Conservatism in Methodologies for Moderator Subcooling Sufficiency for Fuel Channel Integrity upon Pressure Tube and Calandria Tube Contact

Liqun Sun
Point Lepreau Generating Station, PO Box 600, Lepreau, NB, Canada E5J 2S6
(LSun@nbpower.com)

Abstract

During a postulated large LOCA event in CANDU reactors, the pressure tube may balloon to contact with its surrounding calandria tube to transfer heat to the moderator. To confirm the integrity of the fuel channel in this case, many experiments have been performed in the last three decades. Based on the extant database of the pressure tube/calandria tube (PT/CT) contact, an analytical methodology was developed by Canadian Nuclear Industry to determine the sufficiency of moderator subcooling for fuel channel integrity. At the same time a semi-empirical methodology with an idea of Equivalent Moderator Subcooling (EMS) was also developed to judge the sufficiency of the moderator. In this work, some discussions were made over the two methodologies on their conservatism and it is demonstrated that the analytical approach is over conservative comparing with the EMS methodology. By using the EMS methodology, it is demonstrated that applying glass-peened calandria tubes, the requirement to moderator subcooling can be reduced by 10ºC from that for smooth calandria tubes.

1. Introduction

During a postulated large LOCA event in CANDU reactors, the pressure tube may balloon to contact with its surrounding calandria tube to transfer heat to the moderator. To confirm the integrity of the fuel channel in this case, many experiments have been performed in the last three decades (References [1] to [4]). Based on the extant database of the pressure tube/calandria tube (PT/CT) contact, an analytical methodology was developed by Canadian Nuclear Industry to determine the sufficiency of moderator subcooling for fuel channel integrity (Reference [5]). At the same time a semi-empirical methodology with an idea of Equivalent Moderator Subcooling (EMS) was also developed to judge the sufficiency of the moderator (Reference [6]). In this work, some discussions were made over the two methodologies on their conservatism and it is demonstrated that the analytical approach is over conservative comparing with the EMS methodology. By using the EMS methodology, it is demonstrated that by applying glass-peened calandria tubes, the requirement to moderator subcooling can be reduced by 10ºC from that for smooth calandria tubes.

2. Variations of Key Heat Transfer Parameters on Horizontal PT/CT Surfaces

Depending on the heating power, PT pressure and the moderator subcooling, the heat transfer from the surface of a CT to the moderator may experience free convection, nucleate boiling, transition boiling and film boiling as demonstrated in Figure 1. When transition boiling occurs or subsequently film boiling occurs the CT temperature will increase markedly, which in turn will strain up the CT. If the strain in the CT is sufficiently high, the fuel channel will rupture.

Currently all the heat transfer models for pool boiling of a horizontal cylinder such as the calandria tubes in a water tank are average ones around the perimeter of the cylinder. In reality, some key parameters such as the nucleate boiling heat transfer coefficient and the critical heat flux (CHF) may be relevant with the position on the calandria tube. So far, no correlation is found to describe the variations in these parameters with the positions around the calandria surface.

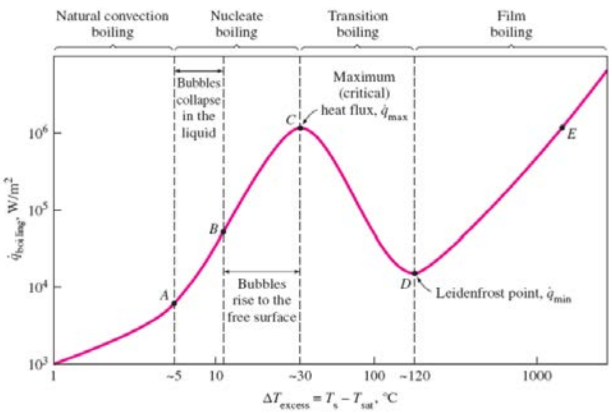


Figure 1: Demonstration of boiling curves

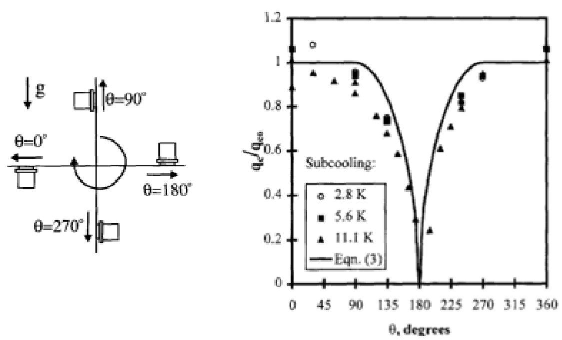
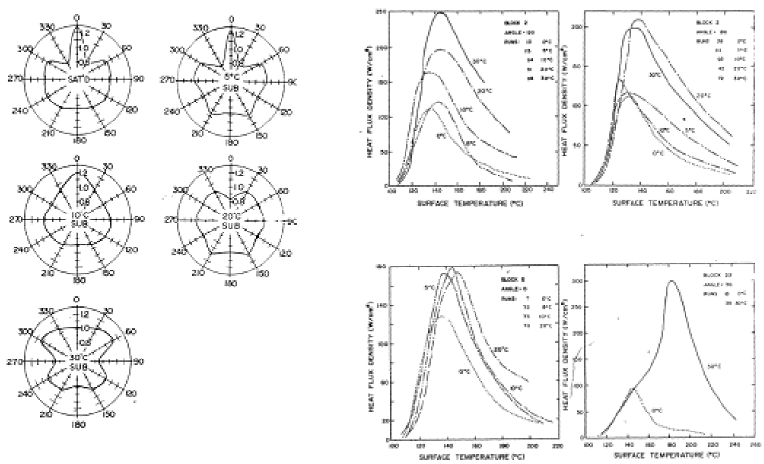


Figure 2: CHF on flat surface with different orientations and subcoolings

In Reference [7], the effects of a flat heater surface orientation on the CHF were investigated experimentally. The demonstration of different angles and the effect of orientation on the CHF for various subcooling levels with an imposed flow velocity of 0.04m/s are shown in Figure 2, which is excerpted from Reference [7].

In Reference [8], boiling heat transfer around a cylinder was studied thoroughly. Part of the results in Reference [8] is published in Reference [9]. Quenching experiments were performed with cylindrical surfaces of a horizontal copper tube with a diameter of 12.7cm and a water pool to investigate the variation of the boiling curve along the outside surface of the tube. The results showed a considerable variation in the CHF around the cylinder. The results also show a linear relationship between the average CHF and the subcooling level. Also it was found that the locations of the maximum and the minimum CHF changed as the level of subcooling increases, as shown in Figure 3 (a) which are excerpted from Reference [8]. The boiling curves with different subcoolings and different surface positions of the cylinder were also determined, as shown in Figure 3 (b), where θ = 0º corresponds to the top of the cylinder and θ = 180º corresponds to the bottom of the cylinder. This graphic clearly demonstrates the significant effects the subcooling and surface positions had on the flow characteristics around the cylinder. For example, Figure 3 (a) shows that with subcooling of 20°C, the CHF at the top of the cylinder is smaller than that at the bottom and Figure 3 (b) indicates that with subcooling of 20°C, the nucleate boiling heat transfer coefficient at the top of the cylinder is smaller than that at the bottom. This may explain why the dry patches concentrate at the top of the calandria tubes in some existing PT/CT contact experiments.



(a) (b)

Figure 3: Variation of CHF around a cylinder for different subcoolings and angles

Similar work was also performed by other researchers for different diameter of the cylinder and different fluids (Reference [10] to [17]), but the cylinders are much larger or smaller than 12.7cm.

In addition to the non-uniformity of heat transfer parameters on the CT outer surface, the heat transfer coefficient on the PT inner surface may not be uniform, either. No free convective heat transfer correlations at different angles on the internal wall of a horizontal pipe is available, but the existing PT/CT contact experiments indicate the heat transfer coefficients at the top and bottom could be higher than those for the side wall, which also makes the PT temperature at these positions higher than the side wall, though the thermal radiation heat transfer from the heater/fuel to the PT may be uniform. Thus in reality, the PT is not ballooning uniformly.

3. Discussion over the Conservatism of the Analytical Methodology

In the existing PT/CT experiments, the results can be categorized into following cases:

(A) The initial PT temperature upon PT/CT contact is high, but the heat flux on the inner surface of the PT is low. Due to the high initial PT temperature, the heat transfer on the whole calandria tube surface will enter the film boiling mode very soon due to the large heat storage in the pressure tube. However, with the stored heat depleted, the heat added by the heater may be lower than the heat dissipated through film boiling, thus the calandria temperature will drop and rewet occurs.

(B) The initial PT temperature upon PT/CT contact and the heat flux to the PT inner surface is very high. In this case, after the whole CT surface enters the film boiling mode, the CT temperature will be kept high due to the high heat flux to the PT is more than that dissipated via film boiling on the CT surface. Thus the dryout will not quench and the CT temperature will increase or stay around a constant temperature

(C) The initial PT temperature upon PT/CT contact and the heat flux are not sufficiently high. If the initial PT temperature is not high enough, dryout will not occur. Otherwise, if initial dryout occurs, while the heat flux is low, the dryout will never exceed the rewet temperature to enter the film boiling mode. In this case the heat added to the PT internal surface will be smaller than that dissipated via transition boiling and the dryout will quench.

(D) The initial PT temperature and surface heat flux are high but only part of the CT surface enters the film boiling mode (usually the top part). In this situation, the surface in film boiling can dissipate heat in two ways: to moderator through the vapour film and to non-dryout area or the dryout area that rewets quickly. Thus, the dryout area adjacent to the nuclear boiling surface will quench, which in turn to work as a heat sink of the adjacent dryout areas, then with the elapse of time, dryout area will quench little by little until the whole surface rewets. At same time, if the top part of the CT surface is in film boiling mode, the vapour produced at bottom will flow to the top. With the quench of the lower part of the dryout area, less vapour will flow upward which makes the vapour blanket thickness smaller at the top and this could increase the film boiling heat transfer coefficient in that area and accelerate the dryout quenching.

The idea of the analytical methodology is to simulate the process of PT heatup and balloning, PT/CT contact, CT dryout, CT rewet if the rewet occurs and the CT strain. The simulation process is easy to implement in analysis codes provided appropriate heat transfer models are available.

So far, the models applied in the proposed analytical approach are average ones around the CT surface positions, i.e., it is assumed that distributions in the heat transfer coefficient, CHF, film boiling heat transfer coefficient and temperature are uniform around the surface. With this model, the results described in Items (A), (B) and (C) can be captured, but the results described in item (D) can't be, so excessive conservatism will be built in and safety margins will be masked.

To demonstrate the conservatism of the analytical approach, simulations were performed for an artificial case with moderator subcooling of 20°C, PT heatup rate of 12°C/s and PT pressure of 4MPa with CATHNEA code (Reference [19]). Two simulations were conducted: (1) with circumferential variation in CHF and nucleate boiling coefficient on CT surface and (2) with uniform CHF and nucleate boiling coefficient on CT surface. To perform the former simulation, the

CHF values from Reference [7] were used. At the same time, the nucleate heat transfer coefficients at CHF were obtained using the CHF values and CHF temperature values from Reference [7]. It is assumed the nucleate heat transfer coefficients for lower temperatures have same changing tendency as that at the CHF temperature. Correction factors for CHF and nucleate heat transfer coefficients to those predicted using the code correlations at different angles were obtained (interpolations were made when necessary) and applied to the outer surface of the CT at different angles. The film boiling heat transfer coefficient is calculated using Gillespie-Moyer correlation (Reference [16]) and the rewet temperature is assumed to be 500°C per Reference [5], which were considered constant on the whole CT outer surface. The PT/CT contact thermal conductance of 16.6kW/(m^2•°C) was obtained empirically (Reference [18]) and is assumed constant through the contact period. This assumption is not real, however, if the dryout can quench, the CT temperature will be determined by nucleate boiling and the value of the thermal conductance will impact the PT temperature only. If the dryout doesn't quench, it is reasonable to assume the thermal conductance to be a constant since the PT temperature and pressure will not change significantly. Due to the symmetry, only half of the fuel channel is simulated where both the PT and CT were divided into 36 divisions of equal size in the circumferential direction and the CHF and nucleate boiling heat transfer coefficient corresponding to different angles were applied to the outer surface of each division. To perform the latter simulation, the average nucleate heat transfer coefficient and the CHF were applied to the whole CT surface. In both cases, the heat flux in the internal surface of the pressure tube is assumed uniform, i.e., the PT temperature increases uniformly and the PT balloons uniformly before contacting the CT. The results of CT outer surface temperature of these two cases are shown in Figure 4 and Figure 5 which indicate with the variations in CHF and nucleate boiling heat transfer coefficients considered, the dryout on the CT surface will quench eventually with a total engineering strain of 2%, otherwise, the CT temperature will keep increasing and the CT will keep straining until failure. Thus it is very possible that safety margin may be masked by simplifying the heat transfer to a 1-D heat transfer in radial direction only.

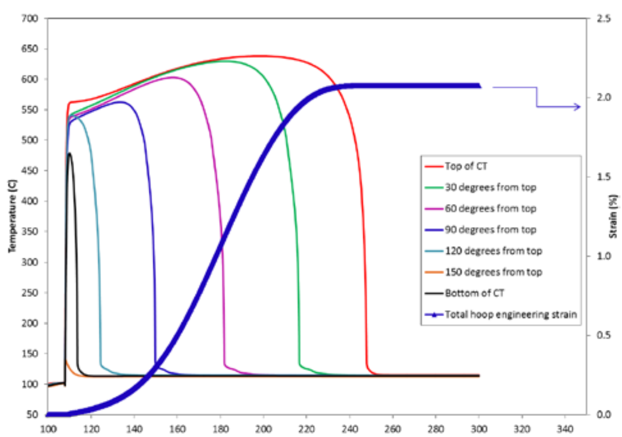


Figure 4: CT Temperature with variations in heat transfer on CT surface (with uniform heat transfer on PT surface)

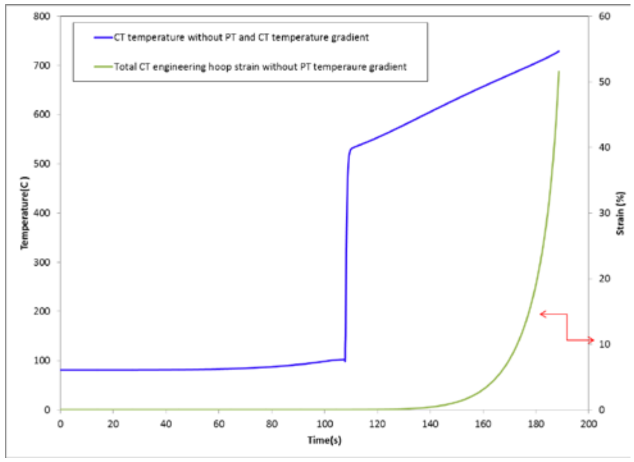


Figure 5: CT Temperatures without circumferential variations in heat transfer for PT and CT surfaces

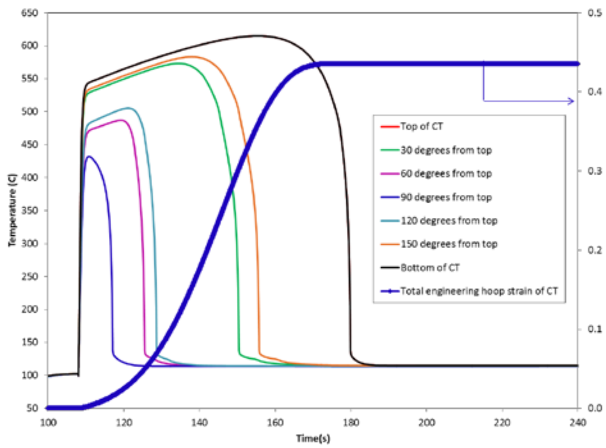


Figure 6: CT temperature with circumferential variations in heat transfer coefficient on PT surface (uniform heat transfer on CT surface)

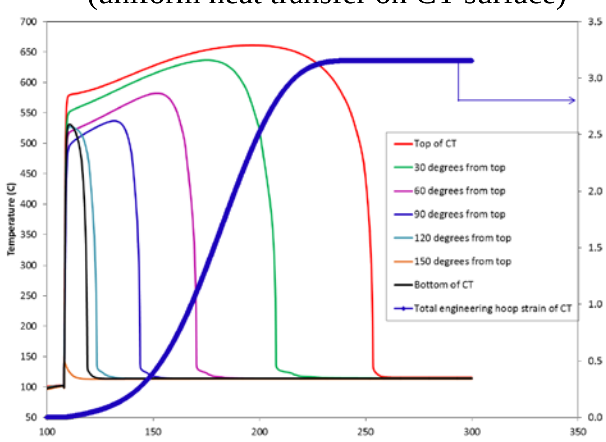


Figure 7: CT Temperature with circumferential variations in heat transfer on both PT and CT surfaces

Another simulation was performed to demonstrate the impact of the non-uniform heat transfer on the inner PT surface which causes PT temperature gradient in the circumferential direction, but with a uniform heat transfer on the CT surface. The results for this case are shown in Figure 6 which indicates that due to the temperature gradient in the circumferential direction of PT, the maximum temperature of the CT is much higher than the rewet temperature of 500°C, but this non-uniformity formed not only hot areas on the CT surface, but also some cold areas which work as a heat sink for the hot areas. Dryout quenches finally and the total hoop strain in the CT is less than 0.5%. The effects of the variation in the heat transfer on both PT and CT surfaces are also simulated and the simulation results are shown in Figure 7 which indicates that the maximum CT temperature could be higher than the cases with non-uniformity in heat transfer for each surface separately, but the total CT hoop strain is less than 3.5% when CT rewets, which is still beneficial than the results without CT rewet at all, i.e., the case with uniform heat transfer coefficients and CHF on PT and CT surfaces.

The above discussion indicates that without considering the variations in the heat transfer on both the PT and CT surfaces, simulation results in the PT/CT strain could be over conservative upon PT/CT contact. This is particularly true when part of the CT temperature is higher than the rewet temperature but the CT dryout quenches finally, which can't be captured by the current average analysis models. However, the heat transfer variations on the PT and CT surfaces are complicated and are hard to be modelled accurately. Thus to avoid the difficulty to model heat transfer and also to avoid unnecessary conservatisms, a semi-empirical methodology was proposed in Reference [6] and is discussed in more details below.

It should be noted that the simulations discussed above are used to demonstrate the conservatism in the analytical methodology, thus only the relative difference between the different cases are meaningful and the absolute results in CT temperature/strain may not be accurate.

4. **Introduction of EMS Methodology**

After reviewing the results in References [1] to [4], it is discovered that different PT pressures, PT heatup rates and moderator subcoolings can lead to similar dryout area on the CT outer surface. If the PT pressure and PT heatup rate are given for a smooth CT, the dryout area of the CT surface should be only a function of the moderator subcooling. Based on this fact, it is assumed that for a reference case with a given PT heatup rate of Hr and a PT pressure of Pr, the CT dryout area is only a function of the moderator subcooling of ΔTr. For any other cases which have same dryout area as the reference case, but different PT heatup rate, PT pressure and moderator subcooling, the impacts of the PT heatup rates and PT pressures of these cases can be corrected to the values of the reference case, while the impacts of these factors are expressed in temperatures and combined with the moderator subcooling. This new parameter obtained by adding these impacts to the actual moderator subcooling (AMS) is termed as equivalent moderator subcooling (EMS) and the an Equation is obtained in Reference [6],

$$EMS = AMS + B_2(P^2 - P_r^2) + B_1(P - P_r) + C(H - H_r) + E \qquad (1)$$

where EMS is the Equivalent Moderator Subcooling with reference PT pressure of Pr and reference PT heatup rate of Hr, AMS is the Actual Moderator Subcooling, P is the actual PT pressure, H is the actual heatup rate, B_1 and B_2 are the coefficients to correct for the impact of pressure difference from the reference case, C is the coefficient to correct for the impact of the heatup rate difference from the reference case, E is the coefficient to correct for the impact of the CT surface condition difference from the reference case and the subscript r denotes the reference state. For non-glass-peened calandria tube, the equation is written as:

$$EMS_{SCT}\left(AMS,\, H,\, P\right) = AMS - 0.1061(P^2 - 3.5^2) + 1.6724(P - 3.5) - 0.85(H - 25) \tag{2}$$

For glass-peened calandria tube, the equation was written as following in Reference [6]:

$$EMS_{GCT}\left(AMS,\, H,\, P)\right) = EMS_{SCT}\left(AMS,\, H,\, P\right) + E \tag{3}$$

"E" was determined to be 9ºC in Reference [6]. After being refined, this value is updated to be 10ºC in this work. Here 3.5MPa and 25ºC/s are considered the reference case parameters.

The relationship between the CT dryout area and the AMS for all the smooth CT experiment data are shown in Figure 8 which doesn't indicate any obvious tendency between the AMS and the dryout area. The relationship between the CT dryout area and the EMS for all the qualified smooth CT experiment data are shown Figure 9 which indicates an obvious variation tendency in dryout area versus EMS. It should be noted here that the tests in which the heater power was turned off as soon as PT/CT occurred or before PT/CT contact fully occurs were excluded and will not be discussed. In addition to the data shown in the figures, the preliminary results of four experiments performed by CNSC were assessed and are also consistent with the tendencies shown in Equation (3) and Figure 9, though these data are not included due to their preliminary nature.

The dryout area versus EMS for the glass-peened CT determined using Equation (3) is also shown in Figure 9. After Equations (2) and (3) are applied, the dryout areas are same or close for smooth tubes and glass-peened tubes which have same EMS. A comparison between Figure 8 and Figure 9 shows that the impacts of the PT pressure and PT heatup rate on CT dryout area can be transformed to the impact of change in moderator subcooling. The range of EMS for same dryout area above 10% is decreased to 2ºC (In Reference [6] it is demonstrated that the results of SC9 and SC10 could be impacted by the non-uniformity heating of the PT inner surface) which is far smaller than the 20ºC range demonstrated in Figure 8.

After the actual PT parameters (heatup rate and pressure) have been corrected to the reference values, the CT dryout area is only a function of the EMS. If more experiments are performed with the reference PT pressure Pr, reference PT heatup rate Hr in a moderator with different AMS values, the obtained CT dryout areas should be same as or close to those shown Figure 9 with an EMS value equal to the AMS used in the new experiments.

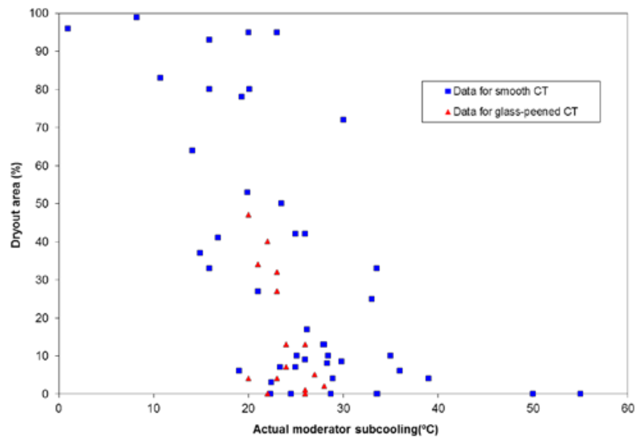


Figure 8: The CT dryout area versus the AMS for the smooth and glass-peened CT

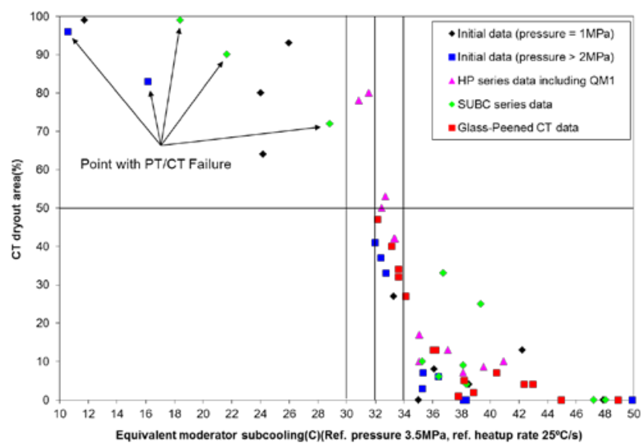


Figure 9: The CT dryout area versus the equivalent moderator subcooling for the smooth and glass-peened CT experimental data

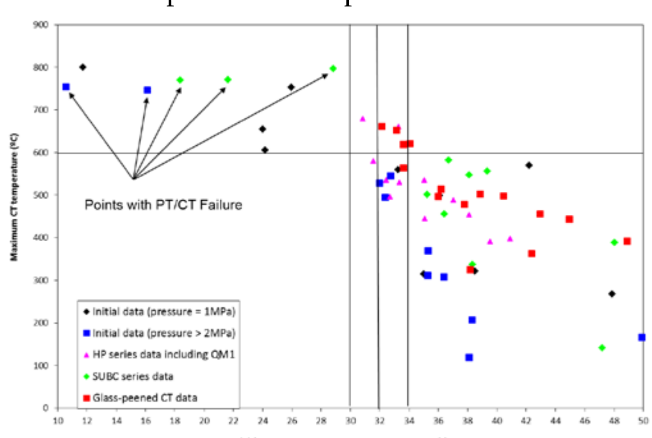


Figure 10: Relationship between maximum CT temperature and EMS

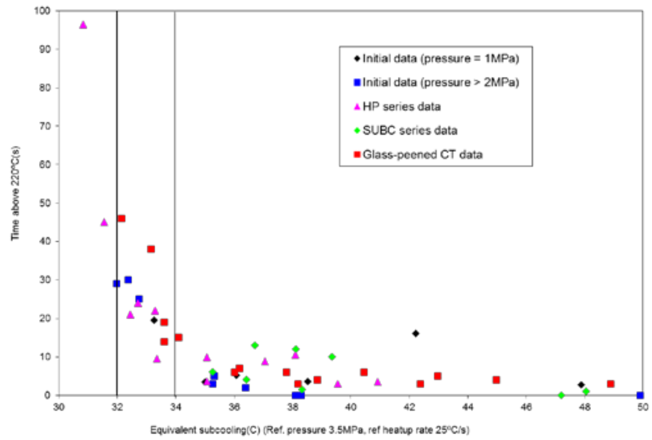


Figure 11: Relationship between the CT rewet time and EMS

The relationship between the maximum CT temperature and the EMS is shown in Figure 10 which indicates that after applying the EMS, the changing tendency of the maximum CT temperature versus EMS is more obvious. Figure 9 and Figure 10 also indicates that all the cases with EMS less than 30°C, the measured maximum sheath temperature is close to 800°C and dryout area close to 100%. With a sufficient high pressure (>2MPa), the calandria tube would fail, as the five failure cases demonstrated in these figures.

The relationship between CT rewet time (i.e., the time for CT temperature above 220ºC) and the EMS for EMS higher than 30ºC is shown in Figure 11, which shows that when EMS is less than 34°C, the CT rewet time tends to increase exponentially with EMS decrease.

Figure 9, Figure 10 and Figure 11 indicate that there are three regions for the PT/CT contact experiment results, i.e., the patchy dryout region with EMS higher than 34ºC, sustained dryout region with EMS lower than 30ºC and transition region for EMS between 30 and 34ºC. In the patchy dryout region, the dryout area is basically smaller than 25%, the maximum CT temperature is below 600ºC and the rewet time is smaller than 15s and not sensitive to the change in the EMS value. In this region, the CT will not strain significantly and fuel channel integrity can be insured. In the sustained dryout region, the dryout area is higher than 70%, the maximum CT temperature is around 700 to 800ºC and the rewet time does not make too much sense since the channel is highly probable to fail pending on the pressure. In the transition region, the dryout area, the maximum CT temperature and the rewet time increase markedly even if with a small change in EMS value, i.e., the results in this region is very sensitive to the AMS, PT heatup rate and PT pressure.

For cases with EMS values higher than 32°C but lower than 34°C, it is not excluded that some dry patches are experiencing film boiling. However, only less than 50% of CT surface is hot. Although some dry patches may have an instant high temperature, but the size of the hot area is still small.

With the heat dissipation to the moderator and to the colder area, especially to the area that still undergoing nucleate boiling, the hot dry patches will quench before any significant strain occurs in the CT to fail the tube.

For cases with EMS values lower than 32°C, but higher than 30°C, the size of the dry patches experiencing film boiling is getting larger and also hotter and it may not be appropriate to call them patches any more. Additionally, more than 50% of the CT surface becomes hot and thus the time for the hot area to disposition heat to the moderator via film boiling and via the cold area will increases dramatically. Consequently the CT tube may be allowed to strain enough to fail before the dry patches/area quenches unless the PT pressure is low.

For non-peened CT tube experiments, the experimental data between EMS value of 32°C and 34°C include PT pressure from 1MPa to 8.5MPa, PT heatup rate from 4.3°C/s to 21.4°C/s, water tank subcooling from 4.9°C to 29.3°C. Thus it is believed the spans and distribution density of the parameters are sufficient to cover the interested range for safety analysis. For glass-peened tubes, the experimental data between EMS value from 32°C and 34°C, PT pressure from 4MPa to 5.3MPa, PT heatup rate from 23.5°C/s to 24.8°C/s, and water tank subcooling from 20°C to 23°C. Although the spans of the key parameter are not as wide as those for non-peened tubes, the parameters are basically the limits that can be met in the interested safety analysis, i.e., the maximum possible PT pressure, the maximum possible PT heatup rate and the minimum possible moderator subcooling. Although a higher PT pressure will increase EMS, but the impact of PT pressure on EMS is smaller than that of PT heatup rate (heater/fuel power), and it impacts the CT strain dramatically with a change of 1MPa. Thus it is confident to declare that with EMS value higher than 32°C, the fuel channel integrity can be ensured upon PT/CT contact and this conclusion is still conservative considering in some cases with low EMS and low PT pressure the CT did not fail during the experiments.

5. Conclusions

The analytical methodology and the EMS methodology to determine the sufficiency of moderator subcooling to ensure fuel channel integrity upon PT/CT contact in the postulated events of large LOCA are discussed in detail by performing simulations and experimental data analysis. It is recognized that the analytical methodology may be over conservative in comparison with the EMS methodology due to the limitation in analysis models. This over conservatism may mask some safety margins and introduce operation restrictions.

With a more profound discussion over EMS methodology and spans of the key parameters in experiments, it is confident that if the EMS value is higher than 32°C with reference PT heatup rate of 25ºC/s and reference PT pressure of 3.5MPa, the fuel channel integrity can be ensured upon PT/CT contact. Based on the EMS concept, it is proved that the requirement in the moderator subcooling to prevent extensive CT dryout can be reduced by10ºC after using the glass-peened calandria tubes to replace the smooth calandria tubes. By applying the EMS methodology, some safety margins can be restored conservatively without performing significant design change and without performing expensive research work to establish more complicated heat transfer models.

6. References

[1] K.R. Mayoh and D.B. Sanderson, Updating the Contact Boiling Curve, CANDU Owners Group Report, COG-00-033, 2002 March.

[2] P.D. Neal, C.R. Fraser, R.J. Klatt, and C.C. Bramburger, Contact Boiling Experiment SUBC11, CANDU Owners Group Report COG-05-2027, 2006 June.

[3] T. Nitheanandan, R.W. Tiede, D.B. Sanderson, R.W.L. Fong and C.E. coleman, EEnhancing the Moderator Effectiveness as a Heat Ssink During Loss-Of-Coolant Accidents in CANDU-PHW Reactors Using Glass-Peened Surfaces, Presented at IAEA Technical Committee Meeting on Experimental Tests and Qualification of Analytical Methods to Address Thermohydraulic Phenomena in Advanced Water Cooled Reactors, 1998.

[4] H.Z. Fan, R. Aboud, P. Neal and T. Nitheanandan, Enhancement of the Moderator Subcooling Margin Using Glass-Peened Calandria Tubes in CANDU Reactors, 30th Annual Conference of the CNS, Calgary, Alberta, June 1-3, 2009.

[5] D.J. Oh and Q.M. Lei, Validation of New Moderator Subcooling Methodology, COG-06-2078, February, 2008.

[6] L. Sun and B. Willemsen, Equivalent Moderator Subcooling Methodology to Determine Fuel Channel Integrity Upon Pressure Tube and Calandria Tube Contact, 31st Annual Conference of CNS, Montreal, Quebec, May 24-27, 2010.

[7] M. J. Brusstar, H. Merte Jr, R.B. Keller and B. J.Kirby, Effects of Heater Surface Orientation on the Critical Heat Flux – I. An Experimental Evaluation of Models for Subcooling Pool Boiling, International Journal of Heat and Mass Transfer, Vol. 40, No 17, PP 4007- 4019, 1997.

[8] Jules Thibault, Boiling Heat Transfer around a Horizontal Cylinder and in Tube Bundles, A Thesis Submitted to the School of Graduate Studies in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy, McMaster University, 1978.

[9] J. Thibault and T.W. Hoffman, Local Boiling Heat Flux Density around a Horizontal Cylinder under Saturated and Subcooled Conditions”, Proceedings of Sixth International Heat Transfer Conference, Toronto, Vol. 1 pp. 199 – 204, 1978.

[10] G.G Haselden and J.I. Peters, Heat Transfer to Boiling Liquid Oxygen and Liquid Nitrogen, Trans. Of the Institutions of Chemical Engineers, Vol 27, pp 201-208, 1949.

[11] R.P Lance and J.E. Myers, Local Boiling Coefficient on a Horizontal Tube, A. I. CH. E. Journal, Vol. 4, NO. 1, pp 75-80, 1958.

[12] T.M. Flynn, J.W. and J.J. Roos, the Nucleate and Film Boiling Curve of Liquid Nitrogen at One Atmosphere, Adv. Cryogenic Eng., Vol. 7 pp 537-545, 1961.

[13] G.E. Gillespie and R.G. Moyer, An experimental Determination of Heat Transfer from Large Cylinders: Film Boiling in Subcooled Water, AECL Report WNRE-569, 1984.

[14] T.G. Theofaneous, S.Syri, T. Salmassi, O. Kymäläinen and H. Tuomisto, Critical Heat Flux through Curved, Downward Facing, Thick Walls, Nuclear Engineering and Design, Vol 151, pp. 247-258, 1994.

[15] T.G. Theofaneous, S.Syri, The Coolability Limit of a Lower Reactor Pressure Vessel Head, Proc. NURETH-7, 1995.

[16] K. Cornwall, R.B. Schuller and J.G. Einarsson, the Influence of Diameter on Nucleate Boiling Outside Tubes, Proc. Of the Seventh International Heat Transfer Conference, Vol. 4 pp 47 – 53.

[17] F.B. Cheung, K.H. Haddad and Y.C. Liu, Critical Heat Flux (CHF) Phenomenon on a Downward Facing Curved Surface, NUREG/CR-6507 PSU/ME-97-7321, June 20, 1997.

[18] L. Sun and B. Willemsen, Heat Transfer Parameters for Glass-Peened Calandria Tube in Pressure Tube and Calandria Tube Contact Conditions, 31st Annual Conference of CNS, Montreal, Quebec, May 24-27, 2010.

[19] B.N. Hanna, "CATHENA: A Thermalhydraulic Code for CANDU Analysis", Nuclear Engineering and Design, 180 (1998), 113-131.