ENHANCEMENT OF THE MODERATOR SUBCOOLING MARGIN USING GLASS-PEENED CALANDRIA TUBES IN CANDU® REACTORS

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Abstract

One of the important design features present in CANDU® reactors is the cool heavy water moderator surrounding the assembly of horizontal fuel channels. The effectiveness of the moderator heat sink to ensure fuel channel integrity after pressure tube/calandria tube contact during postulated accident events in safety analysis is influenced primarily by the moderator subcooling at the time the contact would occur. Through the research and development program, AECL has developed an improved feature of the calandria tub: glass-peening the outside surface of the calandria tube. With an assessment of several full scale qualification contact boiling experiments using glass-peened calandria tubes, the better understanding of the contact boiling test results were achieved. Following that, the moderator subcooling required to ensure fuel channel integrity was derived, and the enhancement of the moderator subcooling margin using glass-peened calandria tubes in CANDU reactors was concluded.

1. Introduction

One of the important design features present in CANDU[1] reactors is the cool heavy water moderator surrounding the assembly of horizontal fuel channels (Figure 1). Each fuel channel consists of a pressure tube inside a calandria tube, with a gap that contains CO_2 insulating gas. The pressure tube containing nuclear fuel and pressurized coolant is separated from the calandria tube by garter springs. The moderator has a large volume of subcooled heavy water that surrounds all the calandria tubes.

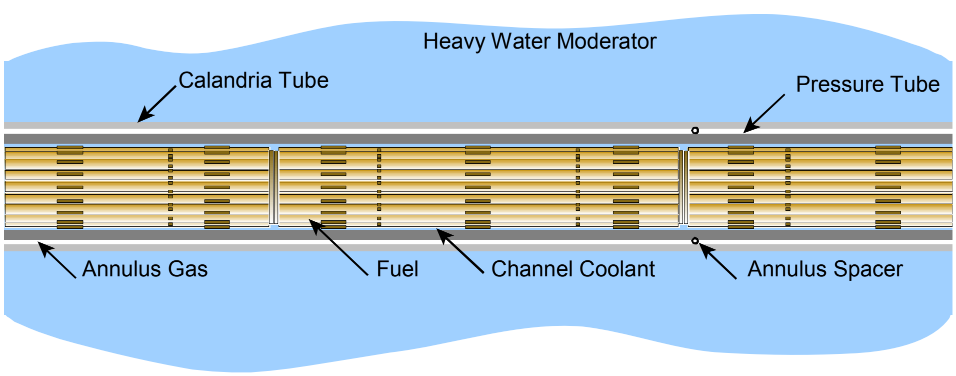

Figure 1 Schematic Diagram of the CANDU Fuel Channel

[1] CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL)

For the analysis of a postulated large break loss-of-coolant accident (LOCA), a break is assumed to occur in the primary heat transport system piping. A range and locations of such postulated breaks would result in severely degraded cooling conditions in some fuel channels. With such degraded fuel cooling in addition to transient increase of reactor power from primary coolant void reactivity followed by rapid shutdown, the energy generated in the nuclear fuel at decay power would be partially stored in the fuel and could cause the fuel temperature to increase. In the limiting cases considered, the pressure tube temperature may increase, due to convective heat transfer from the hot coolant steam as well as the thermal radiation from the overheated fuel. If the pressure tube is sufficiently hot while the channel pressure is still relatively high, the pressure tube may deform radially and would fully contacts its calandria tube (pressure tube/calandria tube ballooning contact).

An outward heat removal path would form as a result of pressure tube/calandria tube ballooning contact, and cool down the pressure tube. Consequently, the fuel would gradually cool down even before high pressure emergency core cooling injection. After pressure tube/calandria tube ballooning contact, the heat stored in the pressure tube and generated in the channels is transferred into the moderator. Because of the design configuration, the heat from the fuel channels can be transferred radially to the moderator, and eventually removed by its cooling system. Therefore, the moderator would act as a supplementary heat sink during postulated LOCA events with or without emergency core cooling available.

The analysis results of pressure tube/calandria tube ballooning contact are based on limiting assumptions, and only applicable to some high bundle power location in the affected core pass (a quarter core for CANDU 6). The effectiveness of the moderator heat sink is required to ensure fuel channel integrity after pressure tube/calandria tube contact, which is influenced primarily by the moderator temperature distribution at the time the contact occurs. For the limiting case, it is the operating moderator temperature distribution, subject to subcooling consideration. The moderator subcooling at a typical location is defined as the difference between the local water saturation temperature and the local water temperature of the moderator. The subcooling margin is the difference between the available subcooling conditions in the moderator analysis and that required conditions purely based on experiments.

A large number of contact boiling experiments were conducted at AECL to assess contact boiling heat transfer when a pressurized CANDU pressure tube section deformed through a CO_2 gas gap to come into contact with a calandria tube in an open tank of water (References [1] and [2]). Through the research and development (R&D) program, AECL has developed an improved feature of the calandria tub: glass-peening the outside surface of the calandria tube. By small glass balls peening on the outer surface of the calandria tube during the manufacture, its roughness increase, hence, the critical heat flux (CHF) on the calandria tube outer surface increase (References [3] and [4]). This has been implemented into several CANDU reactors.

The glass-peened calandria tube was first time used in the Qinshan CANDU Nuclear Power Plant (NPP). The Point Lepreau Refurbishment Project, Wolsong 1 Refurbishment Project, as well as the Bruce Power Retube Project, have also adopted the glass-peened calandria tube for the replacement of the calandria tubes. Enhancement of the moderator subcooling margin using glass-peened calandria tubes in CANDU reactors was concluded through several full scale qualification contact boiling experiments using glass-peened calandria tube. The achievement of AECL R&D program over past decades has been implemented in recent CANDU applications with a consequential enhancement of safety margins. With annulus gas thermal isolation effect, there is no penalty for heat loss due to using glass-peened calandria tube during normal operation.

This paper presents the assessment of the contact boiling test results with glass-peened calandria tubes for use in reactor safety analysis. This assessment considers the calandria tube contact boiling behaviour observed in the experiments and the important factors that influence the behaviour, such as the presence of multiple boiling regimes appearing on different areas of the calandria tube. The better understanding of the contact boiling test results were achieved. Following that, the moderator subcooling required to ensure fuel channel integrity was derived based on the results of the contact boiling experiments with glass-peened calandria tubes.

2. Ballooning Contact Boiling Tests using Glass-peened Calandria Tubes

2.1 Test Facility Description

A series of contact boiling experiments, Q-series, using glass-peened calandria tubes was completed for the Qinshan project. The Q-series of contact boiling experiments studied the potential for improving the moderator subcooling margin by glass-peening the outer surface of the calandria tube. In the Q-series, thirteen contact boiling experiments were conducted by AECL. The test cross-section of the channel is at full scale.

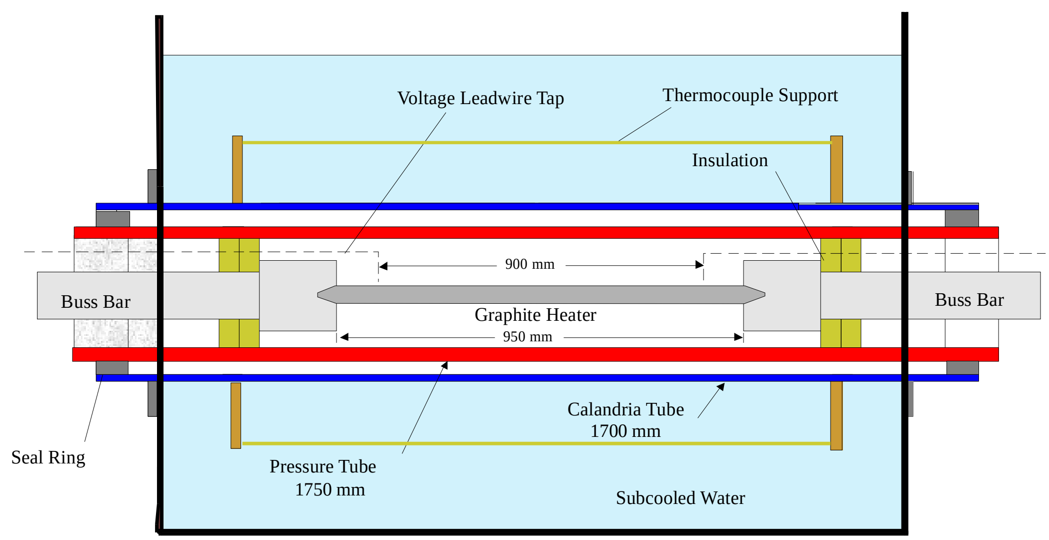

Figure 2 Schematic of Apparatus Used for Q-Series Contact Boiling Test (not to scale)

The typical experimental apparatus for the contact boiling experiment is shown in Figure 2. The apparatus consisted of a test section with a concentric pair of the pressure tube (about 1750 mm long) and calandria tube (about 1700 mm long). The calandria tube was submerged in a nearly stagnant, open tank of water, which was heated to a temperature that was representative of the individual test condition. A graphite rod heater was located at about the midpoint inside the test section of the assembly. The inside of the pressure tube was pressurized with argon. The annulus gap between the pressure tube and the calandria tube was purged with CO_2 at essentially atmospheric pressure throughout the experiment.

In the Q-series experiments, the pressure tube and calandria tube were instrumented with thermocouples at three axial rings along the test section heated length (Figure 3). Four platinum resistance temperature detectors were placed inside the water tank to measure the water temperature.

A DC power supply was used to heat the test section. The actual power applied to the heater was determined by voltage and current measurement, including the total circuit voltage measured by voltage taps across the buss bars and the heater voltage measured by voltage taps on the heater as shown in Figure 2.

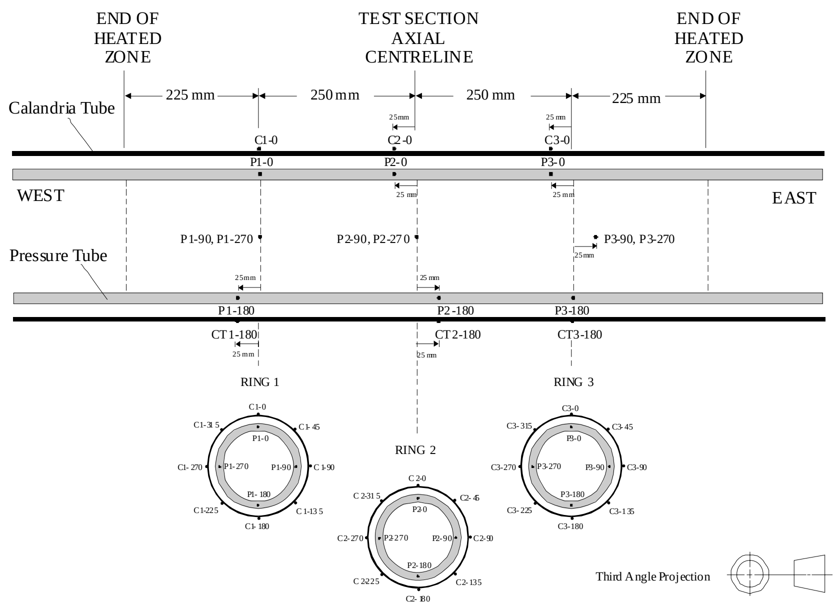

Figure 3 Pressure tube and Calandria tube Thermocouple Locations for Q-series Tests

Pressure transducers rosemount were used to measure the test section pressure, and a data acquisition system was used to record the pressure as gauge pressure. The test section pressure was controlled by an automatic pressure control system able to feed and bleed gas as required to maintain a set point pressure. The annulus pressure was initially set near atmospheric.

2.2 Test Procedure Description

Prior to the experiment, the tank coolant water surrounding the calandria tube was heated to 10°C higher than the predefined test temperature and stirred using a submersible pump to prevent stratification and to maintain a uniform water temperature. As the water was heating up, the pressure tube was purged and pressurized with argon gas. Just prior to the test, when the water cooled down to the predefined test temperature, the height of water above the calandria tube, the barometric pressure and the room temperature were recorded. Then, the submersible pump was turned off. The pressure tube was then pressurized to the predefined test pressure with argon gas, and the pressure tube/calandria tube annulus was supplied with carbon dioxide at a low flow rate at atmospheric pressure.

At the beginning of the test, the power to the test section was ramped to the target power to simulate reactor decay power. The power was maintained as the pressure tube was heating and contacting the calandria tube. Once stable nucleate boiling was established on the outer surface of the calandria tube, or a significant amount of film boiling was observed, the power was turned off and the test section depressurized to end the test.

2.3 Test Conditions and Results

The test conditions and experimental results using glass-peened calandria tubes are summarized in Table 1, thirteen of them for Q-series tests. As shown in Table 1, those tests incorporated pressure tube internal pressures of 4.0 MPa(g) to 5.3 MPa(g), water subcooling of 20.0 ºC to 28.4 ºC, and pressure tube heatup rates of 10.5 ºC/s to 27.1 ºC/s. The pressure tube heatup rate is established with the duration of the measured pressure tube temperature changing from 400 ºC to 700 ºC.

The tests listed in Table 1 were identified with boiling regimes based on the classification given in Table 2. The determination of such characteristic boiling regimes in each contact boiling test was based on visually examination of the oxide patches formed on the calandria tube, video observations, calandria tube temperatures, and the length of time the calandria tube temperature remained above 220 ºC. Under atmospheric saturated pool boiling conditions, the film boiling regime starts at a wall temperature of 220 ºC [6], which is considered as the low temperature bound of the film boiling regime for applications with subcooled moderator conditions. Patchy film boiling can also be identified as discoloration on the outside surface of the calandria tube, which was observed with random shape, size, and location. With the test condition ranges, first three boiling regimes (immediate quench, small patches of film boiling or patchy film boiling) appeared in the tests Table 1. None of the Q-series experiments resulted in extensive film boiling or the entire surface film boiling, and there was no surface crack/rupture for the Q-series.

Recently, two contact boiling experiments using glass-peened calandria tube (GPCB-series) were completed under the AECL R&D program. The test conditions and experimental results for two of these tests (GP1 and GP2) are also summarized in Table 1. These experiments are intended to provide contact boiling experimental data using glass-peened calandria tubes, and pressure tubes manufactured from quad-melted ingots supplied by Teledyne Wah Chang, at test conditions applicable for safety analysis for the Bruce Power Re-tube and the Point Lepreau refurbishment projects. The results of these two tests showed that the contact boiling behaviour observed was similar to the current contact boiling database of experiments performed with glass-peened calandria tubes with different pressure tube manufacture process (Table 1).

Table 1 Summary of Contact Boiling Experiments with Glass-Peened Calandria Tubes

Test Condition / Result	**Q1***	**Q2***	**Q3***	**Q4***	**Q5***	**Q6***	**Q7***	**Q8***	**Q9***	**Q10***	**Q11***	**Q12***	**Q13***	**GP1**	**GP2**
PT Pressure (MPa)	4.1	4.1	4.2	4.3	4.1	4.4	4.6	4.0	4.5	4.8	4.7	5.3	4.6	4.3	4.3
PT Identification [A]	X005	X004	X004	X004	X013	CC838	CC838	CC838	CC347	CC575	CC575	CC575	CC522	RX231	RX231
CT Identification [B]	U612	202-2	U612	192-2	202-5	W782	W782	W782	W779	W779	W779	W797	W797	U690	U442
Water Subcooling (°C)	26.2	28.4	25.9	22.3	26.1	22.7	23.0	23.0	24.3	24.0	20.0	21.1	22.0	27.1	20.0
PT Heating Rate (°C/s)[C]															
Average	25.6	24.6	10.5	10.5	23.5	24.6	14.3	25.6	23.4	18.6	23.1	23.5	24.7	24.4	11.2
Minimum	22.1	22.9	10.0	10.0	22.0	23.4	13.7	23.8	22.3	17.7	21.7	22.0	23.3	22.0	10.3
Maximum	31.7	27.1	11.1	11.2	25.2	26.4	15.5	29.7	24.2	19.4	25.1	25.8	26.5	27.9	12.6
PT Contact Temp. (°C)															
Average	774	813	757	757	837	831	791	864	815	797	815	798	793	851	799
Minimum	755	784	747	741	799	815	772	820	780	762	786	768	780	813	782
Maximum	795	858	782	776	878	862	810	917	846	830	877	825	812	890	833
CT Maximum Temp. (°C)	497	503	392	443	478	621	456	619	514	498	661	564	653	325	363
Max. Time to Rewet (s)[D]	6	4	3	4	6	15	5	19	7	6	46	14	38	3	3
Percent Dryout (%)	13	2	0	0	1+	27	4	32	13	7	47	34	40	5	4
Boiling Regime	◔	○	○	○	○	◒	○	◒	◔	◔	◒	◒	◒	○	○

Notes:

A. X004, X005 and X013 are pilgered pressure tubes manufactured from double-melted ingots supplied by Teledyne Wah Chang. CC838, CC347 and CC575 are pressure tubes manufactured from double-melted ingots supplied by Chepetsky Manufacturing Plant. RX231 is a pressure tube manufactured from a quad-melted ingot supplied by Teledyne Wah Chang.

B. Calandria tube (CT) outside surface glass-peened with bead size GP35, Almen intensity N9-N11 and 100% coverage. Seam-welded. Inside surface as-received.

C. Pressure-tube (PT) heating rates are calculated for the temperature change between 400 and 700°C.

D. Maximum time to rewet is the maximum time that a calandria tube thermocouple exceeded 220°C.

* Data for Qinshan experiments.

\+ Boiling regime for Q5 deemed immediate quench due to very small dryout patch.

Shaded columns indicate tests performed at heating rates under 23°C/s.

Table 2 Boiling Regime Classifications

Boiling Regime	Symbol	Description
Immediate Quench	○	Calandria tube surface does not experience any film/transition boiling that lasts for more than 5 s and no visible calandria tube deformation
Small Patches of Film Boiling	◔	<15% of the calandria tube surface experiences periods of film boiling that rewet within 20 s with no significant calandria tube deformation
Patchy Film Boiling	◒	16-50% of the calandria tube surface experiences periods of film boiling
Extensive Film Boiling	◕	51-75% of the calandria tube surface experiences periods of film boiling
Entire Surface Film Boiling	●	>76% of the calandria tube surface in film boiling

3. Considerations for Fuel Channel Integrity

Examination of the contact boiling tests performed to date (References [1] to [5]) shows that for large diameter tubes, such as calandria tubes, the boiling regime can be different on different portions of the tube wall surface after pressure tube/calandria tube ballooning contact. Patchy film boiling (or patchy dryout) on the calandria tube external surface was observed in most of the contact boiling experiments, including those using glass-peened calandria tube. Although a portion of the calandria tube went beyond the nucleate boiling regime, it did not necessarily result in further deformation and failure of the fuel channel, provided that the size of the dryout patch was limited and the calandria tube rewets in a timely manner.

The contact boiling experiments using glass-peened calandria tubes provided data that are directly comparable to experiments performed with smooth calandria tubes used in CANDU reactors prior to Qinshan CANDU NPP. When a test on a glass-peened calandria tube is directly compared with a test performed with smooth calandria tubes at the same or similar test conditions, there is an improvement for the moderator subcooling requirement when a glass-peened calandria tube is tested. First, there is an improvement in the extent of dryout observed (less severe extent of film boiling) when a glass-peened calandria tubes is tested at the same test conditions as a smooth calandria tube; and, secondly, that the same extent of dryout may be achieved at a lower subcooling when a glass-peened calandria tube is used.

With understanding of the contact boiling behaviour from examination of the experimental data and boiling curve [6], the consideration for the fuel channel integrity is discussed in this section. The factors influencing the extent of calcandria tube dryout patch and its rewet, as well as the key influence factors on fuel channel integrity, are identified after pressure tube/calandria tube ballooning contact.

3.1 Factors Influencing the Extent of the Calandria tube Dryout Patch

While the bulk surface of calandria tube would remain in nuclear boiling regime, the occurance of patch dryout would be immediately after the pressure tube/calandria tube contact as the outcome of a short-lived thermal-mechanical impact (Figure 4 and Figure 5). The size or extent of the dryout patches is strongly influenced by the pressure tube temperature at contact, applied pressure and the degree of the subcooling at the calandria tube surface.

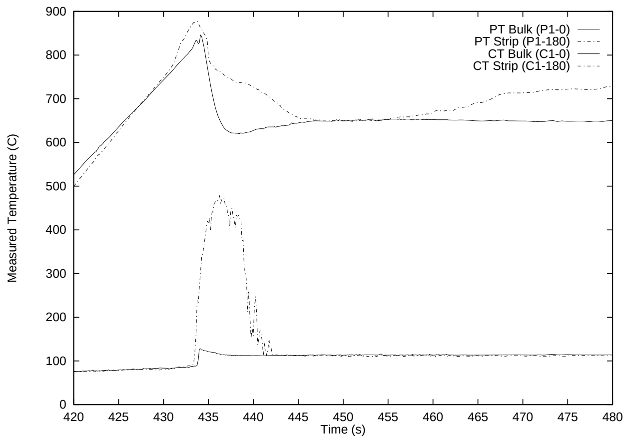

Figure 4 PT and CT Temperature Measurement in a Typical Q-series Test

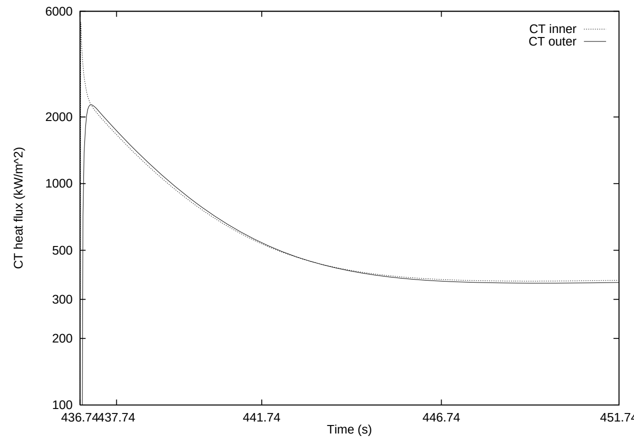

Figure 5 Calculated Heat Flux on CT Inner and Outer Surfaces in a Typical Q-series Test

The pressure tube temperature at contact reflects the stored heat in the pressure tube just prior to contact. This determines the initial transient heat load being transferred to the calandria tube. The calandria tube wall thickness is only about one third of the pressure tube wall thickness. Therefore, the calandria tube heatup rate has a theoretical potential to be three times faster than the pressure tube cool-down rate after the contact. A higher pressure tube contact temperature tends to lead to a higher calandria tube temperature, hence, a tendency for larger dryout patch size if the calandria tube is in dryout. However, the calandria tube temperature is always bounded by the pressure tube temperature (Figure 4), and depends on the heat balance between the heat fluxes on its inner and outer surfaces (Figure 5), then its temperature tends to decrease due to heat removal up to the CHF level on its outer surface (Figure 4 and Figure 5).

With a high CHF using glass-peened calandria tube ([3] and [4]), tendency to have an early temperature decrease and less extent of the dryout patchy; hence, the subcooling requirement; is enhanced as observed in full scale contact boiling experiments mentioned previously.

The pressure tube temperature at contact also influences the hardness of the tube surface, which together with the applied pressure determines the initial contact conductance between the pressure tube and calandria tube. Higher pressure tube contact temperature or higher applied pressure would result in a higher initial contact conductance. Using the methodology discussed in Reference [7] inferred with the Q-test conditions, the assessed pressure tube/calandria tube contact conductance of the glass-peened calandria tube appears to be in the order of 10.0 kW/(m^2·K) initially, and down to 1.0 to 2.5 kW/(m^2·K) later on (Reference [5]).

The subcooling at the surface of the calandria tube determines the maximum heat removal (CHF) from the calandria tube to the moderator. The size or extent of the film boiling patches is strongly influenced by the degree of subcooling at the calandria tube surface. A higher subcooling gives a higher CHF, which has the potential to limit the extent of dryout forming on the outer calandria tube surface. Higher values of subcooling lead to more likeness of patchy dryout other than wrap-around dryout conditions. The patchiness of the film boiling region is an important factor in the overall thermal-mechanical response of the calandria tube.

3.2 Factors Influencing the Rewet on Calandria tube Dryout Patches

Since avoidance of the entire calandria tube surface beyond nucleate boiling does not appear to be possible, fuel channel integrity then depends on timely rewet of the calandria tube. The calandria tube rewet or the duration of the patchy film boiling is governed by the incident heat flux on the internal surface of the pressure tube at the dryout patch, the local moderator subcooling and the size of the dryout patches.

Areas of the calandria tube experiencing film boiling can rewet either because the incident heat flux is smaller than that required to maintain stable film boiling, or by axial and circumferential heat conduction in the calandria tube from areas of film boiling to those in nucleate boiling. Hence, the incident heat flux is one of the most important parameters that influence rewetting behaviour. The incident heat flux in the contact boiling tests can be estimated based on the measured pressure tube heatup rate prior to the pressure tube/calandria tube contact adjusted with the pressure tube heat capacity of the contact temperature. With a measured pressure tube heatup rate of 25 ºC/s and the pressure tube contact temperature of 820 ºC (such as the Q6 test, Table 1), the incident heat flux on the pressure tube inner surface is about 300 kW/m^2. It can be estimated that the heat load to the calandria tube on the inner surface is above 300 kW/m^2 for a given Q-test at the quasi steady state heat transfer stage as shown in Figure 5.

Subcooling at the surface of the calandria tube determines the calandria tube minimum heat flux, MHF, or the minimum heat removal, at high wall temperature. It is about 250 kW/m^2 for a subcooling of 28 ºC, and about 50 kW/m^2 for a subcooling of 0 ºC (near saturated), based on correlations employed in CATHENA (Bjornard and Griffith for transition boiling, Groeneveld-Delorme for film boiling, and Groeneveld-Berensen for rewet/MHF temperature, see Reference [8]). It is believed that this minimum heat removal would be enhanced with glass peened calandria tube, subject to further study.

Only when the incident heat flux is higher than the MHF (subject to the adjustment for pressure tube and calandria tube area differences), does the size of the dryout patches have significant influence on its rewet. The size of the dryout patch defined in terms of perimeter length to area gives an indication of the level of cooling available at the perimeter of the dryout patch. How soon a dryout patch rewets depends on the effectiveness of the cooling provided by the perimeter. On the same calandria tube outer surface, a larger size of the patch would be a potential worst condition. The rewet front takes a long time to arrive at the centre of such a patch to benefit from the cooling effect of the adjacent wall staying in the nucleate boiling. However, when the incident heat flux decreases as the channel power decays, a faster rewet is expected.

3.3 Internal Channel Loading of Power and Pressure

The internal channel loading is also a key influence factor on fuel channel integrity after pressure tube/calandria tube contact. The internal channel loading is essentially determined by the channel power and pressure.

With LOCA blowdown conditions, both channel power and pressure continuously decrease with respect to the time, with or without pressure tube/calandria tube contact. However, the incident heat flux on the inner surface of the pressure tube varies significantly with two-phase coolant conditions during pressure tube/calandria tube contact.

In the contact boiling experiments, the internal channel loading (that is the applied power to heater and the pressure) basically remains constant, i.e., it does not change with time during pressure tube/calandria tube contact. The tests were performed using stagnant gas and rely strictly on thermal radiation as the heat transfer mechanism, and the tests do not reproduce variations such as those that occur in the incident heat flux to the inner surface of the pressure tube with a two-phase flow in the reactor case. However, these experiments have no loading relief, hence, they give more severe loading conditions than the reactor cases which have the same power and channel pressure at the time of pressure tube/calandria tube contact. Furthermore, although the power remains constant in these experiments, the heat flux output from the graphite heaters continues to increase in the test as the graphite heaters gradually reach steady state. The graphite heaters reach their steady state temperatures sometime after the pressure tube/calandria tube contact, therefore the post-contact heat transfer is conservative as it is severe compared to the reactor conditions.

3.4 Key Influence Factors on Fuel Channel Integrity

Examination of the results obtained from contact boiling tests indicates that the occurrence and extent of patchy dryout depend on the pressure tube temperature at the time of contact, the internal pressure and the subcooling of the water surrounding the channel.

For conditions where patchy dryout occurs, fuel channel integrity is maintained, provided that the calandria tube rapidly rewets to avoid significant calandria tube deformation. Calandria tube rewet occurs when the rate of heat removal from the calandria tube region under the boiling patch exceeds the rate of heat entering the calandria tube at that region. The heat removed from the calandria tube region under the boiling patch can be transferred to the subcooled liquid water surrounding the dryout patch through circumferentially and axially heat conduction inside the calandria tube wall. The heat entering the calandria tube is then governed by the incident heat flux to the inner surface of the pressure tube. It is also governed by the channel pressure and tube wall temperatures. The duration of boiling is governed by the incident heat flux to the inner surface of the pressure tube, by the local moderator subcooling and by the size of the dryout patches.

Overall, it is possible to assess fuel channel integrity under reactor conditions by comparing conditions during a postulated LOCA directly to applicable experimental results. The key influence factors on fuel channel integrity after the pressure tube/calandria tube contact are the pressure tube temperature at the time of contact and the subcooling of the water surrounding the channel, and channel pressure and incident heat load. The important test conditions, that must be considered to apply the test results directly to demonstrate fuel channel integrity for the analyzed scenarios, are the applied channel pressure and incident heat flux on the inner surface of the pressure tube. Predicted channel pressure and incident heat flux must be lower than the experimental conditions to allow the test to be directly used for confirmation of fuel channel integrity.

4. Moderator Subcooling Requirement

To suppress dryout on the calandria tube outer surface, and thus ensure an effective heat removal path from the channels to the moderator, a certain level of moderator subcooling is required to ensure the availability of the moderator as heat sink for an overheated fuel channel.

Each contact boiling test provides measurement data, locally and transient, on the temperatures of pressure tube, calandria tube, and tank water, the applied pressure, and applied power. Each test also provides detailed measured and visual information on contact boiling behaviour. The experimental data from the full-scale contact boiling tests using glass-peened calandria tube are summarized in Table 1 and Table 2. The relationship of average pressure tube contact temperature and subcooling to the boiling regime observed in the database is shown in Figure 6. For each test, a horizontal line segment in Figure 6 represent the measured contact temperature range. These data and information are collected and analyzed to derive the Moderator Subcooling Requirement Curve, shown in Figure 6, for the glass-peened calandria tube.

4.1 Subcooling Requirement Curve

The Subcooling Requirement Curve is to provide the sufficient condition to demonstrate CANDU fuel channel integrity after pressure tube/calandria tube ballooning contact, assuring that calandria tube sustained film boiling is precluded. This curve can then be used as the first screening criterion for fuel channel integrity assessment, recognizing that even with patchy film boiling fuel channel integrity can be maintained.

The Subcooling Requirement Curve (Figure 6) defines the conditions under which the moderator heat sink can suppress dryout on the calandria tube outer surface, preventing further channel deformation after pressure tube/calandria tube contact to ensure fuel channel integrity. This approach is consistent with that used in updating the contact boiling curve [1] for the smooth calandria tubes in early 2000's [9]. The justification for this approach is based on experimental evidence that short-lived periods of small patchy dryout do not threaten fuel channel integrity.

Figure 6 presents the Subcooling Requirement Curve obtained using experimental results from full scale tests plotted in terms of subcooling versus pressure tube temperatures at the time of pressure tube/calandria tube contact. The Subcooling Requirement Curve passes through points of (790 ºC, 23 ºC) and (840 ºC, 26 ºC), and points (840 ºC, 26 ºC) and (900 ºC, 26 ºC) for pressure tube contact temperature and moderator subcooling, respectively. Below and on the curve, only "immediate quench" or "small patches of film boiling" (Table 2) are observed in the experiments for the applied pressure and heat-up rate ranges. The curve is drawn such that all tests that were classified as having "patchy film boiling" are above the curve, even though no fuel channel failure and limited fuel channel deformation was observed in those tests.

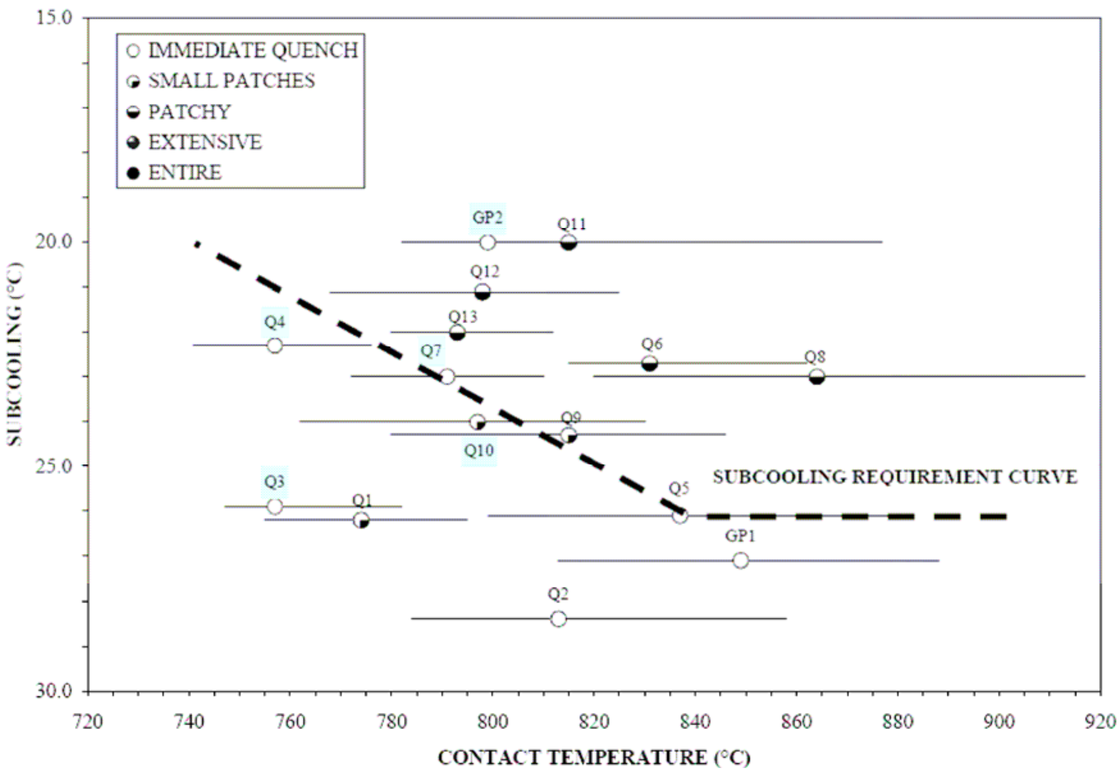

Figure 6 Moderator Subcooling Requirement Curve Using Glass-Peened Calandria Tubes

Based on the current contact boiling database of experiments performed, the enhanced margin to fuel channel integrity provided by the glass-peened calandria tubes compared with the smooth calandria tubes can be quantified. For example, the horizontal portion of subcooling requirement curve for the smooth calandria tube corresponds to 29 ºC subcooling (References [1] and [2], updated in early 2000's [9]); whereas for the glass-peened calandria tubes the horizontal section is at 26 ºC subcooling. Therefore, there is 3 ºC enhancement in the moderator subcooling margin for contact conditions at the upper range of contact temperatures. The results of direct test-to-test comparison also suggests there would be at least 2 ºC moderator subcooling enhancement for the same or similar contact conditions, covering the range of test conditions.

4.2 Application Range of Subcooling Requirement Curve

The Subcooling Requirement Curve is based on contact boiling experiments and on the extrapolation of the contact boiling experiment conditions. Hence, the application range of the subcooling requirement is deemed to be within the following range of key experimental parameters:

- The fuel channel configuration,
- The applied channel pressure, and
- The heat load to the pressure tube.

The fuel channel configuration is the current CANDU reactor design. The applied channel pressure is 4.3 MPa(g) or less, after pressure tube/calandria tube contact. The applied heat load represented by the incident heat flux is below 300 kW/m^2. The above application range of

Subcooling Requirement Curve (Figure 6) using glass-peened calandria tubes was based on data examination of tests on or below the Curve, which was extended beyond the smooth calandria tube databases, typically for the high incident heat flux range.

The subcooling requirement is satisfied if the pressure tube contact temperature and moderator subcooling at the location of contact results in a point below this curve. The Subcooling Requirement Curve also provides the condition for direct use of experimental data for in reactor safety analysis for those cases in which the incident heat flux on the inner surface of the pressure tube after pressure tube/calandria tube contact is less than or equal to 300 kW/m^2.

If any fuel channel condition is beyond the application range of the subcooling requirement, the channel will not necessarily fail, but a more detailed assessment would be required. In such an assessment, it has to be realised that in the reactor the channel pressure decreases during a LOCA whereas in the test channel pressure remained constant, and that in the reactor the decay power decreases, whereas in the tests the incident heat flux was increasing. Under a CANDU Owners Group (COG) program, a methodology was developed to mechanistically analyze the effect of sustained calandria tube dryout conditions on fuel channel integrity during a large break LOCA based on the existing contact boiling test data for the smooth calandria tube. Such methodology can be extended for the glass-peened calandria tube to assess, in more details, of calandria tube post-dryout thermal and mechanical behaviour.

5. Summary and Conclusions

With an assessment of several full-scale qualification contact boiling experiments using glass-peened calandria tubes, the moderator subcooling required to ensure fuel-channel integrity was derived, and the enhancement of the moderator subcooling margin using glass-peened calandria tubes in CANDU reactors was concluded.

The Moderator Subcooling Requirement Curve using glass-peened calandria tube was obtained for the analysis of the postulated LOCA events with pressure tube/calandria tube ballooning contact. The Subcooling Requirement Curve passes through points of (790 ºC, 23 ºC) and (840 ºC, 26 ºC), and points (840 ºC, 26 ºC) and (900 ºC, 26 ºC) for pressure tube contact temperature and moderator subcooling, respectively.

The Subcooling Requirement Curve can be used as the basis for fuel channel integrity assessment. The Subcooling Requirement Curve provides the sufficient condition to demonstrate CANDU fuel channel integrity after pressure tube/calandria tube ballooning contact when coolant pressure at pressure tube/calandria tube contact is up to 4.3 MPa(g) and the incident heat flux is up to 300 kW/m^2.

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