CRITICAL HEAT FLUX VARIATIONS ON CANDU CALANDRIA TUBE SURFACE

A. Behdadi, J.C. Luxat
McMaster University, Engineering Physics Department, Hamilton, Ontario, Canada L8S 4L7
e-mail: behdada@mcmaster.ca; luxatj@mcmaster.ca

ABSTRACT

Heavy water moderator surrounding each fuel channel is one of the important safety features in CANDU reactors since it provides an in-situ passive heat sink for the fuel in situations where other engineered means of heat removal from fuel channels have failed. In a critical break LOCA scenario, fuel cooling becomes severely degraded due to rapid flow reduction in the affected flow pass of the heat transport system. This can result in pressure tubes experiencing significant heat-up during early stages of the accident when coolant pressure is still high, thereby causing uniform thermal creep strain (ballooning) of the pressure tube (PT) into contact with its calandria tube (CT). The contact of the hot PT with the CT causes rapid redistribution of stored heat from the PT to CT and a large heat flux spike from the CT to the moderator fluid. For conditions where subcooling of the moderator fluid is low, this heat flux spike can cause dryout of the CT. This can detrimentally affect channel integrity if the CT post-dryout temperature becomes sufficiently high to result in continued thermal creep strain deformation of both the PT and the CT. The focus of this work is to develop a mechanistic model to predict Critical Heat Flux (CHF) on the CT surface following a contact with its pressure tube. A mechanistic CHF model is applied based on a concept of wall dry patch formation, prevention of rewetting and subsequent dry patch spreading. Results have been compared to an empirical correlation and a good agreement has been obtained. The model has been used to predict the spatial variation of CHF over a cylinder with dimensions of CANDU CT.

Keywords: CHF, Subcooled pool boiling, Mechanistic modeling, CANDU Moderator

1. INTRODUCTION

In a CANDU reactor during postulated LOCAs, for a particular break size and location referred to as critical break LOCA, the coolant flow through a portion of the reactor core stagnates before the emergency coolant injection restores fuel cooling. In addition, the emergency coolant injection system may fail to operate. In such cases, fuel cooling becomes severely degraded due to rapid flow reduction in the affected flow pass of the heat transport system. This can result in pressure tubes experiencing significant heatup while coolant pressure is still high, thereby causing uniform thermal creep strain (ballooning) of the PT into contact with its CT. Contact of the hot PT with the CT leads to rapid redistribution of stored heat from the PT to CT and a large spike in heat flux from the CT to the moderator fluid. For lower subcooling conditions of the moderator, dryout of the CT can occur. If the CT temperature gets sufficiently high, then failure of the fuel channel may occur. However, quench heat transfer can limit the extent and duration of film boiling as has been observed experimentally. In this study a mechanistic model for boiling over a cylinder will be applied. This mechanistic model can be applicable for safety analysis to determine the conditions under which fuel channel failure will not occur in a postulated critical break LOCA. The object of the project is to investigate the boiling process around the channel after a PT/CT contact and find the nucleation rate and thermalhydraulic conditions under which CT dryout will occur.

The fluid material, system pressure and gravity are the primary factors affecting CHF. Using dimensional analysis Kutateladze [9] derived the following expression for CHF in saturated boiling from a horizontal upward facing flat plate:

$$q_c'' = K_1 \rho_g h_{fg} [\sigma g(\rho_l - \rho_g)/\rho_g^2]^{1/4} \tag{1}$$

From this well known equation the relation between the affecting factors and the critical heat flux can be described. Using CHF data, Kutateladze found $K_1 = 0.16$ while Zuber obtained exactly the same equation but with $K_1 = 0.131$ using a stability analysis.

Secondary factors affecting CHF can be listed as surface roughness, wettability and thermal properties of the heated surface. Another important parameter is the liquid subcooling. There are also some other factors related to the fluid motion that affect CHF such as size and geometry of the heated surface.

Critical heat flux mechanism has been the subject of considerable investigation and debate since 1950s. For CHF in pool boiling Carey [1] classified the postulated mechanisms into the following four groups:

1- Vapor blanketing mechanism proposed by Kutateladze [9] based on an analogy between the CHF and flooding phenomena. He suggested that at high heat fluxes merging bubbles form vapor columns in which there are liquid droplets that fall back to the surface. When the vapor velocity becomes high enough to carry the droplets away from the surface against gravity, vapor blanket and CHF occurs. Using dimensional analysis Kutateladze [9] proposed the foregoing relation (1) for maximum heat flux.

2- Bubble packing mechanism in which by increasing the nucleation site density, a critical bubble packing is reached that inhibits liquid flow to the surface in such a degree that a vapor blanket forms over a portion of the surface. This analogy is not supported by the experimental evidence and has been largely abandoned in favor of hydrodynamic CHF models.

3- The hydrodynamic instability model was proposed by Zuber [12] for a flat horizontal surface and was subsequently refined and extended to other geometries by Lienhard et al. [10,11].

4- The macro-layer dryout model developed by Haramura and Katto [5] focuses on the layer of liquid under the large vapor bubbles.

Katto [6] proposed a preliminary model of the macro-layer dry out which was completed later by proposing the mechanism of macro-layer formation [5]. At high heat flux levels small vapor jets connected with individual nucleation sites carry vapor to a large vapor bubble which is fed by a number of the small jets. The jets carry vapor through a thin film of liquid that exists under the large slugs of vapor. The large slugs of vapor *hover* over the surface, accumulating vapor until buoyancy of the vapor pulls the bubble upward to escape from the surface. CHF occurs when the liquid film evaporates completely during the *hovering* time interval needed for the bubble to grow large enough to escape.

The hydrodynamic instability as the cause of CHF in pool boiling heat transfer used in the above described models has been claimed and disputed many times considering the confusion over the number of physical models that have been proposed and the effect of certain parameters on the maximum heat flux such as geometry, orientation and surface conditions which few of the models, if any, are able to account for. Nevertheless, the great success already achieved in treating this very complex problem by analysis based on the hydrodynamic instability theory is truly impressive. In a more recent study, Kandlikar [8] developed a model of the critical heat flux mechanism that includes the effect of contact angle and surface orientation and is not based on hydrodynamic wave instability. The model postulates that the CHF occurs when the forces acting on the contact line of a bubble on the heated surface become unbalanced causing the bubble to spread laterally and blanket the surface. His analysis agreed well with the few available pool boiling CHF data that determines contact angle as well as CHF. However, in order to fully understand contact angle effects on CHF, more simultaneous measurements of CHF and contact angle need to be done.
In this study a hydrodynamic mechanistic model for boiling over a cylinder will be applied. This mechanistic model can be employed in safety analysis to determine the conditions under which fuel channel failure will not occur in a postulated critical break LOCA.

2. THEORETICAL MODELING

The hydrodynamic model proposed by Cheung and Haddad [4] has been used in this study. This model considers a macrolayer underneath an elongated vapor slug on the curved heating surface (see Figure 1). The macro-layer consists of a continuous liquid film with vapor stems penetrating it. The local rate of liquid supply, $\dot{m}_s$, from the two phase boundary layer to the macro-layer is given by:

$$\dot{m}_s = \rho_l u_l A_m \tag{2}$$

On the other hand, the local rate of depletion, $\dot{m}_d$, of the liquid film is given by:

$$\dot{m}_d = q''_{NB} A_w / h_{fg} \tag{3}$$

Local dryout of the liquid film is considered to occur when the local rate of liquid supply becomes smaller than the local rate of liquid depletion. Therefore, by setting $\dot{m}_s$ equal to $\dot{m}_d$

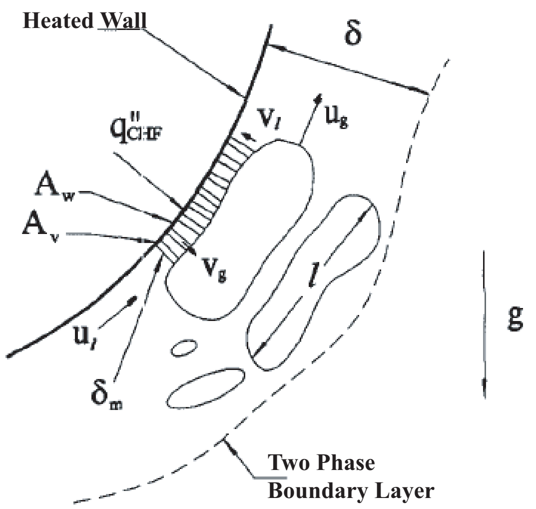

Figure 1. Schematic of the macro-layer underneath a vapor slug [4]

and q''_{NB} equal to q''_{CHF}:

$$q''_{CHF} = \rho_l h_{fg} u_l (\frac{A_m}{A_w}) \tag{4}$$

where A_m is the net flow area across the macro-layer at the local CHF point.

Assuming the characteristic length of the vapor slug as l, the net flow area can be expressed by $A_m \sim (\delta_m)_{CHF} l$ and the heating surface area as $A_w \sim l^2$. $(\delta_m)_{CHF}$ is the thickness of the macro-layer at the local CHF point. From experimental observations [2,3] the characteristic length l is found to be proportional to the local two phase boundary layer thickness in the bottom center region, δ_0, i.e. $l = C_4\delta_0$ where C_4 is a constant having a value very close to four. Substituting these values into Equation (4) gives the following expression for the local critical heat flux

$$q''_{CHF} = \rho_l h_{fg} u_l (\delta_m)_{CHF} / C_4 \delta_0 \tag{5}$$

Helmholtz instability is acting over the macro-layer throughout the entire high heat flux nucleate boiling regime including the CHF point and it gives the thickness of the liquid film which is the same as the thickness of the vapor stems as [4]

$$(\delta_m)_{CHF} = C\sigma\rho_g(1 + \frac{\rho_g}{\rho_l})(\frac{\rho_g}{\rho_l})^{0.4}(\frac{h_{fg}}{q''_{CHF}})^2 \tag{6}$$

Substituting Equation (6)into (4) gives

$$q''_{CHF} = B\rho_g h_{fg}[\frac{\sigma u_l}{\rho_l \delta_0}(1 + \frac{\rho_g}{\rho_l})(\frac{\rho_g}{\rho_l})^{-1.6}]^{1/3} \tag{7}$$

where $B = (C/C_4)^{1/3}$ is a new constant. Evidently, the critical heat flux depends on the local liquid velocity in the two-phase boundary layer.

Figure 2 shows the external buoyancy-driven two phase boundary layer flow on the outer surface of a cylinder. The cylinder has a radius R equal to the CT outer radius and is considered to be heated by conduction from the hot PT after contact. The ambient liquid is subcooled and quiescent and the boundary layer motion is induced by pool boiling of the liquid on the outer surface of the cylinder. An axisymmetric cylindrical coordinate system is employed. The radial and angular positions in the boundary layer are given by r and θ, respectively. Under the influence of gravity, the buoyancy force driving the two-phase motion is proportional to $\alpha(\rho_l - \rho_g)g\sin\theta$, where α is the local void fraction of the two-phase mixture and $g\sin\theta$ is the local acceleration of gravity in the direction parallel to the heating surface.

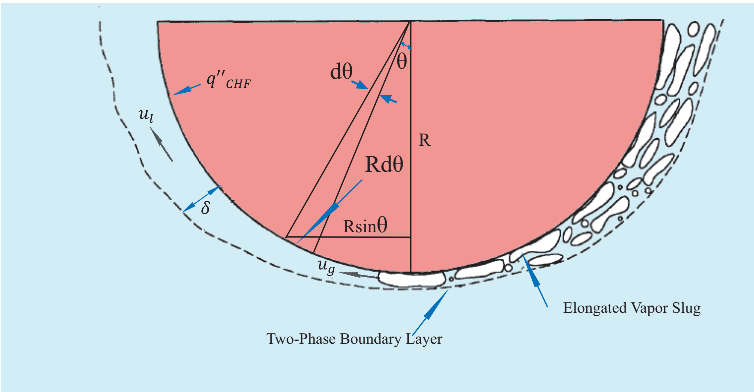

Figure 2. Two-phase boundary layer on the outer surface of a heated cylinder [4]

3. RESULT AND DISCUSSION

Katto [7] developed an empirical generalized correlation to predict CHF in saturated boiling on a heated cylinder in cross flow for different vapor-to-liquid density ratios.

$$\frac{q''_{CHF}}{Gh_{fg}} = K(\frac{\sigma\rho_l}{G^2 d})^m \tag{8}$$

where

$$K = 0.00588 + 0.500(\rho_g/\rho_l)^{1.11} \tag{9}$$

and

$$m = 0.42(\rho_g/\rho_l)^{0.0428} \tag{10}$$

The results obtained from the model have been compared with the empirical correlation of Katto for different diameters. Figure 3 shows the comparison between the results obtained from the model and the empirical correlation of Katto et al [7] for a heated cylinder with diameter of 1 mm and 3.18 mm. Figure 4 shows the same results for diameter of 13 cm, which is close to Candu CT. In this analysis the boundary layer thickness in the bottom center of the cylinder, , is assumed to be 0.025d. There is good agreement between the model and Katto equations for saturated condition and different tube diameters with the assumed boundary layer thickness.

By increasing the diameter the results underpredict the CHF value and this is because the Katto correlation has been developed using the experimental data over small diameter tubes while the model considers the effect of buoyancy on a larger diameter tube.

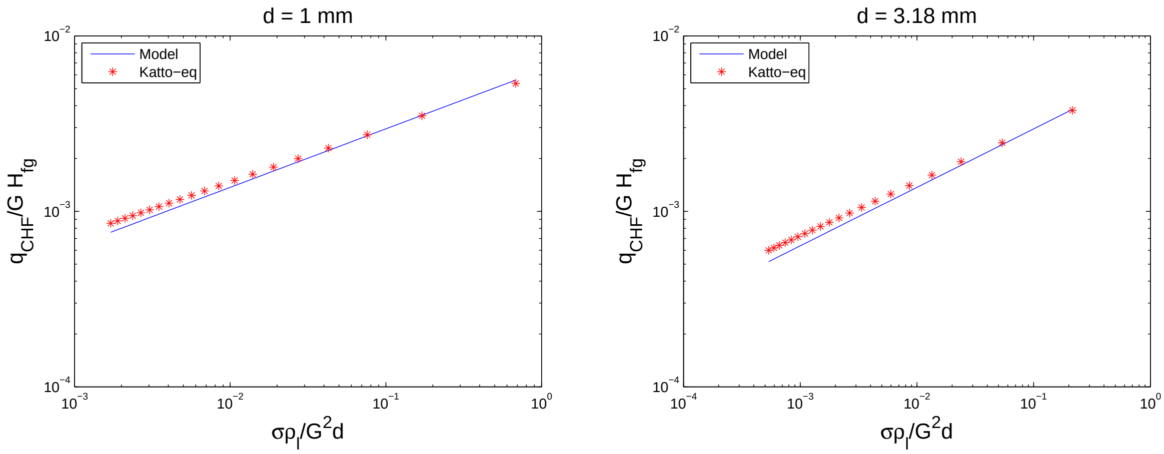

Figure 3. Model and Katto correlation data for CHF of saturated water on small diameter cylinder

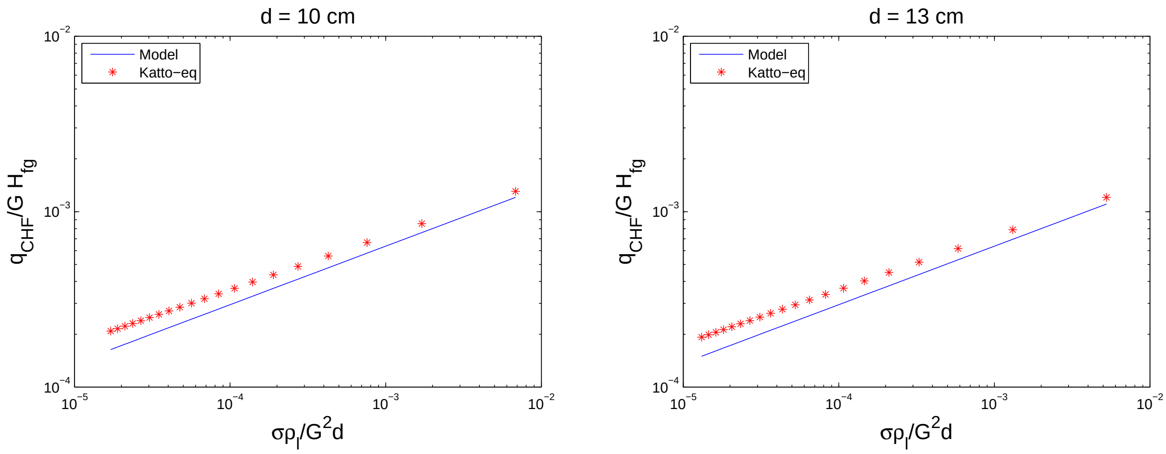

Figure 4. Model and Katto correlation data for CHF of saturated water on large diameter cylinder

Using the theoretical model, the spatial variation of liquid and vapor velocities and critical heat flux around the heated cylinder with dimensions of Candu CT have been predicted and depicted in the following graphs. Water properties at atmospheric pressure have been used, i.e. $\sigma = 0.0588 Nm^{-1}$, $\rho_l = 958 kgm^{-3}$, $\rho_g = 0.598 kgm^{-3}$ and $h_{fg} = 2.257 MJkg^{-1}$. Figure 5 shows the spatial variation of liquid and vapor velocity in the two-phase boundary layer around the heated cylinder. $\theta = 0$ indicates the bottom center and $\theta = 90$ is at the side of the cylinder where the boundary layer reaches to its maximum thickness and the velocity in both phases also gets to its maximum value. Figure 6 shows the spatial variation of critical heat flux around the heated cylinder obtained from preliminary application of the model. The graph shows the minimum critical heat flux value at the bottom center region where the velocity is low and its value increases as the velocity increases inside the boundary layer toward the sides of the cylinder. The model needs to be modified in order to take into account the effect of subcooling inside the moderator fluid.

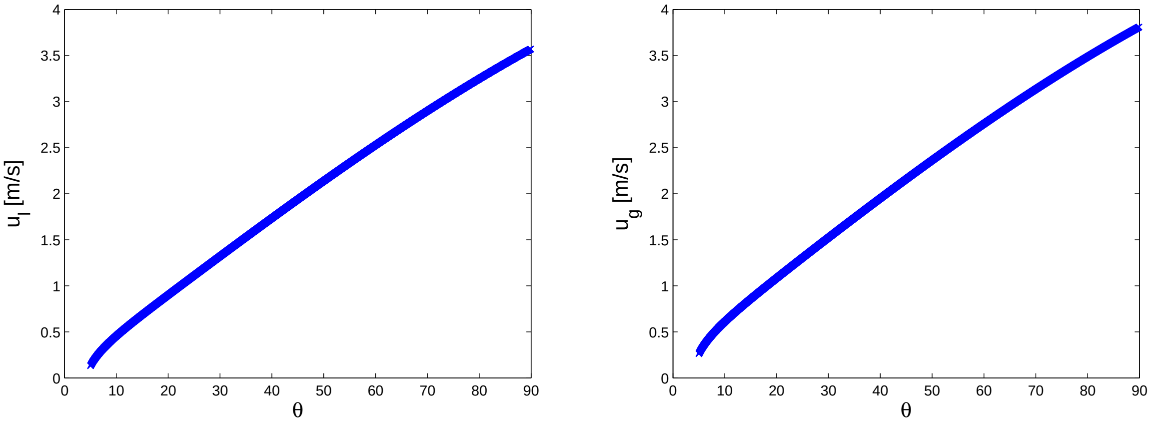

Figure 5. Spatial variation of liquid and vapor velocities on the heated cylinder

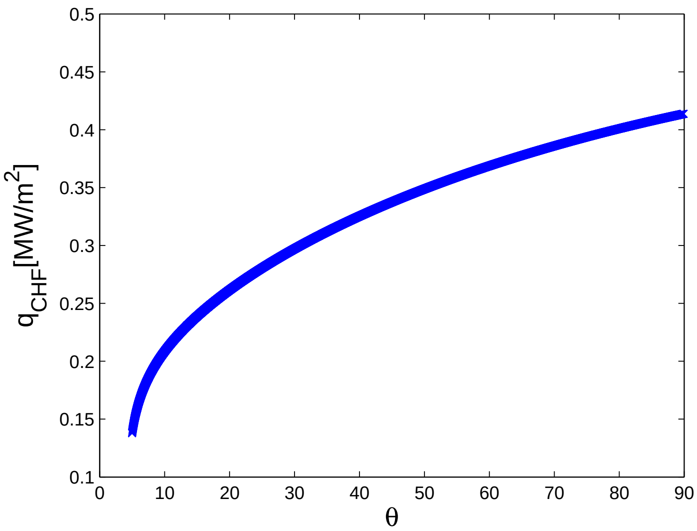

Figure 6. Spatial variation of critical heat flux on the heated cylinder

4. CONCLUSION

The initial focus of this work has been to establish a mechanistic model for predicting the critical heat flux around one single channel to investigate the potential of dryout occurrence on the CT surface following a PT/CT contact. Buoyancy forces have been taken into account. The local thermal hydraulic conditions influencing the boundary layer heat transfer near the CT surface clearly play a significant role in local heat transfer and can have a major influence on local CHF behaviour as has been seen in experimental observations. A mechanistic model to predict local CHF around a cylinder has been applied using some assumptions and the results have been compared to the empirical correlation of Katto. Very good agreement was observed between the model and the empirical correlation. Modifications need to be made in order to consider the effect of subcooling inside the moderator fluid.

NOMENCLATURE

$\dot{m}_s$ local liquid supply rate

ρ_l liquid density

ρ_g vapor density

u_l liquid axial velocity in the two-phase boundary layer

A_m net local flow area across the macro-layer

$\dot{m}_d$ local depletion rate

q''_{NB} local nucleate boiling heat flux

A_w heating surface area under the vapor slug

h_{fg} latent heat of vaporization

q''_{CHF} local critical heat flux

δ_m macro-layer thickness

l vapor slug characteristic length

δ_0 two-phase boundary layer thickness in the bottom center region

g acceleration due to gravity

α local void fraction

G mass velocity of bulk liquid flow, $u\rho_l$

σ surface tension

d cylinder diameter

ACKNOWLEDGMENTS

The financial support of the Natural Science and Engineering Research Council (NSERC) and the University Network of Excellence in Nuclear Engineering (UNENE) is gratefully acknowledged.

REFERENCES

1. Carey, Van P.,"Liquid Vapor Phase Change Phenomena", Taylor and Francis, Inc., ISBN: 1591690358, (2007).
2. Cheung, F.B. Haddad, K.H., "Observation of the Dynamic Behavior of the Two-Phase Boundary Layers in the SBLB experiments", *Proceedings of the 22nd water reactor safety meeting*, v 2, p 87-112, (1994).
3. Cheung, F.B. Haddad, K.H., "Steady-State Observation of Critical heat Flux Phenomenon on a Downward Facing Hemispherical Surface", *Proceedings of the 23nd water reactor safety meeting*, (1995).
4. Cheung, F.B. Haddad, K.H.,"Steady-State Observation of Critical heat Flux Phenomenon on a Downward Facing Hemispherical Surface", *Proceedings of the 23rd water reactor safety meeting*, (1997).
5. Haramura, Y. and Katto, Y.,"A New Hydrodynamic Model of Critical Heat Flux, Applicable Widely to both Pool and Forced Convection Boiling on Submerged Bodies in Saturated Liquids", *Int. J. Heat Transfer*, v 26, p 389-399, (1983).
6. Katto, Y. and Yokoya, S.,"Principal Mechanism of Boiling Crisis in Pool Boiling", *Int. J. Heat Transfer*, v 11, p 993-1002, (1968).
7. Katto,Y. Yokoya, S. Miake, S. Taniguchi, M., " Critical Heat Flux on a Uniformly Heated Cylinder in a Cross Flow of Saturated Liquid Over a Very Wide Range of Vapor to Liquid Density Ratio", *Int. J. Of Heat Mass Transfer*, v 30, n 9, p 1971-1977, (1987).
8. Kandlikar, S.G.,"A Theoretical Model to Predict Pool Boiling CHF Incorporating Effects of Contact Angle and Surface Orientation", *Int. J. Heat Transfer*, v 123, n 3,p 1071, (2001).
9. Kutateladze, S.S.,"Heat Transfer in Condensation and Boiling", *USAEC Rept. AECU-3770*, (1952).
10. Lienhard, J. H. and Dhir, V.K.,"Hydrodynamic Prediction of Peak Pool-Boiling Heat Transfer from Finite Bodies", *J. Heat Transfer*, v 95, p 152-158 (1973).
11. Sun, K. H. and Lienhard, J. H.,"The Peak Pool Boiling Heat Flux on Horizontal Cylinders", *Int. J. Heat and Mass Transfer*, v 13, p 1425-1439, (1970).
12. Zuber, N.,"Hydrodynamic Aspects of Boiling Heat Transfer", AEC Report AECU-4439, (1959).