flux correlations are available in the open literature.

Subcooled Flow Boiling

One of the most well known design correlations for predicting departure from nucleate boiling is the W-3 correlation developed at the Westinghouse Atomic Power Division by Tong. The W-3 correlation is a function of inlet subcooling, pressure and coolant mass flux as indicated in Equation 1.

$$\begin{aligned}\frac{q''_{c,EU}}{10^6} = {} & \{(2.022 - 0.0004302P) + (0.1722 - 0.0000984P) \\ & \times \exp[(18.177 - 0.004129P)x_c]\} \\ & \times [(0.1484 - 1.596x_c + 0.1729x_c|x_c|)G/10^6 + 1.037] \\ & \times (1.157 - 0.869x_c) \times [0.2664 + 0.8357\exp(-3.151D_e)] \\ & \times [0.8258 + 0.000794(h_f - h_{in})]\end{aligned} \tag{1}$$

where:

$q''_{c,EU}$ = Critical heat flux in a uniformly heat channel (Btu/hr-ft^2)
P = Pressure (1000 to 2300 psia)
x_c = Quality at the critical location (-0.15 < x_c < 0.15)
G = Mass Flux (1×10^6 to 5×10^6 lbm/hr-ft^2)
D_e = Equivalent diameter (0.2 - 0.7 inches)
h_f = Saturated liquid enthalpy (Btu/lbm)
h_{in} = Inlet enthalpy (> 400 Btu/lbm)

The correlation given above is for critical heat flux in uniformly heated channels. To account for non-uniform heat fluxes, Tong introduced the following correction factor

$$q''_{c,N} = \frac{q''_{c,EU}}{F} \tag{2}$$

$$F = \frac{C}{q''(\ell_{c,N})[1-\exp(-C\ell_{c,EU})]}\int_0^{\ell_{c,N}} q''(z)\exp[-C(\ell_{c,N}-z)]dz \tag{3}$$

$$C = 0.44\frac{(1-x_c)^{7.9}}{\left(G/10^6\right)^{1.72}} \quad \text{inches}^{-1} \tag{4}$$

where:

$q''_{c,N}$ = Critical heat flux in the non-uniformly heated channel (Btu/hr-ft^2)
$\ell_{c,N}$ = Axial location at which DNB occurs in the non-uniformly heated channel (inches)
$\ell_{c,EU}$ = Axial location at which DNB occurs in a uniformly heated channel (inches)

We are generally interested in assuring the operating heat flux at any location in the core does not reach the critical heat flux at that location. One measure of the margin to critical heat flux is the DNB Ratio (DNBR), defined to be the critical heat flux at a specific location divided by the operating heat flux at that location, or

$$\text{DNBR} \equiv \frac{q''_{c,N}}{q''(\ell_{c,N})}$$

As with other critical heat flux correlations, the W-3 correlation gives the heat flux necessary to produce DNB for a given set of local conditions. For example, at the channel inlet where the coolant subcooling is the highest, we would expect the heat flux necessary to cause DNB at this location to be extremely high. On the other hand, at the channel exit where the fluid enthalpy is its highest, the heat flux necessary to cause DNB should be at its lowest. This is illustrated in the figure below.

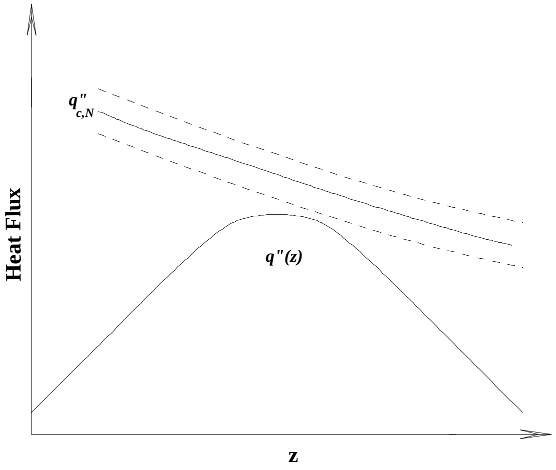

Figure 7: Local and Critical Heat Flux Versus Axial Position

The Minimum DNB Ratio (MDNBR) occurs at the location where the critical heat flux and the operating heat flux are the closest. If the critical heat flux correlation were “perfect”, then any location with a DNB ratio less than or equal to one would indicate departure from nucleate boiling at this point. In reality, all empirical correlations involving experimental data include some uncertainty due to experimental error in the critical heat flux measurement, as well as error in the empirical fit. These uncertainty bands or error bounds establish a minimum acceptable value for the DNB Ratio, which may be significantly greater than one as indicated in Figure 7. The MDNBR for the W-3 correlation is set at 1.3.

To utilize the W-3 correlation for a given set of operating conditions, i.e. pressure, flow, heat flux, etc.

1) Select a location $\ell_{c,N}$ starting in the vicinity of the core midplane at which you wish to compute the critical heat flux.

2) Compute the local enthalpy and quality at this location. This is typically performed with computer models that can account for mixing between subchannels, grid spacers, etc. For the sake of illustration we assume a single channel model such that the enthalpy at $\ell_{c,N}$ is

$$h_c = h_{in} + \frac{1}{\dot{m}} \int_0^{\ell_{c,N}} q''(z) \pi D dz$$

   and the quality is then

$$x_c = \frac{h_c - h_f}{h_{fg}}$$

3) Compute $q''_{c,EU}$ from the W-3 correlation for a uniformly heated channel. Note, $q''_{c,EU}$ is the heat flux in a uniformly heated channel necessary to produce DNB for the given local fluid conditions.

4) Compute the length ($\ell_{c,EU}$) that must be heated at $q''_{c,EU}$ to give the same local conditions.

$$h_c = h_{in} + \frac{1}{\dot{m}} \int_0^{\ell_{c,EU}} q''_{c,EU} \pi D dz$$

$$h_c = h_{in} + \frac{1}{\dot{m}} q''_{c,EU} \pi D \ell_{c,EU}$$

$$\ell_{c,EU} = \frac{\dot{m}(h_c - h_{in})}{q''_{c,EU} \pi D}$$

   where h_c is the same local enthalpy as calculated in step 2.

5) Compute F (this generally requires numerical integration) and then

$$q''_{c,N} = \frac{q''_{c,EU}}{F}$$

   Again, the computed value of $q''_{c,N}$ is the heat flux in a non uniformly heated channel required to produce DNB for the given local fluid conditions.

6) Increase $\ell_{c,N}$ and repeat.

This procedure is repeated over the entire channel length, and the minimum DNB ratio computed.

Note, in order to prevent clad failure, the Minimum DNB Ratio must not only be satisfied during normal operation, but also during transient (or accident) conditions. The W-3 correlation was used to calculate the change in the

Minimum DNB Ratio a result of changing pressure, mass flux and inlet subcooling for a channel having a sinusoidal heat flux and nominal conditions given in Table 1 below. These results are given in Figures 8-10. Note, changing the channel pressure while maintaining constant inlet enthalpy also has the effect of changing inlet subcooling.

Maximum Channel Heat Flux	429,100	Btu/hr-ft^2
Axial Peak to Average Ratio	1.51	
Active Fuel Length	150	inches
Rod Diameter	0.382	inches
Rod Pitch	0.506	inches
Coolant Mass Flux	2.65×10^6	lbm/hr-ft^2
Channel Pressure	2250	psia
Inlet Enthalpy	557.2	Btu/lbm

Table 1: Nominal Channel Conditions for Computing MDNBR

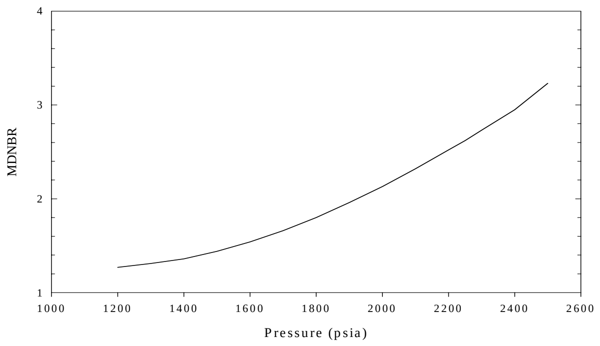

Figure 8: Minimum DNB Ratio as a Function of Pressure

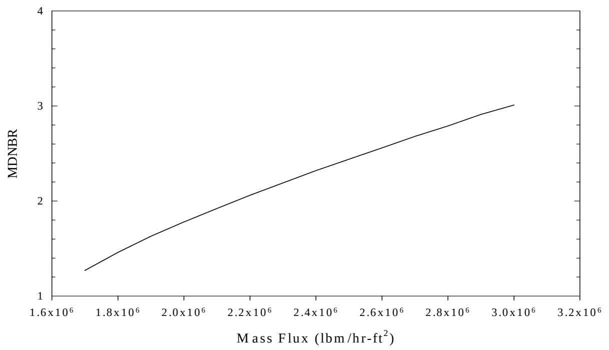

Figure 9: Minimum DNB Ratio as a Function of Mass Flux

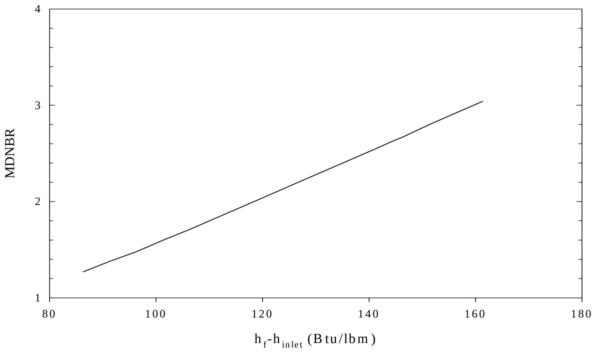

Figure 10: Minimum DNB Ratio as a Function of Inlet Subcooling

<u>Saturated Flow Boiling (Dryout)</u>

The simplest approach to correlating dryout data, is to develop a conservative lower envelope or *limit line* to the critical heat flux data, such that virtually no data points fall below this line. One correlation of this type developed for multi-rod boiling data is the Hench-Levy correlation. The Hench-Levy lines have the form

$$\frac{q_c''}{10^6}=\begin{cases}1. & x_c \le (x_c)_1 \\ 1.9-3.3x_c-0.7\tanh^2(3G/10^6) & (x_c)_1 \le x_c \le (x_c)_2 \\ 0.6-0.7x_c-0.09\tanh^2(2G/10^6) & x_c \ge (x_c)_2\end{cases} \qquad \text{Btu/hr-ft}^2$$

where

$$(x_c)_1 = 0.273-0.212\tanh^2(3G/10^6)$$
$$(x_c)_2 = 0.5-0.269\tanh^2(3G/10^6)+0.0346\tanh^2(2G/10^6)$$

and are illustrated in Figure 11 below. The range of validity for the Hench-Levy lines are $G \in [0.2\times 10^6, 1.6\times 10^6]$ lbm/hr-ft^2, $D_e \in [0.324, 0.485]$ inches and $P \in [600, 1450]$ psia. The correlations given here are for 1000 psia. At pressures other than 1000 psia, the correction factor

$$\frac{q_c''(P)}{q_c''(1000)} = 1.1-0.1\left(\frac{P-600}{400}\right)^{1.25}$$

can be employed.

To apply the Hench-Levy correlation, a location along the boiling channel is selected at which the critical heat flux is to be determined. Then similar to the approach taken in applying the W-3 correlation, the local enthalpy and quality are calculated at this location. The critical heat flux can then be computed from the limit line correlations and the critical heat flux ratio determined. This process is repeated along the entire length of the boiling channel. The minimum critical heat flux ratio for the Hench-Levy correlation is 1.9.

While the limit line approach is easy to apply and assures safe operation under saturated boiling conditions, correlations of this type tend not to follow the data trends, and generally do a poor job of predicting the location at which dryout would occur. As a result, more advanced correlations have been developed to predict dryout, many having a similar form to the F-Factor approach used to describe DNB.

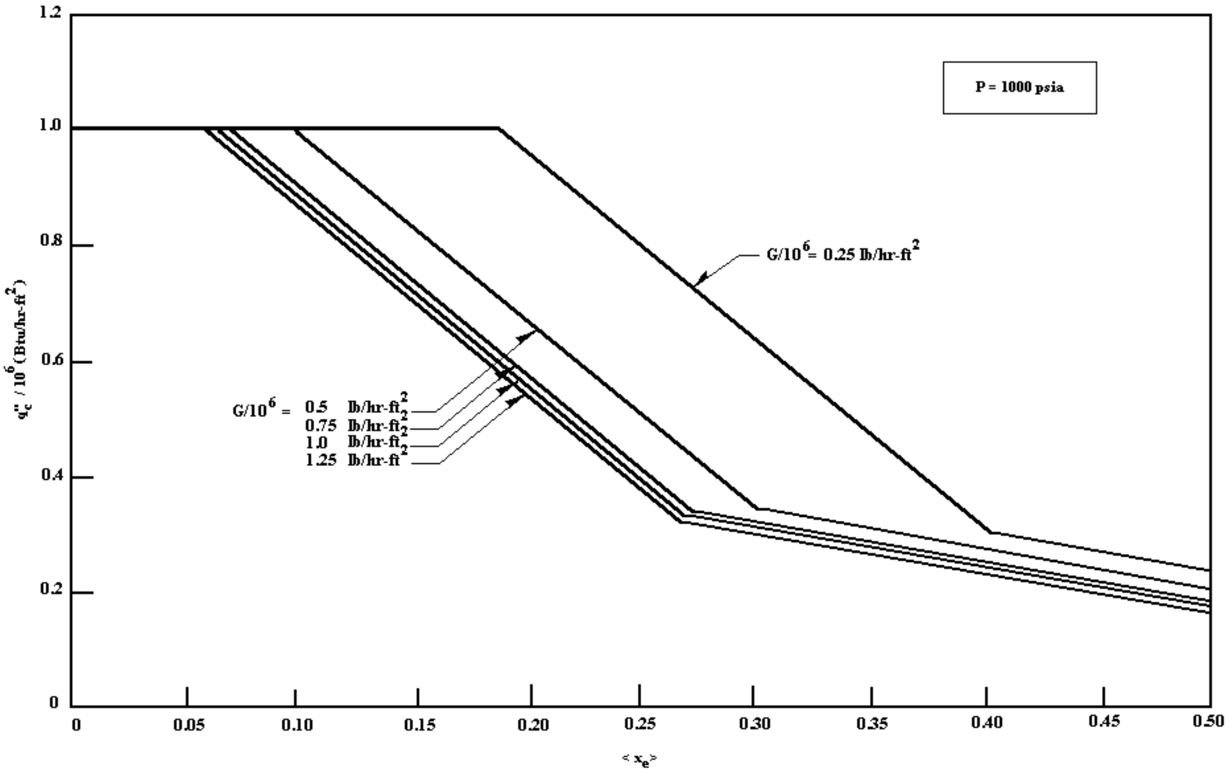

Figure 11: Hench-Levy Limit Lines