EQUIVALENT MODERATOR SUBCOOLING METHODOLOGY TO DETERMINE FUEL CHANNEL INTEGRITY UPON PRESSURE TUBE AND CALANDRIA TUBE CONTACT

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Abstract

During a postulated event of large LOCA 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 after the contact with a given moderator subcooling, many experiments have been performed in the last three decades by applying different pressure tube heatup rates, different pressure tube pressures and different moderator subcoolings. In this work, the available pressure tube/calandria tube contact experiments data were collected to analyse the impacts of the pressure tube pressure, the pressure tube heatup rates and the calandria tube surface conditions on the requirements of the moderator subcooling to ensure fuel channel integrity. A new methodology is put forward by using the concept of equivalent moderator subcooling (EMS) to determine the integrity of fuel channels after pressure tube/calandria contact. The EMS is an artificial term combining all the parameters that impact the dryout area and the maximum calandria tube temperature. This EMS value may help to determine experiment and analysis matrices before applying more complicated methodologies for a detailed analysis. An empirical equation is recommended to determine the maximum calandria tube temperature based on the obtained EMS values for a reference state and the safety boundary for fuel channel integrity upon PT/CT contact is also provided. The equation can be used to estimate the maximum calandria tube temperature in a conservative manner. In the mean time, it is determined that with the application of glass-peened calandria tubes, the moderator subcooling can be reduced by 9ºC in comparison with the smooth calandria tubes to ensure fuel channel integrity upon the PT/CT contact.

1. Introduction

During the postulated large loss of coolant accident (LOCA) in CANDU reactors, pressure tubes (PT) will be heated up by decay heat in fuel and finally the PTs will be so hot that they may balloon to contact the surrounding calandria tubes (CT). Thus heat will be transferred to moderator through the CTs and the moderator is considered as a heat sink. The integrity of the fuel channels after the PT/CT contact was considered to be controlled by the moderator subcooling. To determine the required moderator subcooling to ensure fuel channel integrity after PT/CT contact, PT/CT contact experiments have been performed extensively in last three decades. The first set of data was obtained for low internal pressures and lower heater powers and later on more experiments were performed at high internal pressures for smooth CTs (SCT) (Reference [1]). Recently, more experiments data were obtained at both high internal pressures and high heater powers (Reference [2]). Some experiments for the glass-peened CTs (GCT) were also performed recently (References [3] and [4]). A schematic of the experiment facility and the arrangement of thermal couples are shown in Figure 1 and Figure 2 (from Reference [4]). A summary of the significant experiment results are documented in References [1], [2], [3] and [4]. Presently the condition to ensure fuel channel integrity after PT/CT contact is to prevent sustained film boiling on CT surface after PT/CT contact, which is sufficient but not necessary. Recently a new methodology has been developed and validated against the existing PT/CT contact experiments for SCTs to analyze the integrity of the fuel channel after the PT/CT contact with the input of available moderator subcooling (Reference [5]). The validation work against the experiments for GCTs is still in progress.

In this work, a new methodology is put forward by using the concept of equivalent moderator subcooling (EMS) to determine the integrity of fuel channels upon PT/CT. The EMS is an artificial term combining all the parameters including the PT pressure, PT heatup rate, the actual moderator subcooling (AMS) and the CT surface conditions which impact the dryout area and the maximum calandria tube temperature. This EMS value may help to determine experiment and analysis matrices before applying more complicated methodologies for a detailed analysis. An empirical equation is recommended to determine the maximum calandria tube temperature based on the obtained EMS values for a reference state and the safety boundary for fuel channel integrity upon PT/CT contact is also provided. The equation can be used to estimate the maximum calandria tube temperature in a conservative manner. In the mean time, it is determined that with the application of GCTs, the moderator subcooling can be reduced by 9ºC in comparison with the SCTs to ensure fuel channel integrity upon the contact.

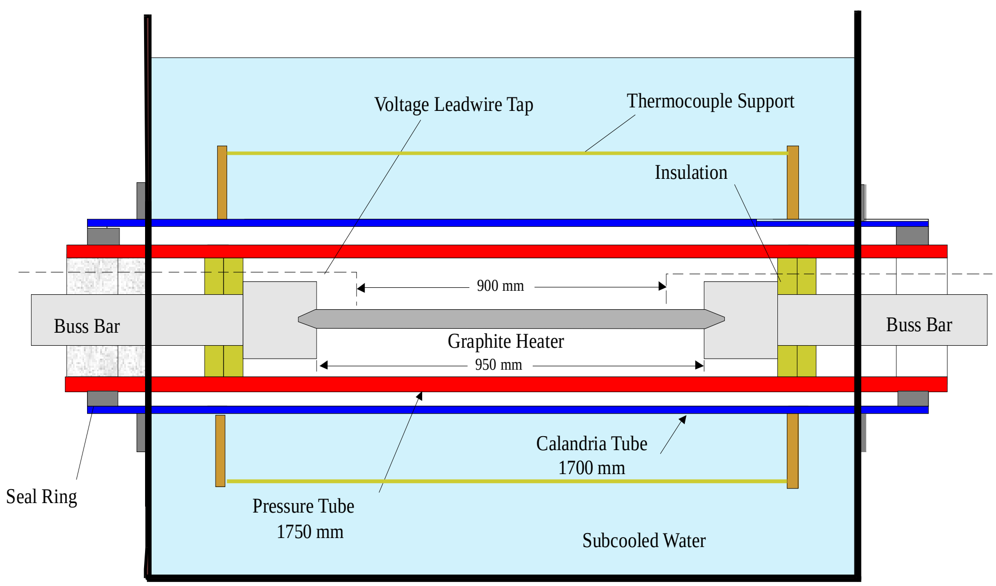

Figure 1   A simplified schematic of PT/CT contact experiment facility (Reference [4])

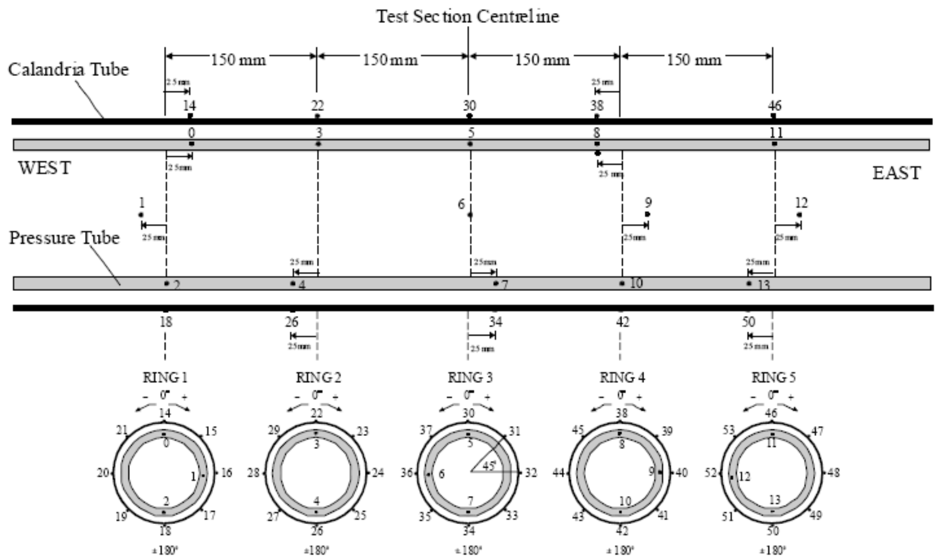

Figure 2   Demonstration of thermal couple arrangement for PT/CT contact experiment (Reference [4])

2. Methodology

The PT ballooning is essentially a plastic PT deformation with significant PT temperature increase. With high PT temperatures, the PT yield stress decreases significantly, which would result in the PT diameter increase after the onset of strain which can be described using creep equations. The measurement and modelling on the yield stress of pressure tube material (Zr-Nb%2.5) have been performed elsewhere (References [6] and [7]) and the dependence of the yield stress of Zr-Nb%2.5 alloy on the material temperature is shown in Figure 3, Figure 4 and Figure 5.

The results in Figure 3, Figure 4 and Figure 5 indicate that the yield stress of the PT material decreases with temperature. Above 600ºC, the transverse yield stress decreases to below 100MPa and above 800ºC the value decreases to around 10MPa for a given strain rate. These results imply that for a given internal pressure (or applied transverse stress) the PT temperature must be sufficiently high to render a transverse yield stress low enough the applied hoop stress for the PT to have significant strain and to balloon plastically. Thus, for a given internal pressure, there is a minimum PT temperature for the PT to have onset of ballooning and this temperature has been termed PTBT in Reference [8]. Based on the results in Figure 3, Figure 4 and Figure 5 and the experimental results in References [1] to [4], the temperatures at which the PTs begin to balloon for different PT pressures (PTBT) are determined as following for PT pressure between 1MPa to 5MPa

$$PTBT = -38.35P + 822 \qquad (1)$$

where *PTBT* is in *ºC* and *P* is the PT pressure in *MPa*. In Reference [8], it has been proved that the average hoop stress in the PT before ballooning is same as the average hoop stress in the PT and CT after PT/CT contact, which implies that Equation (1) is applicable to CT after PTCT contact.

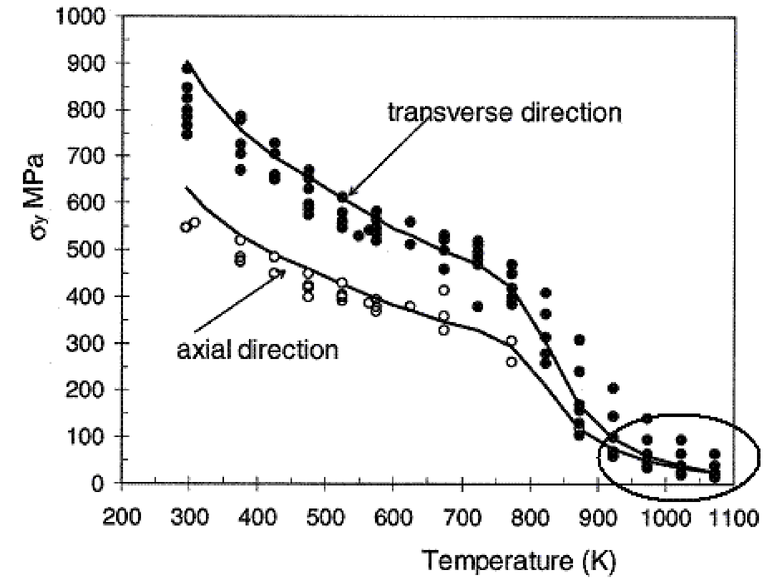

Figure 3 Dependence of the Zr-Nb%2.5 yield stress on absolute temperature for pressure tube material tested in the axial and transverse directions (Figure 8(a) in Reference [6]).

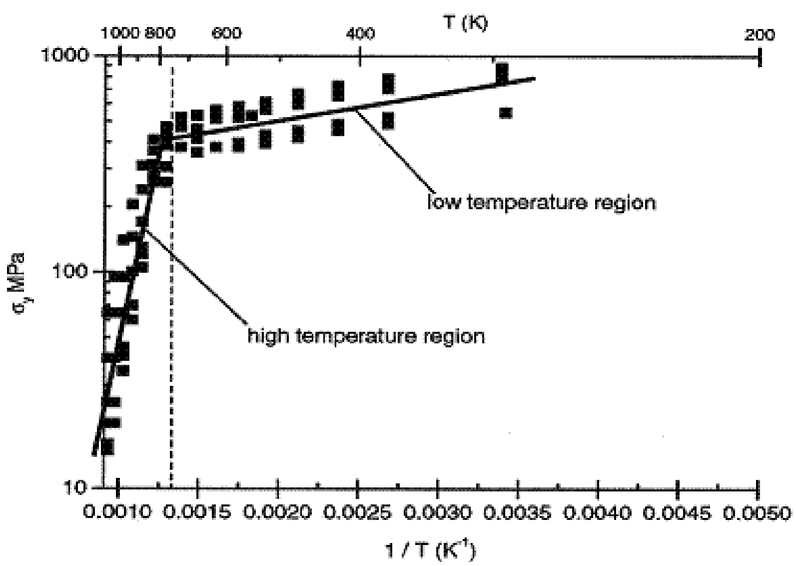

Figure 4 Dependence of the Zr-Nb%2.5 yield stress on the inverse of absolute temperature (Figure 9 in Reference [6])

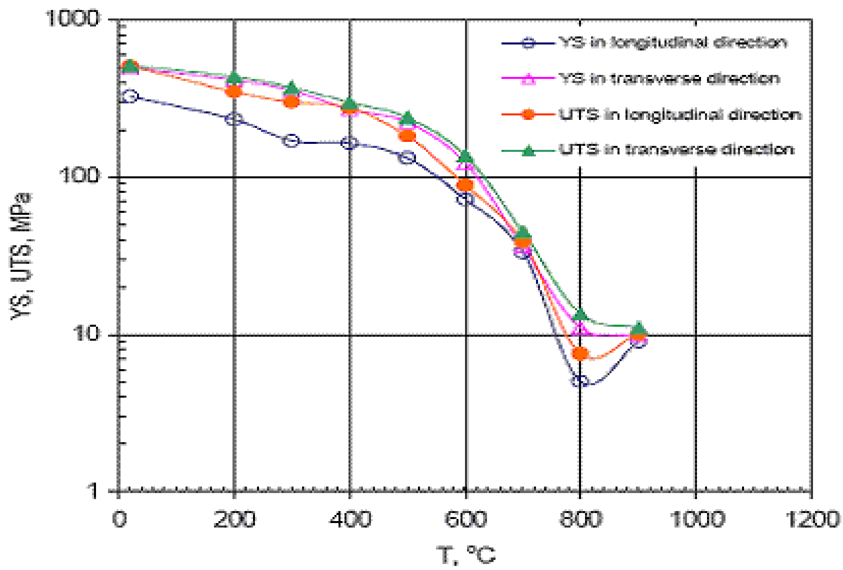

Figure 5 Zr-2.5%Nb alloy temperature dependence of yield strength (YS) and ultimate strength (UTS) (Figure 2(a) in Reference [7])

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 H_r and a PT pressure of P_r, the CT dryout area is only a function of the moderator subcooling of ΔT_r. 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 term obtained by adding these impacts to the actual moderator subcooling (AMS) is termed as equivalent moderator subcooling (EMS).

3. Development of EMS Methodology

3.1 Technical Basis for EMS

After PT/CT contact, it is assumed that the percentage dryout area on the CT surface can be calculated using the following equation

$$A_{DO} = \frac{q_{CHF} - q}{q_{CHF} - q_{MFB}} \qquad (2)$$

where A_{DO} is the dryout area, q_{CHF} is the critical heat flux, q is the actual heat flux on the CT outer surface and q_{MFB} is the heat flux corresponding to the minimum film boiling temperature. Generally q_{MFB} is much smaller than q_{CHF}, thus Equation (2) can be approximated as

$$A_{DO} \approx 1 - \frac{q}{q_{CHF}} \tag{3}$$

Thus to keep same dryout area, the following condition should be met

$$\frac{dq}{q} = \frac{dq_{CHF}}{q_{CHF}} \tag{4}$$

Upon PT/CT contact, heat is transferred from the high temperature PT to the low temperature CT and the heat transfer equations can be written as following

$$\rho C_p \frac{\partial T_{PT}}{\partial t} = \lambda \left(\frac{1}{r} \frac{\partial T_{PT}}{\partial r} + \frac{\partial^2 T_{PT}}{\partial r^2} \right) \tag{5}$$

$$\rho C_p \frac{\partial T_{CT}}{\partial t} = \lambda \left(\frac{1}{r} \frac{\partial T_{CT}}{\partial r} + \frac{\partial^2 T_{CT}}{\partial r^2} \right) \tag{6}$$

with boundary conditions of

$$\begin{aligned} r = r_1, &\quad -\lambda \left(\frac{\partial T_{PT}}{\partial r} \right)_{r=r_1} = q_1 \\ r = r_2, &\quad -\lambda \left(\frac{\partial T_{PT}}{\partial r} \right)_{r=r_2} = -\lambda \left(\frac{\partial T_{CT}}{\partial r} \right)_{r=r_2} = D\left(T_{PT} - T_{CT}\right) \\ r = r_3, &\quad -\lambda \left(\frac{\partial T_{CT}}{\partial r} \right)_{r=r_3} = h\left(T_{CT} - T_M\right) \end{aligned} \tag{7}$$

In the above equations, t denotes time, q_1 denotes heat flux at the inner PT surface, T_{PT}, T_{CT} and T_M denote the temperature of the PT, CT and the moderator, λ, ρ and C_p denote thermal conductivity, density and specific heat of PT and CT, D denotes contact thermal conductance between the PT inner surface and the CT outer surface, r_1, r_2 and r_3 denote the radii of PT inner surface, PT outer surface (or CT inner surface) and the CT outer surface, h denotes the heat transfer coefficient between the CT and the moderator. The PT/CT upon contact is shown in Figure 6.

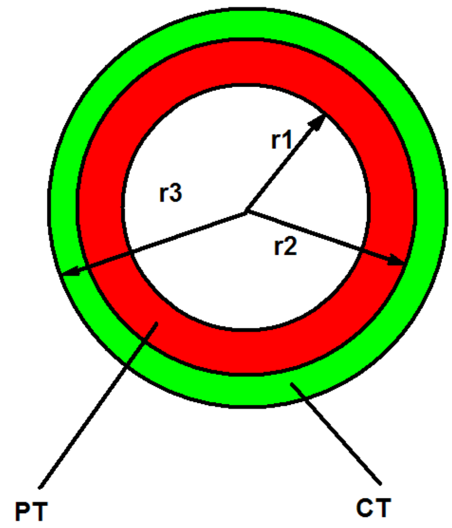

Figure 6 Demonstration of PT/CT contact

When the CT temperature reaches the maximum, the CT temperature changing rate will be zero or close to zero and the PT temperature decreasing rate will also be small. Thus the heat transfer process from the PT to CT will be close to the steady state process and the average heat flux is close to the heat flux at the outer surface of the CT. The steady state heat transfer equation between the PT and the CT upon PT/CT contact can be calculated as

$$\Delta T = \frac{Q}{2\pi\lambda}\ln\frac{r_2}{r_1} + \frac{Q}{2\pi\lambda}\ln\frac{r_3}{r_2} + \frac{Q}{2\pi D r_2} \qquad (8)$$

Thus the heat flow from PT to CT and then to the moderator per unit length of PT, Q, can be written as

$$Q = \frac{\Delta T}{\frac{1}{2\pi\lambda}\ln\frac{r_2}{r_1} + \frac{1}{2\pi\lambda}\ln\frac{r_3}{r_2} + \frac{1}{2\pi D r_2}} \qquad (9)$$

And the heat flux at the outer surface of the calandria tube can be written as

$$q = \frac{Q}{2\pi r_3} = \frac{(T_{PT})_{r=r_1} - (T_{CT})_{r=r_3}}{\frac{r_3}{\lambda}\ln\frac{r_2}{r_1} + \frac{r_3}{\lambda}\ln\frac{r_3}{r_2} + \frac{r_3}{D r_2}} \qquad (10)$$

Usually the initial CT temperature is slightly above the moderator temperature and does not change significantly for different cases. Thus as per Equation (10) the heat flux from the PT to the CT and then to the moderator is mainly influenced by the initial PT temperature and PT/CT contact thermal conductance after PT/CT contact.

As per References [9] and [10], the relationship between the critical heat flux and moderator subcooling can be written as

$$q_{CHF} = q_{CHF0}\left[1 + \chi \times AMS\right] \tag{11}$$

where q_{CHF} is the critical heat flux, q_{CHF0} is the critical heat flux in saturation fluid, χ is a coefficient determined by the state of the moderator and AMS is the actual moderator subcooling. Substituting Equations (10) and (11) for q and q_{CHF} in Equation (4), the following equation can be obtained

$$\frac{d(T_{PT})}{T_{PT} - T_{CT}} + \frac{dD}{\frac{D^2 r_2}{\lambda}\ln\frac{r_2}{r_1} + \frac{D^2 r_2}{\lambda}\ln\frac{r_3}{r_2} + D} = \frac{\chi d(AMS)}{(1 + \chi \times AMS)} \tag{12}$$

Equation (12) shows that to keep same dryout area on CT surface, any change in the moderator actual subcooling corresponds to a change in the PT temperature or a change in the PT/CT conductance or both.

The PT temperature upon PT/CT contact is controlled by three factors: the temperature for the PT to begin to balloon (*PTBT*), the PT ballooning time to contact the CT (t_{bl}) and the average PT heat up rate (H_{PT}). For a given pressure, the PT temperature upon PT/CT contact can be calculated using following equation

$$(T_{PT})_{t=0} = PTBT + H_{PT}t_{bl} \tag{13}$$

As per Reference [8], the PTBT decreases with PT pressure and is not impacted by the PT heatup rate. In addition, based on the observation of the PT/CT contact experiments, it is discovered that with same PT pressure, the PT ballooning times, i.e. the time periods from the moment the PT begins to balloon until the PT/CT contact, do not differ significantly from each other, which implies the ballooning time is mainly determined by the PT pressure. Thus for a given PT pressure, the PT temperature upon the contact is a linear function of the PT heatup rate.

The changes in the PT/CT thermal contact conductance are determined by PT pressure, and the temperature of the pressure tubes and calandria tubes. The detailed mechanism is not very clear. However based on the observation of the experimental data, it is expected that for the temperature ranges of the pressure tube and calandria tube, the initial PT/CT thermal conductance mainly changes with PT pressure at the initial contact period.

Based on Equation (12) and (13) and the discussions above, it is considered that with every 1ºC/s of increase in PT heatup rate for a given PT pressure, an increase of γ ºC in moderator subcooling is needed to keep the dryout area unchanged, where γ is assumed to be a constant for the given PT pressure and may also be considered a constant for the PT pressure ranges used in PT/CT experiments approximately.

The impact of the PT pressure is more complicated since it impacts the PTBT value, PT ballooning time and PT/CT contact thermal conductance at the same time. Thus it is assumed that every 1ºC increase in moderator subcooling for a given PT heatup rate will need a certain amount of PT pressure increase to keep the same dryout area and this value is a function of pressure but may be independent of PT heatup rate. Based on the observation on the experiment results, a parabolic curve will be used.

Based on the assumptions discussed above, after a reference PT heatup rate and a reference PT pressure are chosen, the EMS with the reference parameters for any case can be obtained after correcting the PT heatup rate and PT pressure to the reference values. The EMS is written as

$$EMS = AMS + B_2(P^2 - P_r^2) + B_1(P - P_r) + C(H - H_r) + E \qquad (14)$$

where EMS is the Equivalent Moderator Subcooling with reference PT pressure of P_r and reference PT heatup rate of H_r, 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.

3.2 EMS for Smooth CTs

As per the results of experiments 6, HP3, SC3, SC5, SC8 and SC11 for smooth CTs whose dryout areas are less than 10% and the PT pressures are around 3.5MPa which are considered same, the relationship between the moderator subcooling and PT heatup rate is shown graphically in Figure 7. In the considered heatup rate range and moderator subcooling range, the moderator subcooling increases linearly with the PT heatup rate as

$$AMS = 0.8488H + 15.247 \qquad (15)$$

It should be noted the nominal PT test pressure in Test 6 and Test HP3 is 4MPa which is a bit higher than 3.5MPa, but it is assumed the impact on the results is limited and can be ignored. Equation (15) can be differentiated as

$$\left(\frac{\partial AMS}{\partial H}\right)_{P=3.5MPa} = 0.8488 \qquad (16)$$

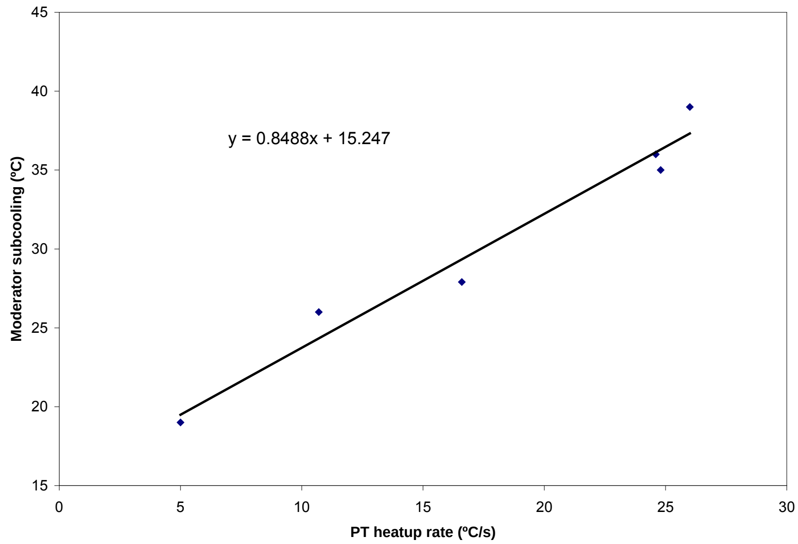

Figure 7 Relationship between moderator subcooling and PT heatup rate for smooth calandria tube with CT dryout area less than 10% and PT pressure around 3.5MPa.

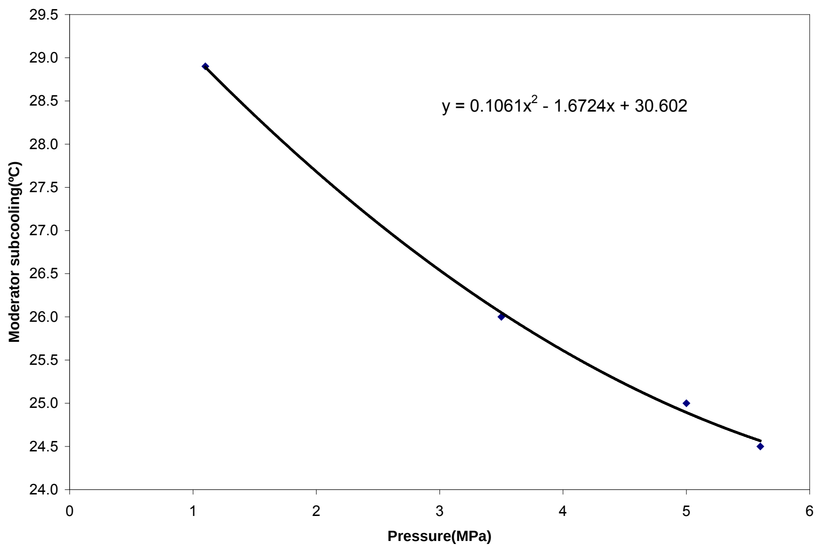

Figure 8 Relationship between moderator subcooling and PT pressure for smooth calandria tubes with CT dryout area less than 10% and PT heatup rate around 10.5ºC/s.

As per the results of experiments 18, HP9, 6M3 and SC11 for smooth CTs whose dryout areas are less than 10% and the PT heatup rates are around 10.5ºC/s, the relationship between the moderator subcooling and PT pressure is shown in Figure 8.

In the pressure range and moderator subooling range considered, the moderator subcooling decreases linearly with PT pressure as

$$AMS = 0.1061P^2 - 1.6724P + 30.602 \qquad (17)$$

In Equation (17), the unit pressure is in MPa. It should be noted that the nominal heatup rates in all these tests deviate from 10.5ºC/s, but it is expected the impact of the tiny difference can be ignored. Equation (17) can be differentiated as

$$\left(\frac{\partial AMS}{\partial P}\right)_{H=10.5C/s} = 0.2122P - 1.6724 \qquad (18)$$

Although the maximum PT pressure when deriving Equations (16) and (18) are 5.5MPa, it is assumed this correlation can be used to the cases with PT pressure up to 8.5MPa.

In the previous discussions, it is assumed that Equation (16) should be independent of PT pressure and Equation (18) should be independent of PT heatup rate. If these assumptions are reasonable, for two different cases with same CT dryout area and same AMS values, there should be a trade-off between the PT pressure change and PT heatup rate change meeting the requirement of Equations (16) and (18). For example, as per the results of experiments D1 and HP12 whose dryout areas are less than 10% and the moderator subcoolings are around 28.3ºC, the relationship between the PT heatup rate and the PT pressure is shown in Figure 9.

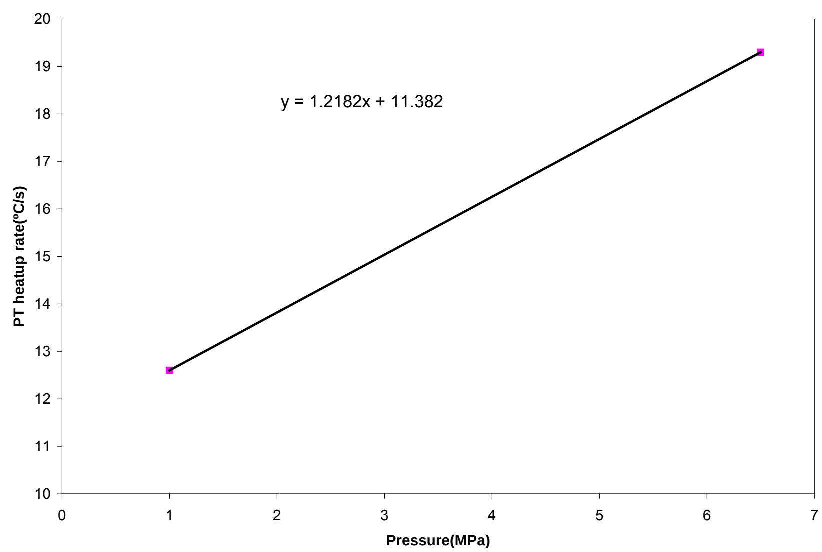

Figure 9 Relationship between PT heatup rate and PT pressure for smooth calandria tubes with CT dryout area less than 10% and moderator subcooling of 28.3ºC.

In the PT pressure and heatup rate ranges, the PT heatup rate increases with PT pressure as

$$H = 1.2182P + 11.382 \qquad (19)$$

In the selected experiment data, the dryout area of the CT are less than 10% and considered sufficiently small to assume that the average heat flux to the moderator is close to the CHF at the outer surface of the CT. Equation (19) can be differentiated as

$$\left(\frac{\partial H}{\partial P}\right)_{AMS=28.3C} = 1.2182 \tag{20}$$

Equations (19) and (20) demonstrates that at the moderator subcooling of 28.3ºC, increasing the PT pressure by 1MPa will require the PT heatup rate to increase by 1.22ºC/s to keep the similar small dryout area, i.e., to keep the same heat flux to the moderator. Since Equations (19) and (20) are obtained using only 2 points, the results may only be sufficiently accurate for the point with average pressure of the two points. The average pressure of the two points is (1MPa + 6.5MPa) / 2 = 3.75MPa and at this point for similar dryout areas, the product of Equations (16), (18) and (20) is approximately -1, i.e.,

$$\begin{aligned}&\left(\frac{\partial AMS}{\partial H)}\right)_{P=3.5MPa} \times \left(\frac{\partial P}{\partial AMS}\right)_{H=10.5C/s} \times \left(\frac{\partial H}{\partial P}\right)_{AMS=28.3C} \\ &= 0.8488 \times (-1.1407) \times 1.2182 \\ &= -1.182 \approx -1\end{aligned} \tag{21}$$

Equation (21) confirms the reasonableness of Equations (16) and (18) and increases the confidence to apply them for further analysis. In addition, although Equations (16), (18), and (20) are obtained using data along single lines of constant pressure, constant PT heatup rates and constant AMS for small CT dryout area, it is expected that these equations can be applied to all other PT pressures, PT heatup rates and AMS values and for higher CT dryout areas with sufficient accuracy. Thus the existing experimental data for smooth CT tubes are manipulated to obtain the EMS value for smooth CTs based on Equations (14), (16) and (18) as following after correcting the PT pressure and PT heatup rate to 3.5MPa and 25ºC/s respectively.

$$EMS_{SCT}(AMS, H, P) = AMS - 0.1061(P^2 - 3.5^2) + 1.6724(P - 3.5) - 0.85(H - 25) \tag{22}$$

Equation (22) implies that for PT/CT experiments, whenever the EMS values are same, the dryout area should be same or close for smooth CTs. 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 10. The relationship between the CT dryout area and the EMS for all the qualified smooth CT experiment data are shown Figure 11. Figure 10 indicates that although the dryout area has a tendency to increase with the decrease of AMS, but the tendency is not obvious due to the wide data band. Figure 11 indicates that except SUBC9 and SUBC10, most of the smooth calandria tube data abide by Equation (22) very well. It should be noted here that Tests 16 and 17 in which the heater power was turned off as soon as PT/CT occurred and Test F1 in which the heat power was turned off before PT/CT contact fully occurs were excluded from Figure 10 and Figure 11 and will not be discussed in this work.

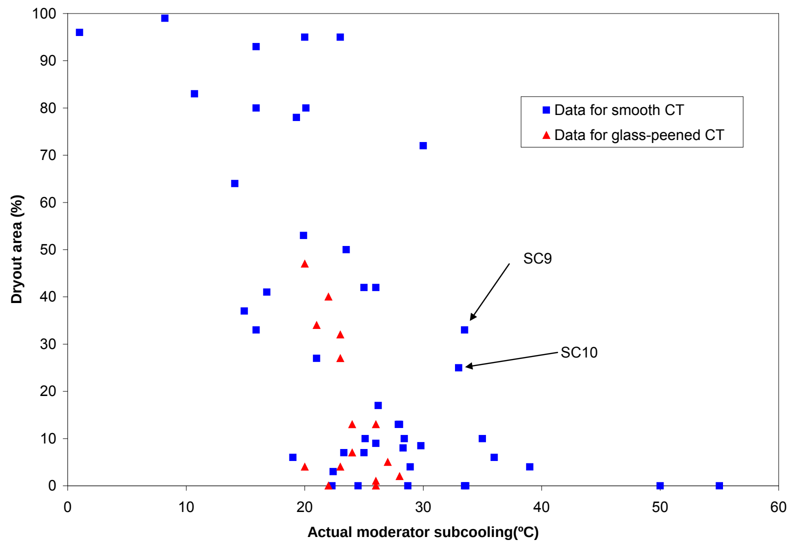

Figure 10 The CT dryout area versus the AMS for the smooth and glass-peened CT experimental data

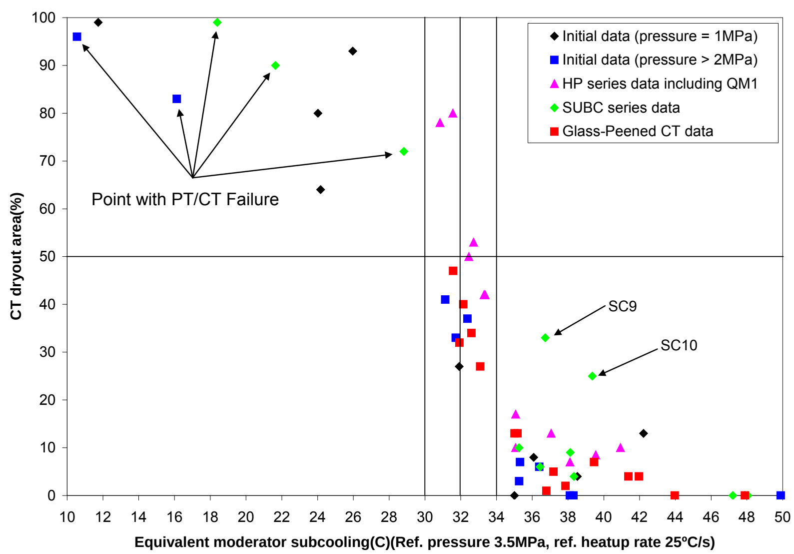

Figure 11 The CT dryout area versus the equivalent moderator subcooling for the smooth and glass-peened CT experimental data

3.3 EMS for Glass-Peened CT

To relax the requirement to the moderator subcooling to prevent fuel channel failure from happening upon PT/CT contact, glass-peened CTs have been developed (References [3] and [4]). The purpose of the glass-peened CT is to increase the critical heat flux on the tube surface in comparison with the smooth calandria tubes. Considering the critical heat flux on the surface of a smooth calandria tube is a linear function of the actual moderator subooling, it is expected the critical heat flux on the surface of a glass-peened calandria tubes may follow the similar rule. However, due to the increase in the CHF value for a glass-peened calandria tube surface, a smaller moderator subcooling is expected to be required to keep the same CHF as that for a smooth calandria tube. Since PT pressure and heatup rate impact the PT temperature upon PT/CT contact and contact thermal conductance, but not the CHF per se, it is expected that to keep same dryout area, a constant additive equivalent subcooling value should be added to that obtained using Equation (22). Based on the examination on the experimental results for the smooth calandria tube and the glass-peend calandria tube, the requirement is expected to be 9ºC which implies Equation (22) can be updated to the following for glass-peened calandria tubes:

$$EMS_{GCT}\left(AMS, H, P)\right) = EMS_{SCT}\left(AMS, H, P\right) + 9 \qquad (23)$$

The dryout area versus EMS for the glass-peened CT determined using Equation (23) is also shown in Figure 11. After Equations (22) and (23) are applied, the dryout areas are same or close for smooth tubes and glass-peened tubes which have same EMS values. Figure 11 indicates that the glass-peened tube results are along the left edge of the narrow data band. A comparison between Figure 10 and Figure 11 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 on CT dryout area. The range of EMS for same dryout area above 10% is decreased to 4 to 5ºC and if the results of SC9 and SC10 are excluded, the range is only 2ºC which is far smaller than the 20ºC range demonstrated in Figure 10. This comparison confirms that the methodology of EMS is effective and the required moderator subcooling to prevent dryout can be reduced by 9ºC after using the glass-peened CTs to replace the smooth CTs.

After the actual PT parameters (heatup rate and pressure) have been corrected to the reference values, the impacts of the differences in these parameters on the CT dryout area are expressed in term of EMS and the CT dryout area is only a function of the EMS. If more experiments are performed with the reference PT pressure P_r, reference PT heatup rate H_r in a moderator with different AMS values, the obtained CT dryout areas should be same as or close to those shown Figure 11 with an EMS value equal to the AMS used in the new experiment.

4. Relationship between the Maximum CT temperature and EMS

Figure 11 also indicates when the EMS value is higher than 32ºC, the dryout area of the CT surface is expected to be less than 50%. Based on this figure, the following relationship is assumed in order to make the change smoothly but still reflect the large changing gradient of the dryout area versus EMS between 30 and 34ºC.

$$A_d = 100, \quad EMS < 30\,^{o}C$$

$$A_d = 50 + 50\sin\left[\frac{\pi}{4}\left(32 - EMS\right)\right], \quad 30^{o}C \le EMS \le 34\,^{o}C \qquad (24)$$

$$A_d = 0, \quad EMS > 34\,^{o}C$$

In Equation (24), A_d is dryout area in percent and the equation is demonstrated in Figure 12.

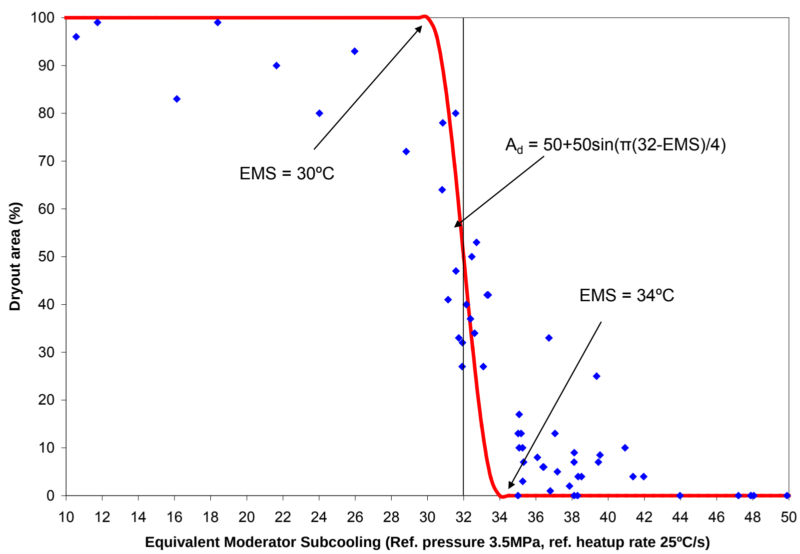

Figure 12: Demonstration of correlation between CT dryout area and EMS

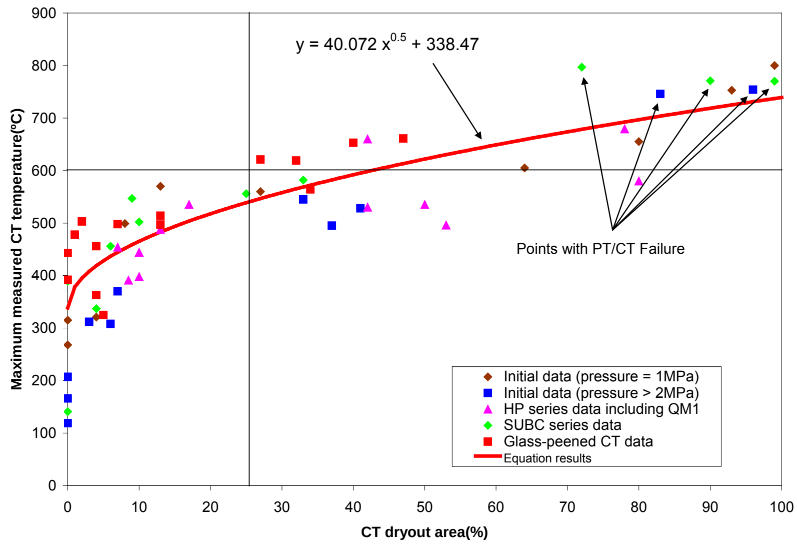

Figure 13 Relationship between maximum CT temperature versus dryout area of CT surface

The relationship between the maximum CT temperature and the CT dryout area for both the smooth CT and glass-peened CT is shown in Figure 13 which indicates that when CT dryout area is smaller than 25% the maximum CT temperature will be smaller than 600ºC. As per Equation (1), when the maximum CT temperature is below 600ºC for PT pressure below 8.5MPa, the CT tube will not balloon locally and the integrity of the fuel channel will not be jeopardized. In other words, if the EMS with reference PT pressure of 3.5MPa and referent PT heatup rate of 25ºC/s is higher than 34ºC and the PT pressure is below 8.5MPa, it is highly probable that the fuel channel integrity can be ensured, though detailed analysis might be needed to confirm the conclusion.

The maximum measured CT temperatures for cases with CT dryout, i.e., dryout area is larger than zero, are correlated to CT dryout areas as shown in Figure 13 and the correlation is written as

$$T_{CT} = 40.072 A_d^{0.5} + 338.47 \qquad (25)$$

The relationship between the maximum CT temperature and the AMS is shown in Figure 14 which indicates that the maximum CT temperature is rather scattering versus AMS. The relationship between the maximum CT temperature and the EMS is shown in Figure 15 which indicates that after applying the EMS, the changing tendency of the maximum CT temperature versus EMS is more obvious.

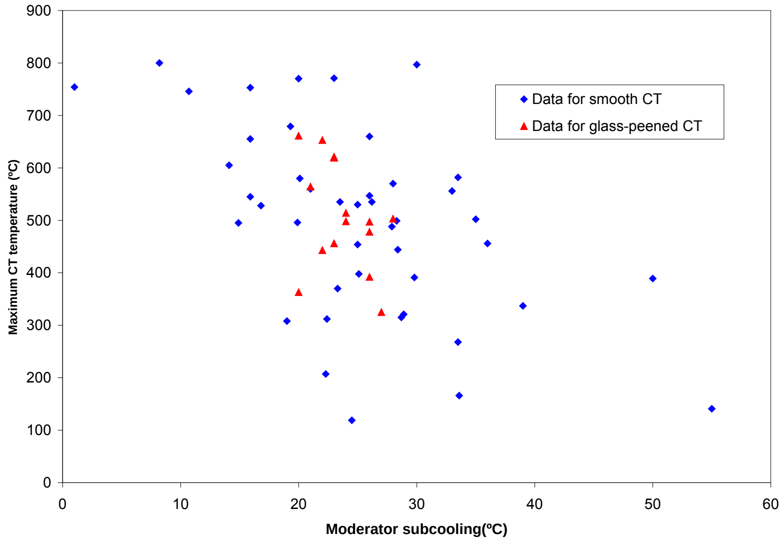

Figure 14: Relationship between maximum CT temperature and AMS

Based on Equations (24) and (25), the relationship between the maximum CT temperature and EMS can be obtained and shown in Figure 15. To be conservative to predict the maximum CT temperature and to accommodate the large uncertainty in Equations (24) and (25) as shown in Figure 12 and Figure 13, another 35% of dryout area is imposed on the results obtained using Equation (24) and the obtained maximum CT temperature is also shown in Figure 15 which indicates that the updated Equation can envelope most of the experiment data. The addition of the 35% of dryout area is used to empirically cater for the impact of the non-uniformity in the CT temperature and dry patch distributions on the CT surface, though a dryout area higher than 100% does not have any physical meaning.

Figure 15 also indicates that above 30ºC of EMS with reference PT pressure of 3.5MPa and reference PT heatup rate of 25ºC/s, the maximum measured CT temperature has a tendency to decrease with the increase of EMS, but when the EMS value decreases to below 30ºC, the maximum measured CT temperature tends to be independent of the EMS. In addition, Figure 11 to Figure 15 also indicate that all the five failure cases where the PT pressures are 2.0MPa and 3.6MPa respectively has an EMS value smaller than 30ºC and dryout area higher than 50% and maximum measured CT temperature higher than 750ºC. The integrity of the fuel channel can be kept in two ways. The first way is that the CT is sufficiently cold and no local ballooning occurs and the second way is that the CT may begin to balloon locally, but the the CT rewet before the whole channel is ruptured. For example, according to Equation (1), with PT pressure of 2MPa, the ballooning temperature of the CT is 745ºC and the CT rewet time for this case is 258s, thus the failure of these channels before rewet could occur.

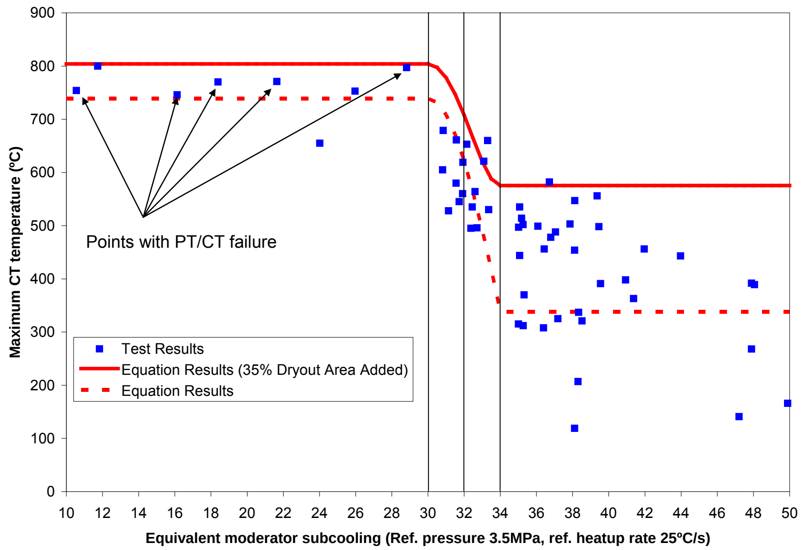

Figure 15: Relationship between maximum CT temperature and EMS

5. Safety Boundary for Fuel Channel Integrity

The relationships between the CT rewet time and dryout area (i.e., the time for CT temperature above 220ºC) for cases without PT/CT failure is shown in Figure 16. The relationship between CT rewet time and EMS for cases without PT/CT failure are shown in and Figure 17. The relationship between CT rewet time and the EMS for EMS higher than 34ºC is shown in Figure 18.

Figure 11, Figure 15 and Figure 18 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. In the patchy dryout region, the rewet time is not sensitive to the change in the EMS value. 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. 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. This is mainly because boiling remains in the transition boiling region for a prolonged time and is not stable. Any perturbation to the experiment condition will either quench the boiling quickly or lead to a sustained film boiling quickly.

Based on the above discussion, it is observed that (a) with EMS higher than 34ºC, the controlling boiling mechanism on the CT surface is nucleate boiling with a small dryout area, low CT temperature and short rewet time, (b) with EMS lower than 30ºC, the controlling mechanism on the CT surface is sustained film boiling with a high dryout area, high CT temperature and long rewet time and it is risky to operate in this region and (c) with EMS between 30 and 34ºC, a more detailed and careful analysis needed in this region and sensitivity of the fuel channel integrity to the channel condition must be performed. Therefore, if it is technically feasible, it is strongly recommended that to ensure the EMS values of the fuel channel to be higher than 34ºC for fuel channel integrity. Considering the only controllable parameters in design are the moderator subcooling and CT surface condition, it is recommended that sufficient low AMS value is applied or a glass-peened CT is used or both.

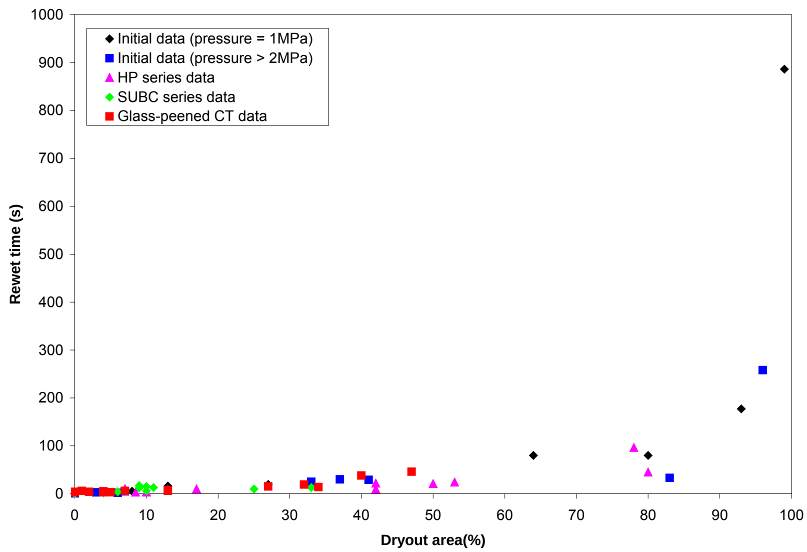

Figure 16: Relationship between CT rewet time and CT dryout area

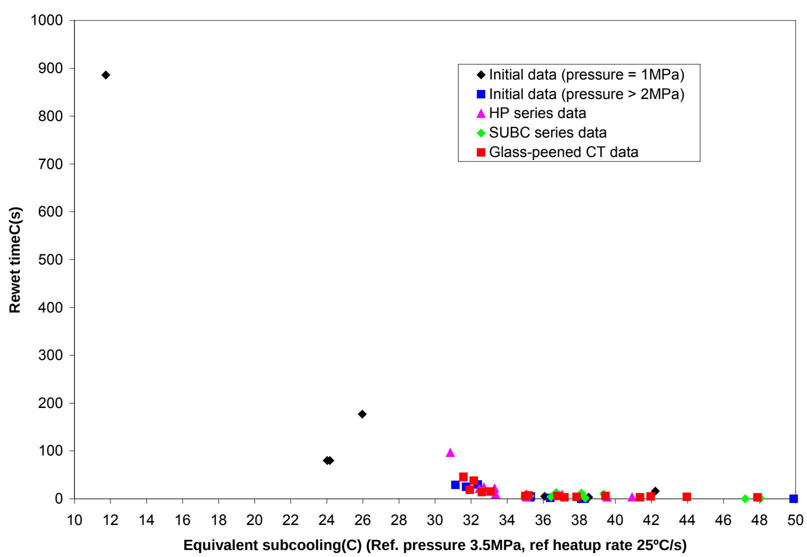

Figure 17: Relationship between CT rewet time and EMS

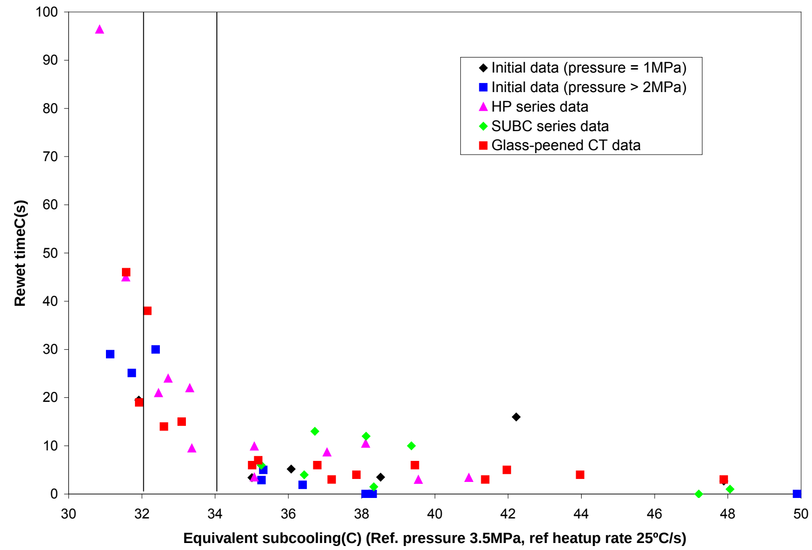

Figure 18: Relationship between CT rewet time and EMS for EMS higher than 30ºC

6. Sensitivity to Local Effect

In Figure 11, the results of SC9 and SC10 do not agree with Equation 22 and 23 very well. One of the reasons could be that the energy distribution around the CT wall is not uniform either in the axial direction, or in the circumferential direction or both. This non-uniformity can be caused by a lot of reasons, such as the non-uniformity in the PT heatup rate at different points, the non-uniformity in the PT/CT contact thermal conductance, the high density and high temperature gas trapping at the top of the channel, or the tiny non-uniformity in the PT and CT surface conditions.

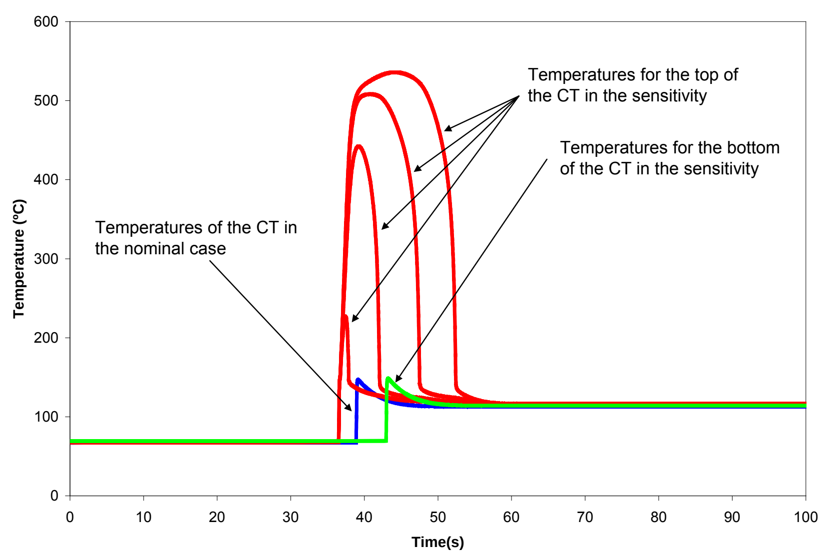

Figure 19: CT temperatures for the simulation of SC10 in both nominal case and sensitivity case

After comparing the dryout maps of Tests SC9 and SC10 to those of HP series tests, it is discovered that the dry patches in tests SC9 and SC10 are more concentrated at the top of the channel, while the dry patches of HP series of experiments are spread more uniformly. This implies that in Tests 9 and 10, the energy is more concentrated at the top and a local sustained boiling dry patch is formed, which will make the dryout area bigger and the maximum CT temperature higher than the case when the energy is uniformly spread around the channel. If only the top part of the fuel channel is considered, the EMS values for SC9 and SC10 will be smaller. Since too many factors may contribute to this energy non-uniformity, it is hard to determine which one is functioning. To understand the impact of non-uniformity in energy distribution, Test SC10 is simulated using CATHENA (Reference [11]) following the methodology recommended in Reference [5], with the exception that (a) the Modified Berenson film boiling correlation is used for film boiling simulation without using any correction factor (b) the PT/CT contact thermal conductance of 14.3kW(m^2·C) is used (c) the heat source is simulated with heat flux boundary condition at the inner surface of the PT to match up the PT heatup rate. Two cases are simulated. The first one has a uniform PT heatup rate at the nominal value. The second one has a 10% higher heatup rate at the top area (25% of the total area) and 10% lower heatup rate at the bottom area (25% of the total area) with the average heatup rate identical to that of the first case. The simulation results are shown in Figure 19 which demonstrates that although the nominal case does not show any dryout, the sensitivity case shows dryout and much higher CT temperature though both of the two cases have same average PT heatup rate, same AMS and same PT pressure. However, the dryout quenched very soon (within 15 seconds) and the maximum CT temperature is still below 600ºC. In safety analysis, it is recommended that the extent of the non-uniformity in energy distribution should be considered in sensitivity analysis. Since the energy in the high temperature area can be transferred to the cold area and dissipated to the moderator, it is expected the dryout can still be quenched very soon before any potential fuel channel failure occurs.

It should be noted that in the reactor with large LOCA event, when the fluid flowing through the fuel channel is steam only, the non-uniformity in energy distribution will be much less severe than that met in the experiment. This is because in the large LOCA event, the steam is still flowing to the break with a significant speed and the force convection effect will dominate the free convection, while in the experiments, the major heat transfer coefficient between the gas (helium or argon) and the PT is free convection and it is very easy to form a large temperature gradient from top to bottom. Thus the situation met in safety analyses will not be worse than the experiments and it is conservative to judge fuel channel integrity based on the criteria determined using experimental data. The ballooning of PT in the experiments is never uniform and this process uncertainty always makes the fuel channel rupture more easily. In addition, in the reactor event, the pressure tube begins ballooning at a higher pressure which will yield a lower contact temperature and after the contact occurs, the PT pressure has decreased to a lower value which will yield a lower PT/CT contact conductance. These factors will make the actual EMS value higher than the case where PT ballooning is caused by a constant pressure, thus the experiment results can cover the safety analysis situation.

7. Conclusions

Based on the discussions on the experimental PT/CT contact data for both smooth CTs and glass-peened CTs with different experimental conditions, the following conclusions are drawn.

Firstly, a concept of equivalent moderator subcooling is put forward. A correlation is obtained to calculate the EMS values based on the AMS value, the PT pressure and the PT heatup rate. This correlation is obtained using some experimental data with CT dryout areas less than 10% and is confirmed applicable to cases with different PT heatup rates, different PT pressures, different AMS values and different CT dryout areas. Based on the observation on the PT/CT experimental results including CT rewet time, maximum measured CT temperatures and CT dryout areas, an empirical correlation to calculate the maximum CT temperatures using the corresponding EMS values is also proposed. The correlation can be used to calculate the maximum CT temperatures conservatively.

Secondly, with the calculated EMS values with reference PT heatup rate of 25ºC/s and reference PT pressure of 3.5MPa for different experiment conditions, three dryout regions are identified: patchy dryout region with EMS higher than 34ºC, sustained dryout region with EMS lower than 30ºC and transition dryout region with EMS between 30ºC and 34ºC. In the patchy dryout region, the dryout area is below 25%, the maximum CT temperature is below 600ºC and the CT rewet time is shorter than 15s. Thus the EMS value of 34ºC (reference PT heatup rate of 25ºC/s and reference PT pressure of 3.5MPa) is considered as a safety boundary for fuel channel integrity upon PT/CT contact. For PT pressure below 8.5MPa, the integrity of the fuel channel can be ensured in the patchy dryout region upon PT/CT contact with EMS value higher than 34ºC. In determining analysis or new experiment cases if necessary, the cases within the transition dryout region should be paid more attention to since the CT dryout area, CT temperature and CT rewet time are very sensitive to the EMS change in this region. In the sustained dryout region, the fuel channel may rupture with PT pressure above 1 MPa.

Thirdly, some potential causes that make a couple of experimental data deviate from the EMS correlation are discussed. The impact of the one of the causes is demonstrated by performing numerical correlations and the results indicate that the deviations in the experimental results from the correlation are not surprising.

Fourthly, based on the EMS concept, it is proved that the improvement of the moderator subcooling requirement to prevent dryout can be 9ºC after using the glass-peened calandria tubes to replace the smooth calandria tubes based on the existing experiment information.

Finally, the experimental results are expected to envelope the transients that may be met in reactor events including the impacts of the process uncertainties. Thus if the EMS value calculated in the reactor transients is higher than 34ºC (reference PT heatup rate of 25ºC/s and reference PT pressure of 3.5MPa), the fuel channel integrity can be ensured and no detailed safety analysis is necessary.

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