EXPLORATION OF PRESSURE TUBE BALLOONING TEMPERATURE

L. Sun
Point Lepreau Generating Station, PO Box 600, Lepreau, NB, Canada E5J 2S6

Abstract

During postulated event of large LOCA with Loss of ECI in CANDU reactors, the pressure tube may balloon to contact with its surrounding calandria tube to transfer heat to the moderator. The integrity of the fuel channel 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, many experiments have been performed in the last three decades. In this work, the available PT/CT contact experiments data were collected and analyzed to determine the temperatures at which the pressure tube begins to balloon when different internal pressures are applied. The obtained data was correlated to internal pressure linearly. By assuming the pressure tube material and calandria tube material have similar mechanical properties, the obtained correlation may be applicable to calandria tubes in judging the integrity of the fuel channel when the calandria tube temperature is known.

1. Introduction

During the postulated accident of large loss of coolant (LOCA) with loss of emergency coolant injection (ECI) 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 (Reference [1]). Recently, more experiments data were obtained at both high internal pressures and high heater powers (Reference [2]). Some experiments for the CTs which have been glass-peened were also performed recently (Reference [3]). A schematic of the experiment facility and the arrangement of thermal couples are shown in Figure 1 and Figure 2 (from Reference [2]). A summary of the significant experiment results are documented in Reference [1]. 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 to analyze the integrity of the fuel channel after the PT/CT contact with the input of available moderator subcooling (Reference [4]).

The objective of this work is to explore the PT and CT ballooning temperatures with different PT pressures. The available PT/CT contact experiments data were collected and analysed.

The temperatures at which the PT begins to balloon with different PT pressures were determined and termed PTBT. The PTBT data was correlated to PT pressure linearly. Assuming the PT and CT materials have similar thermal and mechanical properties, the obtained correlation may also be used to determine the temperature at which the CT begins to balloon, termed CTBT. It is expected that the fuel channel integrity can be ensured if the maximum CT temperature is lower than the CTBT with the corresponding PT pressure.

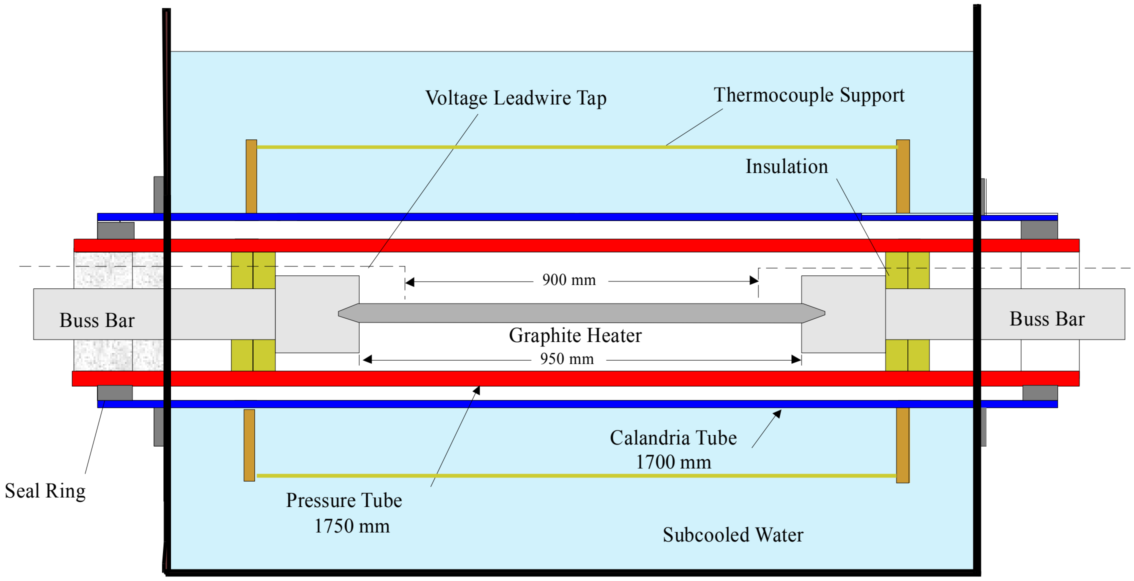

Figure 1 A simplified schematic of PT/CT contact experiment facility (Reference [2])

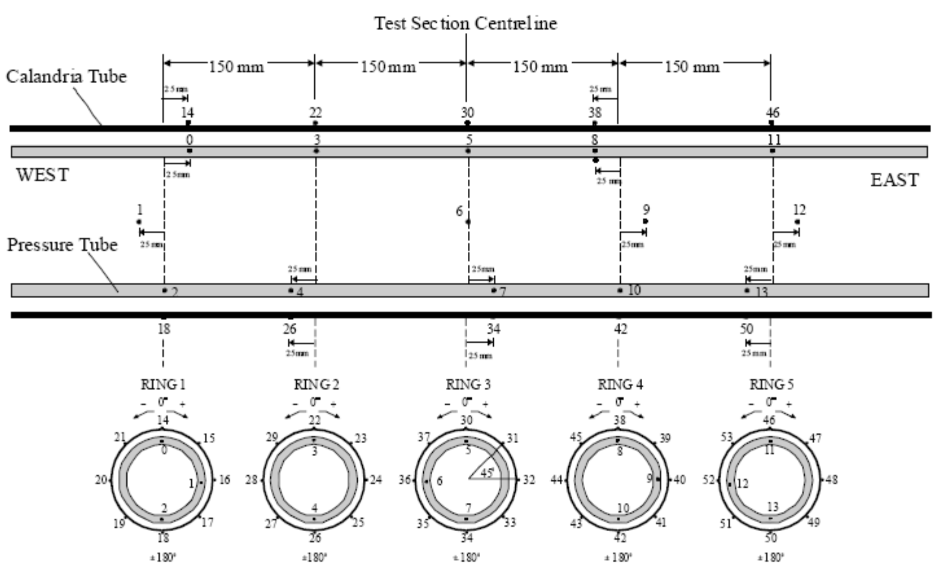

Figure 2 Demonstration of thermal couple arrangement for PT/CT contact experiment (Reference [2])

2. Methodology

In essence, the PT ballooning is a plastic deformation of the tube when the stress in the transverse direction exceeds the yield stress and the PT diameter is increased during ballooning. The measurement and modelling on the yield stress of pressure tube material (Zr-Nb%2.5) have been performed elsewhere (References [5] and [6]) and the dependence of the yield stress of Zr-Nb%2.5 alloy on the material temperature is demonstrated in Figure 3, Figure 4 and Figure 5.

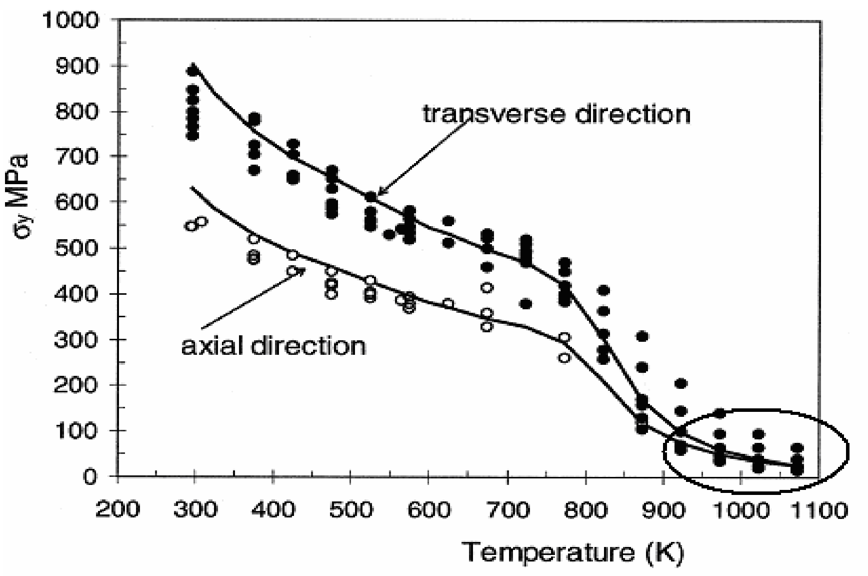

Figure 3 Dependence of the Zr-Nb%2.5 yield stress on absolute temperature for pressure tube material tested in the axial and transverse directions (Figure 8(a) in Reference (5)).

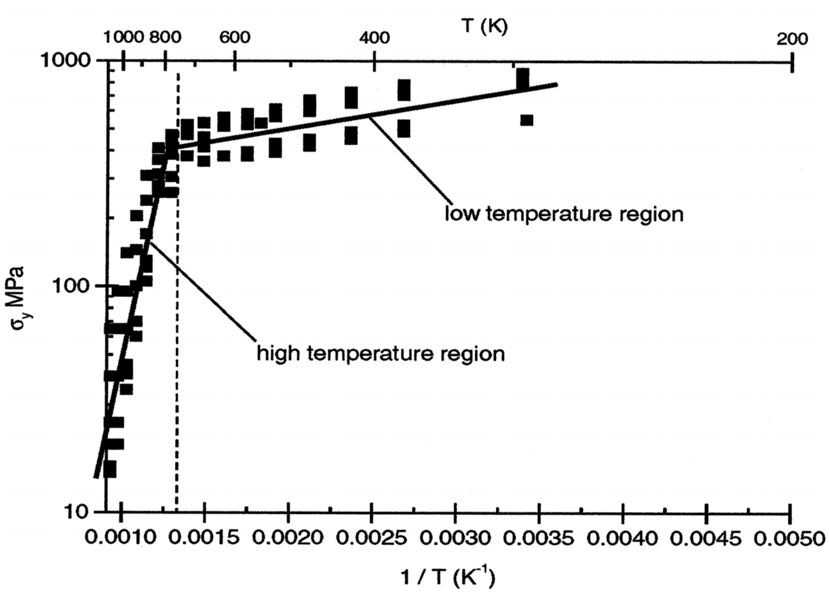

Figure 4 Dependence of the Zr-Nb%2.5 yield stress on the inverse of absolute temperature (Figure 9 in Reference [5])

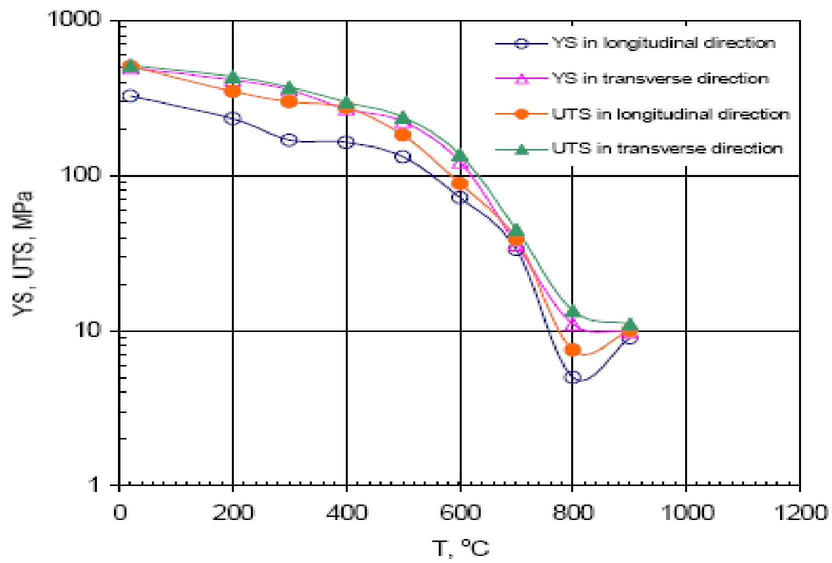

Figure 5 Zr-2.5%Nb alloy temperature dependence of yield strength (YS) and ultimate strength (UTS) (Figure 2(a) in Reference [6])

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. 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 smaller than the applied hoop stress for the PT to balloon plastically. Thus, for a given internal pressure, there is a minimum PT temperature for the PT to start a plastic ballooning and this temperature has been termed PTBT above.

When the PT temperature increases to the PTBT value the PT begins to balloon plastically. If the heatup rate changes to zero after the ballooning process starts, the PT/CT contact temperature will be equal to the PTBT, though it may take a much longer time for the contact to occur. If there is a temperature increase in the PT, the PT/CT contact temperature will be higher than the PTBT, as the cases in all the existing PT/CT experiments. It is very unlikely for the PT temperature to decrease after the PT ballooning begins. Thus when the heatup rate is zero, the PT/CT contact temperature must be the lowest contact temperature among all the cases with different heatup rates and equals to the temperature at which the PT begins to balloon with the applied internal pressure, i.e., equals to the PTBT. Based on this, when the PT/CT contact temperature can be determined when the heatup rate is zero, the temperature at which the PT begins to balloon with a given internal pressure can be determined. Since it is not practical to perform PT/CT experiments with a zero heatup rate and there is no such an experiment in existence, the following methodology will be applied in this work based on the experiment results documented in References [1], [2] and [3]:

(1) Determine the control parameters in the PT/CT contact experiments. In the experiment results documented in References [1], [2] and [3], the major control parameters involved are: heat power which is expressed as heatup rate of the PT, internal

pressure, maximum and minimum PT temperatures after contacting the CT, maximum CT temperature and moderator subcooling.

(2) Search the data with similar internal pressure (within ±0.2MPa) but with different PT/CT contact temperatures and PT heatup rates. In References [1], [2] and [3], only the maximum and the minimum contact temperatures are given, so the average PT/CT contact temperature is calculated as the average of these two values. Actually in experiments, the contact temperatures were measured at many locations in both peripheral and axial directions of the pressure tube (See Figure 2), thus the actual average contact temperature may be a bit different from that obtained from this work. At the same time the PT temperature was measured at half way of the PT wall and CT temperature is measured at outer surface and the temperature differences across the walls are not taken into account in this work. In addition, the heatup rate is provided by the cited references.

(3) Find the relationship between the PT/CT contact temperature and the heatup rate based on the experimental results. Since the heatup rate reflects the magnitude of the heating power, thus a higher heatup rate should produce a higher contact temperature assuming that the uncertainty in measurement and the uncertainty in the transient process are similar in same series of tests. Altogether, the contact temperature data with four different PT pressures were correlated versus the heatup rates.

(4) Extrapolate the obtained correlations and find the value of the contact temperature at the zero heatup rate. This value is the temperature at which the PT begins to balloon with the corresponding internal pressure, i.e., after the pressure tube begins to heat up from the initial temperature in the experiments (close to moderator temperature), the ballooning will not happen until the pressure tube temperature reaches the corresponding PTBT.

(5) Correlate the obtained PTBT values versus pressure to find their relationship.

(6) Assuming that the mechanical properties of the CTs are similar to that of the PTs, the obtained PTBT correlation may be applied to the CTs to determine the CT ballooning temperature, i.e., the CTBT.

(7) Compare the maximum CT temperature in each experiment to predicted CTBT to confirm if there is a pressure tube failure with the maximum CT temperature larger than the CTBT.

3. Results

The relationship between the PT/CT contact temperature and the heatup rate has been determined for the internal pressures around 1MPa, 3.6MPa, 4MPa and 5MPa respectively by performing a linear correlation as

$$T_c = CH + D \tag{1}$$

Where the T_c is the PT/CT contact temperature and H is the heatup rate of the pressure tube and C and D are correlation constants.

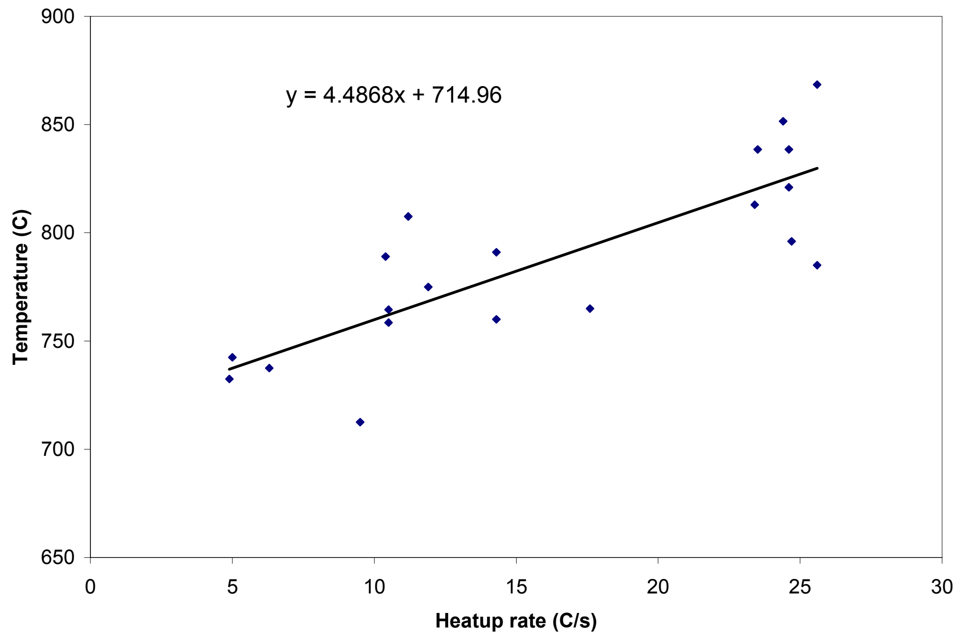

Figure 6 Relationship between average contact temperatures vs. heatup rates with internal pressures around 4.0MPa

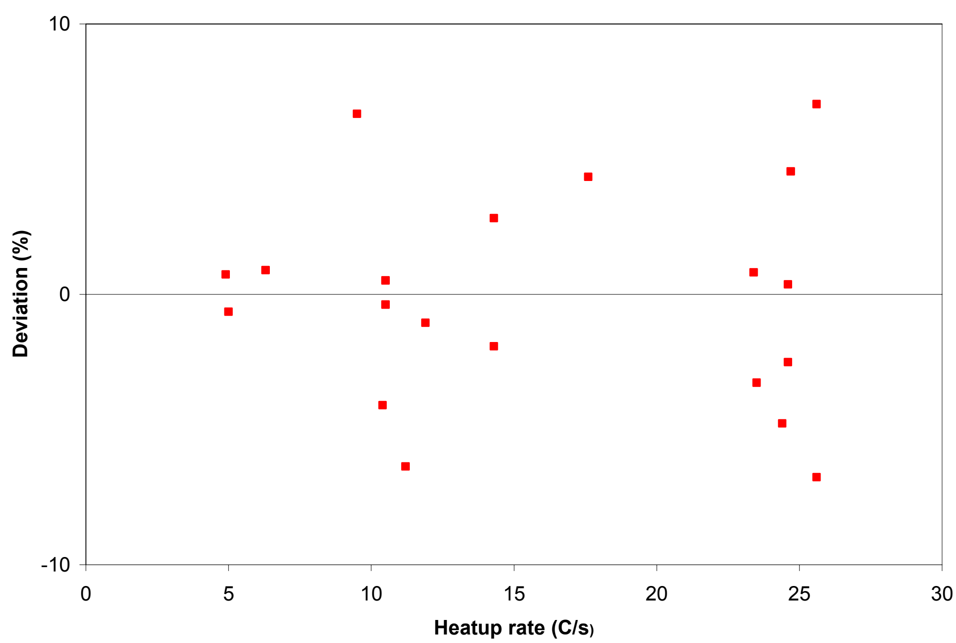

Figure 7 Deviations of data from linear fit of contact temperatures vs. heatup rates for internal pressures around 4.0MPa

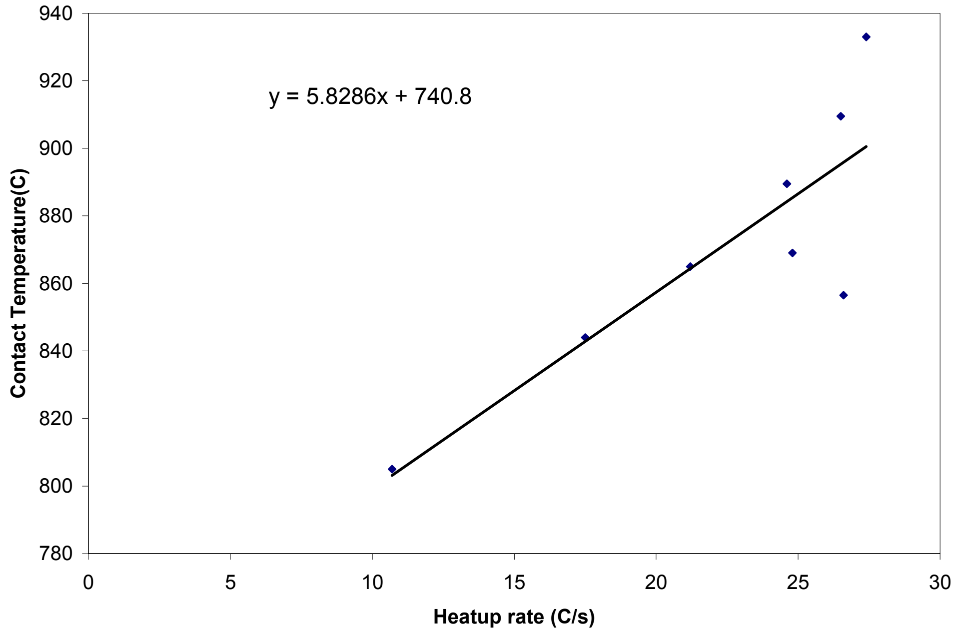

Figure 8 Relationship between average contact temperatures vs. heatup rates with internal pressures around 3.6MPa

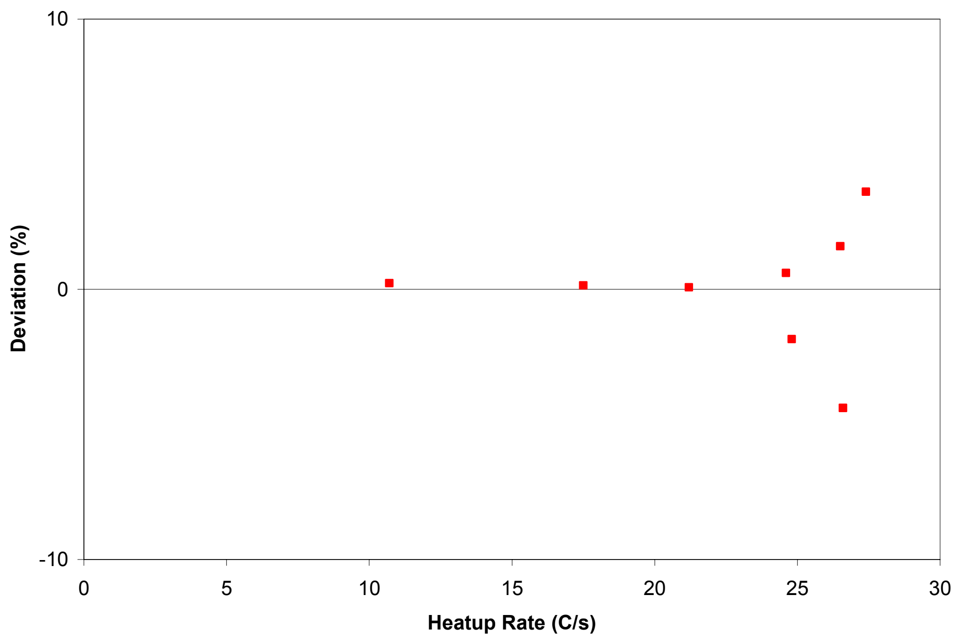

Figure 9 Deviations of data from linear fit of contact temperatures vs. heatup rates for internal pressures around 3.6MPa

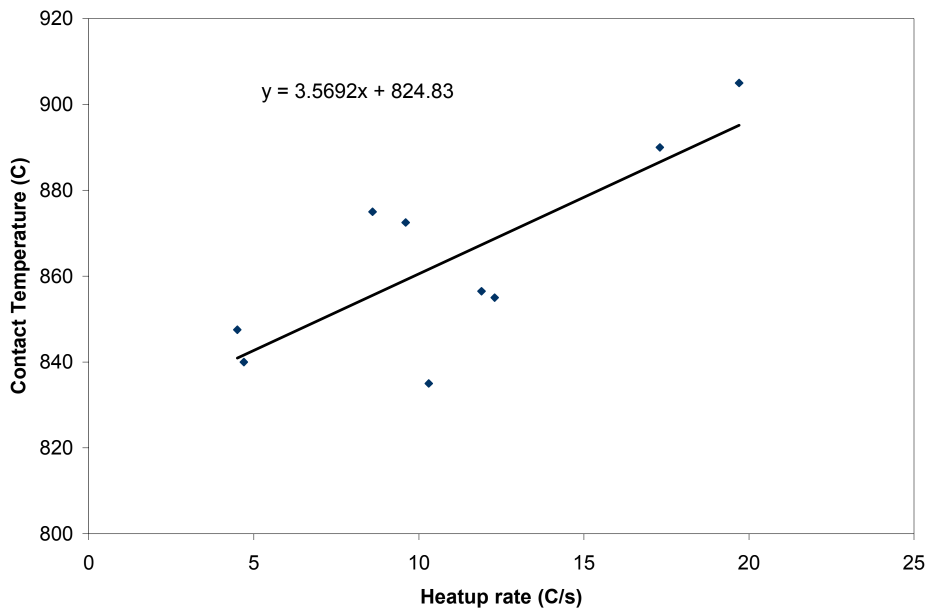

Figure 10 Relationship between average contact temperatures versus heatup rates with internal pressures around 1.0MPa

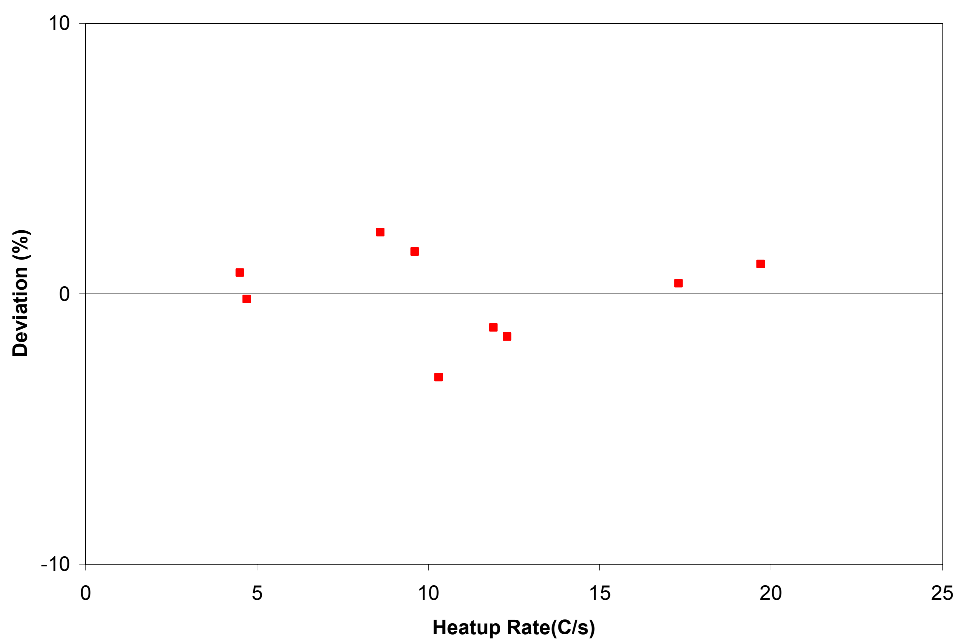

Figure 11 Deviations of data from linear fit of contact temperatures vs. heatup rates for internal pressures around 1.0MPa

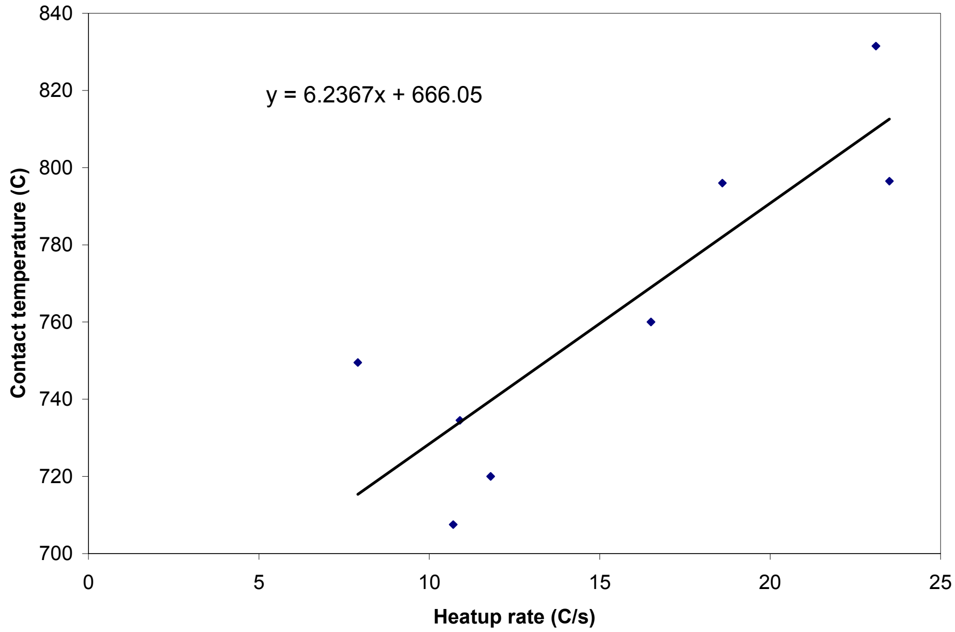

Figure 12 Relationship between average contact temperatures vs. heatup rates with internal pressures around 5.0MPa

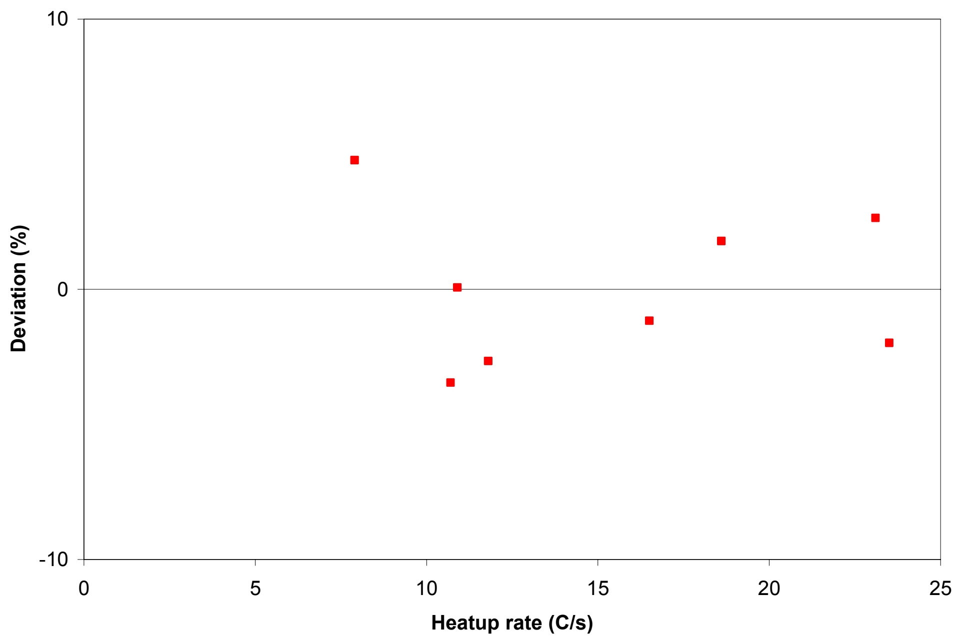

Figure 13 Deviations of data from linear fit of contact temperatures vs. heatup rates for internal pressures around 5.0MPa

The linear fit of the PT/CT contact temperatures versus pressure tube heatup rates with different internal pressures and the deviations of the contact temperatures from the linear fit are shown in Figure 6 to Figure 13. It should be noted that a few points in the database which seem abnormal in comparison with most data points were precluded when determining the correlation. The figures indicate that maximum deviation of experiment data from Equation (1) is smaller than 10%.

Based on Equation (1), the PT/CT contact temperature has a tendency to change linearly with the heatup rate. When the heatup rate is decreased to zero, the PT/CT contact temperature will be the intercept of the straight line, *D*, and considered the minimum temperature for the PT to balloon, i.e., the PTBT corresponding to the internal pressure. Considering the uncertainty in measurements and in the transient process, the values of *D* were modified by subtracting the maximum deviation in the PT/CT contact temperature data from Equation (1) among all PT pressure cases. In this way, the pressure tube will balloon at a lower temperature than predicted by Equation (1). The modified values of *D* for different internal pressure have been correlated linearly as Equation (2)

$$PTBT = EP + F \tag{2}$$

Where *PTBT* and *P* denote pressure tube ballooning temperature and pressure, and *E* and *F* are correlation constants. The correlation is shown in Figure 14 graphically. The deviation of the data from the correlation is shown in Figure 15 which indicates that the maximum deviation in the obtained *PTBT* data from Equation (2) is less than 3%.

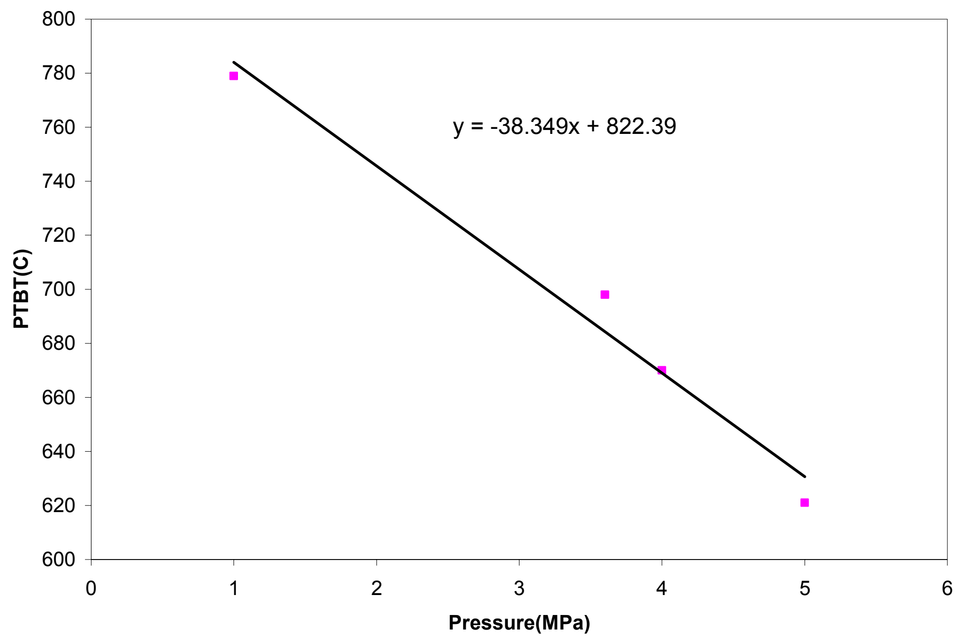

Figure 14 Relationship between pressure tube ballooning temperatures vs. internal pressures

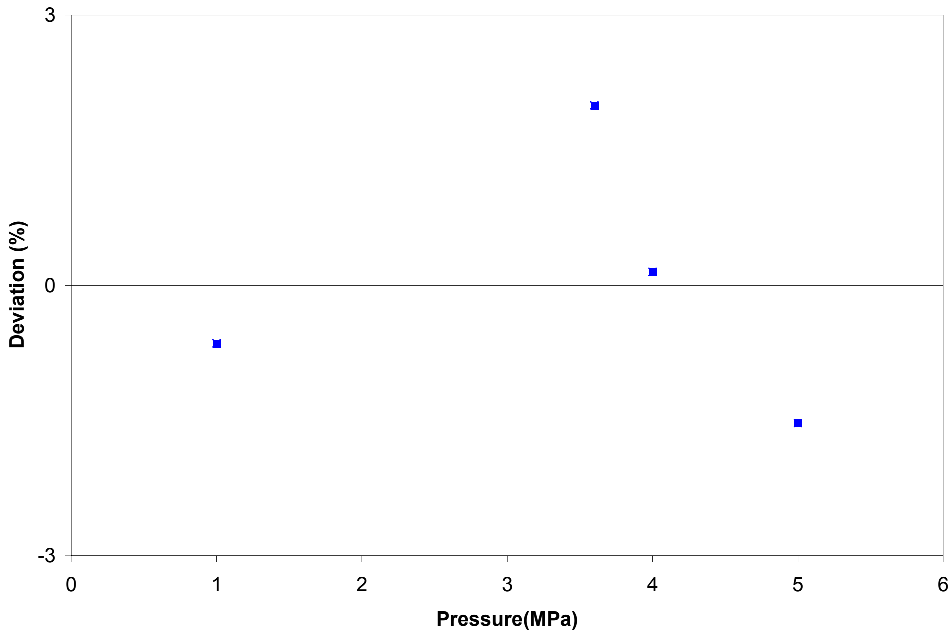

Figure 15 Deviations of pressure tube ballooning temperatures from linear fit vs. pressures

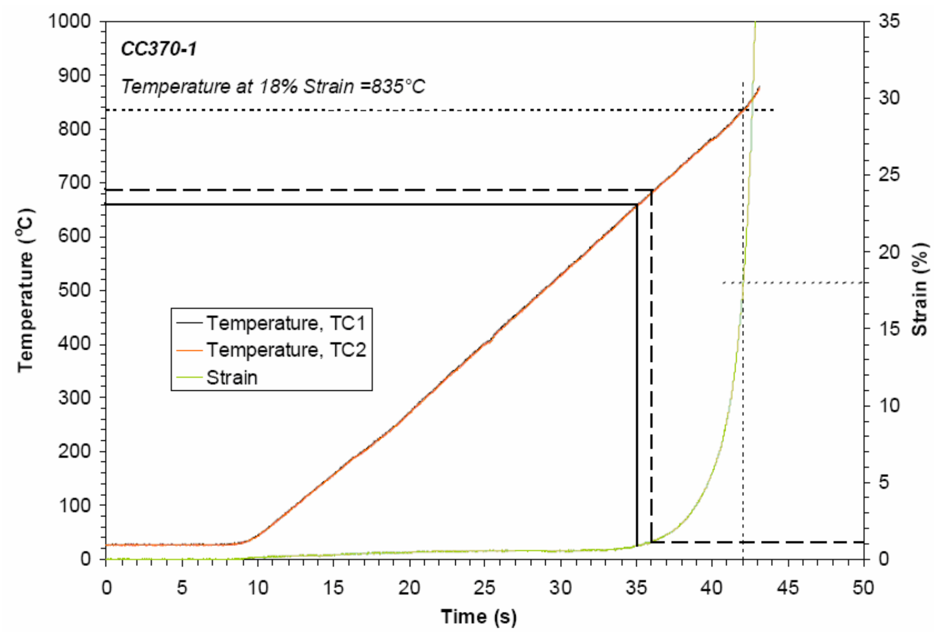

Figure 16 Measured temperatures and strains for sample CC370-1 (Figure C1 in Reference [7], and the thick dashed lines were added for discussion of this work)

The results of PTBT with internal pressure of 3.6MPa are a big higher than the temperature results obtained in Reference [7] for PT material begins to yield, where uni-axial creep tests were performed. The test specimens used in the tests are same with the pressure tube samples used in Tests SUBC4 to SUBC7 (See Reference [2]). In the tests, initial stresses were applied to the specimens, which were identical to the stresses exerted by the PT internal pressure in

SUBC tests, and heated up with heatup rates same as those in the SUBC tests. The temperatures and strains of the specimens at different moments were recorded. For demonstration, Figure C-1 from Reference [7] is shown in Figure 16. Referring to the thick dashed line added for the discussion of this work, it can be seen that when the pressure temperature is as high as 685ºC which is calculated using Equation (2), the strain in the material is around 1% and the strain rate after this point increases markedly. This figure indicates that the temperatures for the pressure tube material begins to yield obtained from these experiments (see the solid line) are a bit lower than those calculated using Equation (2), as shown in Figure 14, but not significantly.

4. Discussion on fuel channel integrity after PT/CT contact

The results in Section 3 indicate that at a given internal pressure, if the PT temperature is below the PTBT, there is no need to worry about the subcooling requirement of the moderator and the fuel channel integrity can be ensured since the PT will not balloon plastically at all.

When the PT balloons to contact its surrounding CT, there is a huge temperature difference between the PT and CT, thus there is a dramatic heat transfer between the PT and CT in a short time. Considering the thickness of the PT is almost twice of that of the CT at contact, one degree of decrease in the PT temperature may cause two degrees of increase in CT temperature considering more than 97% of the PT and CT materials are zirconium and they may have similar specific heat. Subsequently, the CT will transfer the heat to its surrounding moderator fluid.

If the heat transfer coefficient between the CT and the moderator is large, the CT temperature will drop subsequently to a lower value and the temperature of the PT will recover a bit due to the increase in contact thermal resistance caused by the temperature decrease in PT temperature. But the temperature of the PT will not get back to the PT/CT contact temperature since heat is being transferred to the CT and then to the moderator. If the heat transfer coefficient between the CT and the moderator is small, the temperature in the CT may drop a little at the beginning but will then increase again or be kept at a higher stable value close to that of the PT and so will the temperature in the PT. Thus the temperatures of the PT and the CT may be very close to each other.

In the former case where the heat transfer coefficient between CT and moderator is high, the CT temperature may drop to a lower value in time and the CT yield strength may be sufficiently high to stand the internal pressure. In the latter case where the heat transfer coefficient between CT and the moderator is low, both the PT and the CT may continue to balloon and therefore is more limiting in perspective of ensuring fuel channel integrity. When the pressure tube begins to balloon, the stress in the pipe is considered to exceed the yield stress at that temperature. Thus, the yield stress can be determined at five different PTBT values as following:

$$\sigma_s = \frac{\left(D_{pi} - 2t_{pi}\right)P}{2t_{pi}} \tag{3}$$

Where σ_s is the ballooning stress of the PT material at PTBT, D_{pi} and t_{pi}, are outer diameter and thickness of the PT before ballooning. The relationship between the determined pressure tube ballooning stresses and temperatures is shown in Figure 17. The results are similar to the literature results demonstrated in Figure 3, Figure 4 and Figure 5 (References [5] and [6])

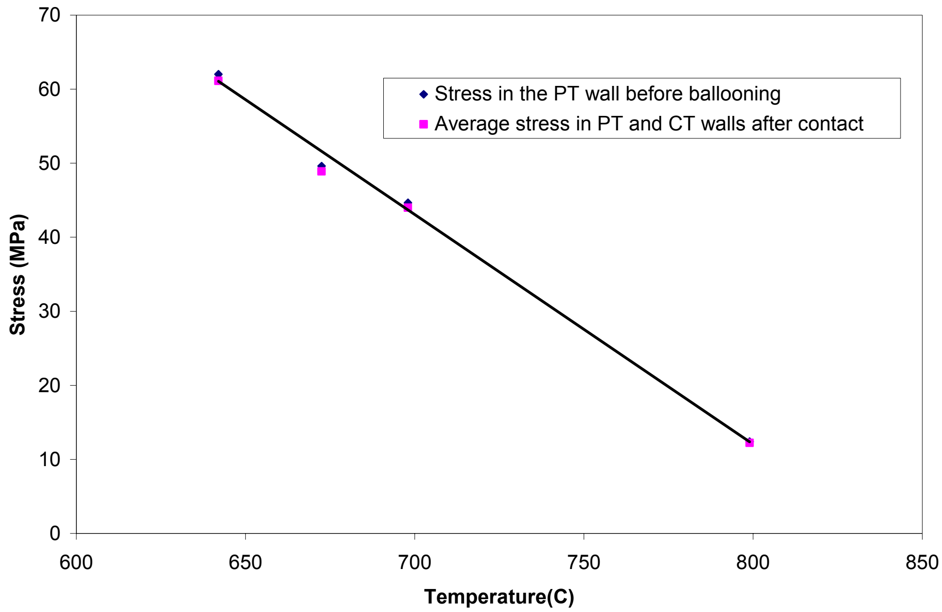

Figure 17 Pressure tube hoop stresses before and after ballooning contact

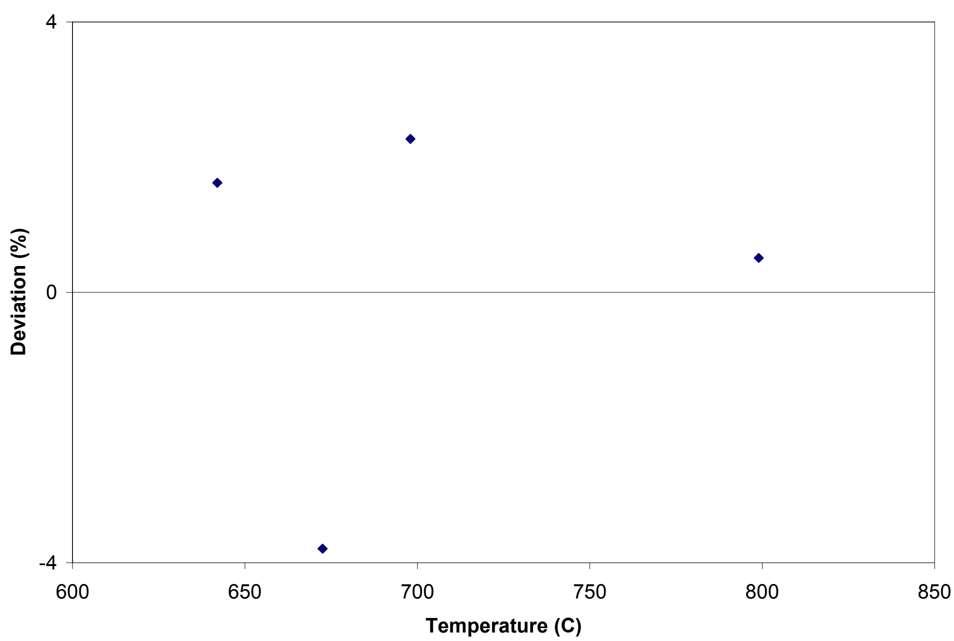

Figure 18 Deviation of the ballooning stress from the linear fit

Asumming that the PT and the CT materials have similar mechanical properties and that the PT and the CT contact with each other closely and have close temperatures, the ballooning stresses of the PT and the CT materials are similar and the internal pressure will be stood by both the PT and the CT at the same time. The assumption that the PT and CT have similar temperature is very pessimistic since this implies the heat transfer coefficient between the CT and the moderator is very small.

The initial outer diameter and thickness of the PT are denoted as D_{pi} and t_{pi}, the outer diameter and thickness of the PT when contact occurs are denoted as D_{pc} and t_{pc}, and the initial inner diameter and thickness of the CT are denoted as D_{ci} and t_{ci}. Assuming the volume of the PT does not change before and after contact and considering D_{pc} equals to D_{ci}, the thickness of the PT after contact can be calculated as

$$t_{pc} = \frac{1}{2} D_{ci} - \frac{1}{2}\sqrt{D_{ci}^2 - D_{pi}^2 + \left(D_{pi} - 2t_{pi}\right)^2} \tag{4}$$

With the obtained diameter and thickness of the PT at contact, the average stress exerted on the PT wall and CT wall are calculated as

$$\sigma_a = \frac{P\left(D_{ci} - 2t_{ci}\right)}{2\left(t_{pc} + t_{ci}\right)} \tag{5}$$

Based on the above calculations, it is discovered that after PT/CT contact, the average hoop stress of the PT and the CT walls do not change from the stress in the PT wall when ballooning begins which is calculated using Equation (3), as shown in Figure 17. The average stress almost changes linearly with temperature and the deviation from the linear fit is less than 4% as shown in Figure 18. This result implies that provided the maximum CT temperature does not exceed the PTBT at the corresponding internal pressure, the CT will not balloon and so the fuel channel integrity can be ensured. Thus CTBT is equal to PTBT at for a given PT pressure. This condition is sufficient but not necessary for fuel channel integrity. If the maximum CT temperature exceeds CTBT (or PTBT), it doesn't mean the fuel channel has to fail since the CT may be quenched at the initial stage of ballooning before the CT is strained sufficiently to rupture the CT.

5. Comparison to Experimental Results

The experiment results in References [1], [2] and [3] reveal that for the tests where there is a claimed PT failure with a PT pressure below 5MPa, the maximum CT temperature is higher than the corresponding CTBT, while for the tests where there is no pressure tube failure, the maximum CT temperature is always lower than the corresponding CTBT. Some typical examples are SUBC1, SUBC2 and SUBC7, where the maximum CT temperature (>770ºC) is higher than the corresponding CTBT (684ºC) by at least 86ºC. No CT deformation is claimed in Reference [2] but the three tests where the PT failure occurred. Two other typical examples are Tests 12 and 20 in Reference [1] where the CT dryout area has been larger than 90%. No pressure tube failure was observed for Test 12 with the maximum CT temperature (753ºC) lower than CTBT (784ºC) by 31ºC, while for Test 20 the pressure tube failed 258s after the contact with the maximum CT temperature (754ºC) higher than CTBT (745ºC) by 9ºC. No PT failure was observed in Reference [3] and all the CT temperatures are below CTBT. The conclusion drawn in the preceding section is further confirmed by these comparisons.

6. Conclusions

The pressure tube and calandria tube contact boiling experiment results were analyzed and the temperatures at which the pressure tube begins to balloon at a specific internal pressure were determined. The pressure tube material yield stress determined in this way is consistent with literature results. If the pressure tube temperature is below this value at the corresponding pressure, it is not necessary to worry about the moderator subcooling requirement. In addition, upon pressure tube and calandria tube contact, if the calandria tube temperature can be kept below that for the pressure tube to balloon, the integrity of the fuel channel still can be ensured. This conclusion is confirmed by the existing experiments.

7. Acknowledgements

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