# New Contact Boiling Experiments to EvaluateCalandria Tube Strain Acceptance Criteria

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**Abstract**

The Canadian Nuclear Safety Commission(CNSC) has contracted the Canadian Nuclear Laboratories(CNL) to conduct additional Contact Boiling (CB) experiments with the main objective of evaluating the acceptance criterion of CalandriaTube (CT) strain limit of 2%, proposed by the industry for fuel channel integrity assessments. The test conditions are selected using analytical tools and guidance from existing CANDU Owners Group (COG) test results, so as to lead to CT strain close to this value. The experiments will also be used to evaluate the CT quench temperature correlation proposed. This paper presents conditions selected for the first three experiments, their most important results and their preliminary analysis, with a focus on the test which produced CT strain in excess of 2%.

## 1. Introduction

In CANDU reactors, the moderator acts as a heat sink to maintain Fuel Channel Integrity (FCI) in accidents where fuel overheats causing the Pressure Tube (PT) to balloon into contact with the calandriatube. The moderator temperature must be sufficiently low to act as an effective heatsink. The adequacy of moderator temperature is confirmed by performing safety analysis for power reactors. Analytical models are developed and validated to simulate the transient thermal/mechanical behaviour of the fuel channel during loss of coolant accidents.

Fuel channel safety can be characterized by the maximum plastic PT/CT strain during heat-up transients. A limit of 2% hoop strain was selected by the CANDU industry based on experimental evidence including the results of full scale CBexperiments [1-3]. The number of existing CB experiments where strain came close to 2% is however limited. Therefore, a new series of these experiments has been sponsored by the CNSC, with its first results presented in this paper.

### 1.1 Accident Scenario

In a number of postulated loss-of-coolant accident (LOCA) scenarios with or without coincidental Loss-Of-Emergency Core Cooling (LOECC), the fuel may overheat causing the PT to overheat, lose strength and plastically deform (balloon) into contact with the surrounding CT. At time of contact, the CT experiences a large increase in heat flux at the contact locations as stored heat is rejected from the PT to the cooler CT. If the heat flux on the outer surface of the CT exceeds the Critical Heat Flux (CHF), film boiling (dryout) may occur on the surface of the CT. If the area in dryout is sufficiently large and the dryout is prolonged, the PT/CT combination can continue to strain radially and may challenge fuel-channel integrity. If moderator has sufficient subcooling, the initial CT dryout will quench prior to straining beyond the acceptable limit.

### 1.2 Contact Boiling Experiments

The apparatus used to conduct CB experiments at CNLis shown schematically in Figure 1. Reactor-grade PT and CT sections are submerged in a water tank simulating the moderator fluid. The test section is about one meter long, and is heated by a graphite heater simulating nuclear fuel.

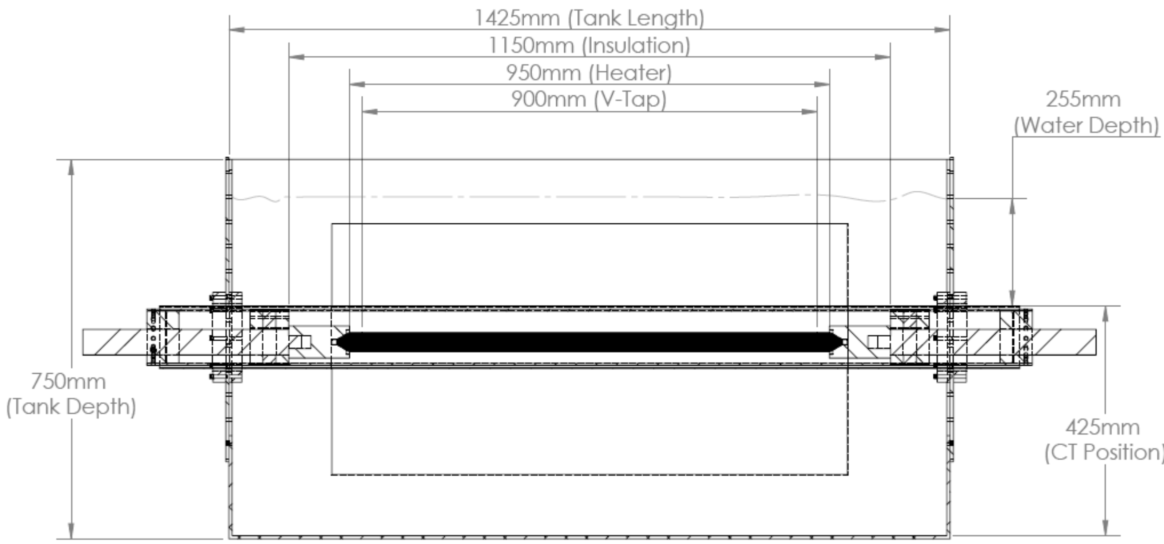


Figure 1 A sketch showing the test section and water tank dimensions

Test parameters are the water subcooling, PT pressure and heater power. Each test is conducted by increasing power gradually over a short period and then keeping it steady until the PT balloons into contact with the CT andwhile film boiling occurs on the CT surface. The test is terminated when the CT film boiling quenches or when the Fuel Channel (FC) fails. After the test, the extent of dryout on the CT outer surface is assessed by examining surface discoloration (oxidation), and the average CT hoop strain at various axial locations is determined by measuringthe post-test CT diameter and comparing it with the pre-test diameter.

### 1.3 PT/CT Contact ModelImplemented in CATHENA

The CANDU industry has developed an analytical model for predicting PT/CT contact and deformation behaviour, which can be applied both to CB tests and to LOCA scenarios. The model represents the following transient phenomena:

- PT heat-up and ballooning into contact with the CT;
- Heat transfer from PT to CT upon contact;
- Heat transfer to the moderator fluid and CT temperature;
- CT dryout and quenching;
- PT and CT strain following contact.

The model consists of a set of equations that can be implemented in system thermalhydraulics codes for predicting post-contact CT quench and maximum strain [4,5]. Inits current implementation in the code CATHENA [6], it consists of equations given in references [7] through [15]. Two somewhat contentious elements of the model, both derived on the basis of a number of CB tests, are the contact conductance function and the CT quench temperature correlation.

For PT/CT contact conductance, the function shown in Figure 2is used. According to this model, PT/CT contact conductance has two distinct values:a high value immediately upon contact, that is pressure dependent, and a much lower value for the longer term.

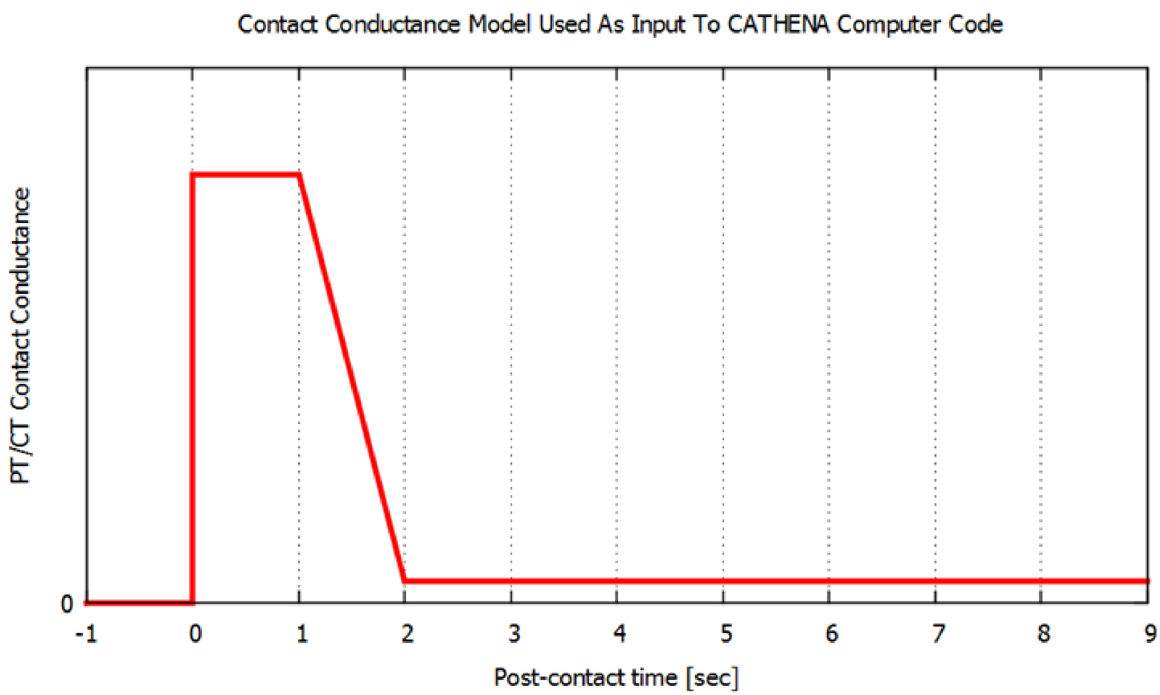


Figure 2  PT/CT contact conductance function

The CT quench temperature (minimum film boiling temperature) correlation is the average of the four correlations in references[12] to [15] with a temperature offset calculated from the results of some contact boiling experiments.

Description of an earlier version of the PT/CT contact and deformation model can be found in Reference 16.

### 1.4 Fuel Channel Integrity(FCI) Acceptance Criterion

Test results of numerous contact boiling experiments demonstrated that the fuel channel can withstand considerable amount of CT dryout before quenching. Therefore, the acceptance criterion for fuel channel integrity proposed by the CANDU industry was set on the basis of the maximum plastic strain the CT encounters prior to quenching. A value of 2% strain was selected for this criterion. The experimental support for this value is mainly based on the results of a limited number of CB experiments, as follows:

- For two experiments where the fuel channel integrity was maintained, the CT strain reached 2.6% and 1.5% respectively;

- For three other experiments where the fuel channel integrity was not maintained, the CT strain was 5% and above.

## 2. CT Strain Contact Boiling (CSCB) Experiments

A new set of CB experiments labeled CT Strain Contact Boiling (CSCB) experiments, sponsored by the CNSC, has been designed so as to further evaluate the acceptance criterion of a 2% CT strain. This is achieved by selecting test conditions that lead to CT strain close to this value. The first three experiments conducted in the planned series of six are presented herein.

### 2.1 Selection of Test Conditions

The test conditions that need to be defined with a view to obtain a strain close to 2% are the internal PT pressure, the PT heat-up rate (determined by the heater power), andthe tank water subcooling.

The CSCB tests are performed at internal pressures of either 3.5 MPa or 4 MPa, as this range of pressures is most relevant to the accident scenario of concern, and a number of earlier CB tests were performed at these values.The target conditions for test CSCB1 were chosen so as to be close to the 2% strain locus on the FCI map in coordinates representing the subcooling and heat-up rate conditionsat internal pressure of 4 MPa,assumed as a straight line on the basis of earlier CB tests.After test CSCB1, an analysis using a model developed to simulate the CSCB experiments with the CATHENA code was carried out to predict the locus more accurately. The resulting locus is shown in Figure 3. The target conditions selected for the consecutive experiments, CSCB2and CSCB3,were chosen very close to this locus, as shown in the figure. The target conditions are also shown in Table 1, along with the actual conditions achieved.

Table 1 Target and actual conditions for tests CSCB1 to CSCB3

| **Test** | **Pressure (MPa)** | | **PT heat-up rate (°C/s)** | | **Subcooling (°C)** | |
|---|---|---|---|---|---|---|
| | Target | Actual | Target | Actual | Target | Actual |
| CSCB1 | 4.0 | 4.0 | 15.0 | 15.7 | 24.0 | 24.4 |
| CSCB2 | 4.0 | 4.0 | 15.7 | 15.6 | 23.4 | 23.2 |
| CSCB3 | 3.5 | 3.5 | 21.9 | 21.4 | 28.8 | 29.1 |

In all the three tests the actual conditions achieved were very close to the target conditions, not only for pressure, which is directly measured and automatically controlled, but also for the heat-up rate (within a fraction of 1°C/s) and for the subcooling (within a fraction of 1°C). This signifies tight control of the experimenters over these parameters that cannot be directly measured and are intrinsically difficult to control.

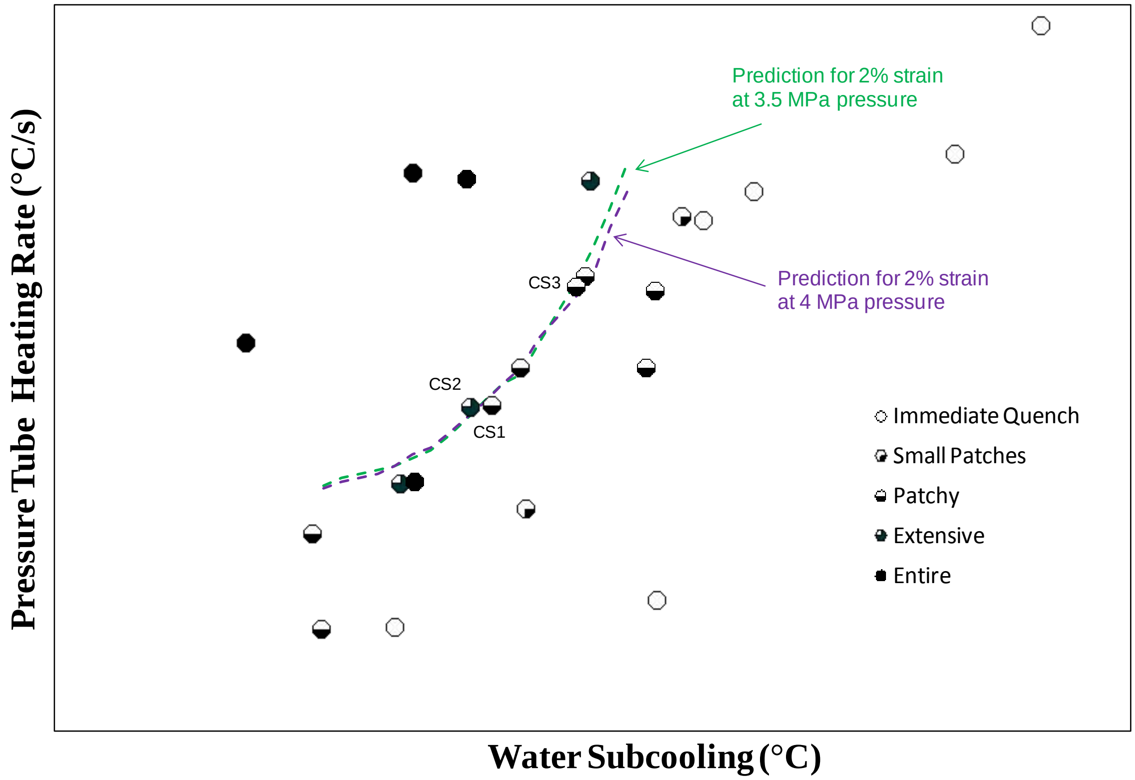


Figure 3 Locus of 2% CT strain on FCI map predicted with CATHENA after test CSCB1

## 2.2 Main Results of Tests CBCS1 to CBCS3

In all the tests, the uncertainty in the temperature measurements is estimated to be ±15°C in the pressure tube wall, ±3°C at the calandria tube surface, and up to ±1.0°C in the water. The uncertainty in calandria-tube hoop strain is estimated to be within 0.5%. The uncertainty in pressure and power supplied to the test section are determined to be within ±0.1 MPa and less than ±1.0 kW, respectively.

In test CSCB1, the selected conditions led to PT ballooning and contact with the CT, with PT temperatures at contact in the range of 788°C to 847°C, resulting infilm boiling on the CT surface. The maximum CT temperature measured after contact was 602°C. Shortly after, orderly rewetting at various CT surface thermocouple locations occurred following periods of dryout of up to 33 seconds.The test was terminated with all the measured CT temperatures stable below 100°C and the test section intact. The extent of dryout was estimated after the test as about 40% of the heated area, which is classified as patchy dryout. The maximum CT strain calculated after post-test diameter measurements was 0.4%.

The main results of testCSCB1 are presented in Table 2, along with those of the other two tests.

Table 2 Main results of the first three CSCB tests

| Test | $T_{PT,max}$ (°C) | $T_{CT,max}$ (°C) | Rewet time (s) | Dryout % | Max strain (%) | Failure ? |
|---|---|---|---|---|---|---|
| CSCB1 | 847 | 602 | 33 | 40 | 0.4 | No |
| CSCB2 | 838 | 737 | N/A | 66 | 12.0 | Yes |
| CSCB3 | 895 | 748 | 36 | 39 | 1.4 | No |

The test conditions for CSCB2 were selected in relation to those of CSCB1 to be harsher, so as to approach the predicted 2% CT strain locus very closely. In order to quantify the needed variations from the CSCB1 conditions, the sensitivity of CT strain was determined in relation to each of the PT heating rate and moderator subcooling for a constant PT pressure. Figure 4 show results of this sensitivity study that assisted in selecting conditions for CSCB2. These figures also clearly indicate a nonlinear behaviour of CT strain with rapid changes in the range of values between 1% and 3 %.

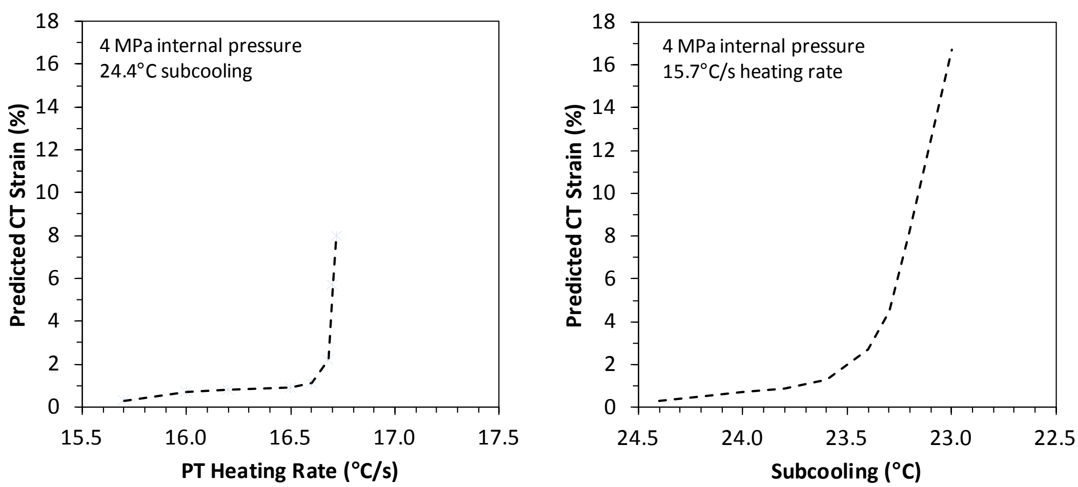


Figure 4 CATHENA predictions for sensitivities of CT strain near CSCB1 conditions

In test CSCB2, the actually achieved conditions (very close to the selected target) led tothe test section failure, withextensive dryout and a maximum CT strain of 12%, as shown in Table 2. The test produced a wealth of information about CT strain behaviour.Its results are summarized in the next section (2.3).

In test CSCB3, PT ballooning and PT/CT contact occurred with PT temperatures in the range of 819°C to 895°C, resulting infilm boiling on the CT surface. The maximum CT temperature measured after contact was 748°C. CT rewetting occurred following periods of dryout of up to

36seconds. The test was terminated with all the measured CT temperatures stable near 100°C and the test section intact. The extent of dryout was estimated after the test as 39% of the heated area, which is classified as patchy dryout. The maximum CT strain calculated after post-test diameter measurements was 1.4%.

## 2.3 Summary of Results of Test CBCS2

Results obtained for CSCB2 can be summarized as follows:

- The CT ruptured at an axial location where the CT hoop strain reached 12%.
- At a different axial location, a bulge in the CT with 2.2% hoop strain was produced.
- Thermocouple measurements indicate continued rise in CT temperature near the failed section, while there are indications of the start of rewetting near the bulged location prior to channel failure.
- Extensive film boiling on CT surface indicated by dryout patches covering about 66% of the CT heated area.
- PT and CT temperature transients at the top of the tube are represented in Figure 5.

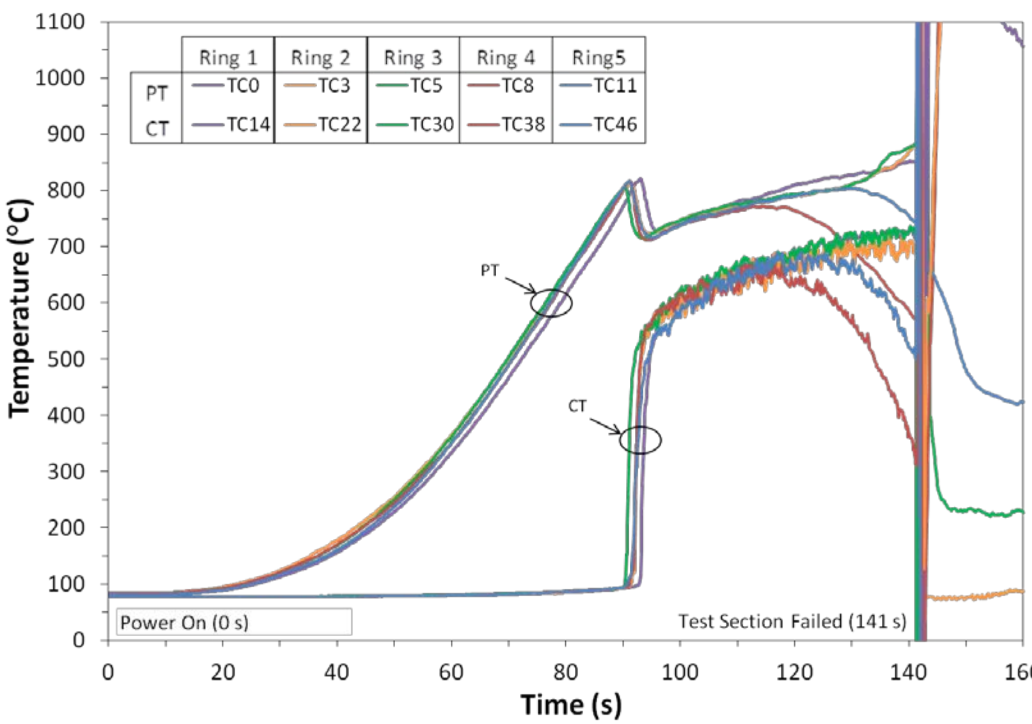


Figure 5 Temperatures measured at the top of the test section in test CSCB2

A view of the test section just before it ruptured and the axial variations in hoop strain measured after the test are shown in Figure 6. Different sections along the channel behaved in different ways for same test conditions. As one section burst, another section started to rewet after bulging. It can therefore be concluded that conditions leading to 2% CT strain can be close to those leading to channel failure. This casts doubts on code abilities to predict with confidence a 2% CT strain without channel failure. Further discussion related to this issue is given in the next section.

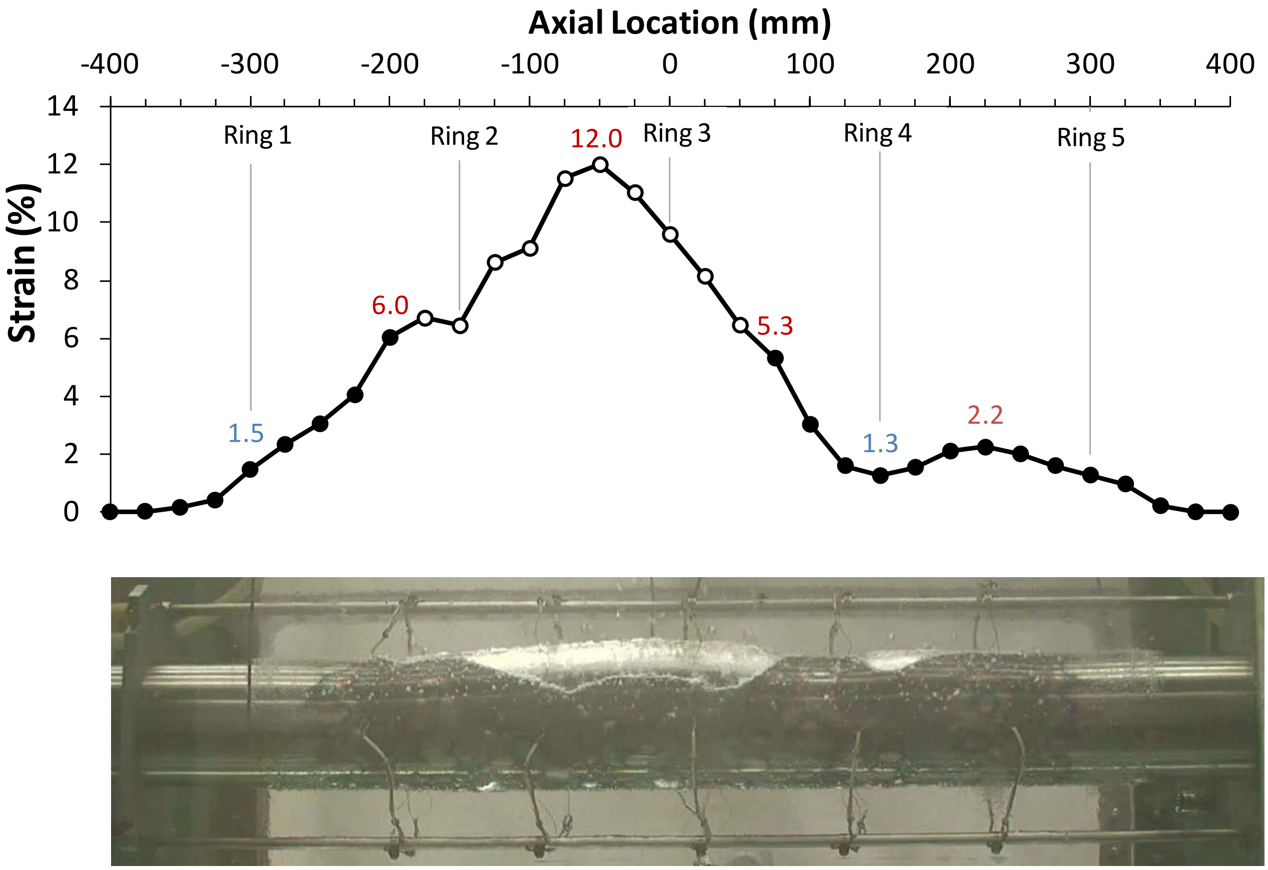


Figure 6  CT strain plotted with a video snapshot of the test section just prior to failure

## 3. Uncertain Factors Affecting Fuel Channel Integrity

### 3.1 Impact and Variability of PT/CT Contact Conductance

The impact of contact conductance on FCI can be described as follows:

- The initial value of contact conductance determines how fast heat stored in the PT is transferred to the CT. This in turn determines the maximum temperatures reached by the CT.
- The value of contact conductance a few seconds after initial contact, although relatively small, can have a strong impact on FCI for conditions close to the failure limit. For such conditions, CT surface rewetting, after relatively long period of dryout, is dependent on the

balance of heat received from the PT and heat rejected to the moderator. This balance may or may not lead to a drop in CT temperature that is necessary for rewetting. The value of contact conductance in this period plays an important role that can directly impact FCI.

- At the end of the transient, after heat stored in the PT has been transferred to the moderator, the value of contact conductance becomes less significant, as heater heat flux alone is relatively small and can be dissipated to moderator even through CT film boiling.

The variability of contact conductance is an important issue. Contact conductance is by its nature difficult to assess, since it depends on many factors, some of them random, such as surface properties and manufacturing tolerances in geometries and material properties. It can also be a function of heat flux and other parameters that vary upon contact.

The contact conductance model shown in Figure 2 is a simplification of a complex parameter, and is based on values extracted from CB experimental measurements. Such values vary from one experiment to another, and were averaged in such a way as to provide best possible predictions of key parameters. The tail value of this model is simply taken as constant in time given that for most test conditions it has small impact on predictions. However, as explained above, it can have strong impact on FCI for conditions close to FC failure. The value of 1 KW/($m^2$°C)usually assumed in CATHENA input represents experimental variations that can be twice or three times as large.

In addition, contact conductance may have steep variations in the temperature range of interest for conditions leading to significant dryout prior to CT rewetting. It can be demonstrated that contact conductance is a strong function of PT/CT interfacial pressure, which in turn is a function of PT and CT temperatures. The PT-CT temperature difference at the end of the initial contact period of about one second is usually in the range between 100°C and 200°C,as can be seen in Figure 5, which is typical for test conditions leading to significant CT dryout. It can be shown that contact conductance has steep variations in this temperature range.

### 3.2 Random Surface Conditions

Figure 7 shows the post-test CT dryout map obtained for testCSCB3. Since surface temperature distribution is random, CT temperature excursions can locally occur for relatively mild conditions. CT failure can therefore locally occur under these conditions if a local hot spot is large enough.

## 4. Main Uncertainties Affecting Code Predictions

### 4.1 PT/CT Contact Conductance Model

As explained in section 3.1, PT-CT contact conductance has large variability, is difficult to accurately model and has strong impact on the predicted FCI in the initial and later phase following PT/CT contact. In the later phase, in particular, modelling of contact conductance can have crucial impact when calculated heat transferred from PT to CT closely matches heat transferred to the moderator at the end of the dryout period. For these cases, an increase in the contact conductance modelled value by a factor of two or three can make the difference between predicting channel safety and predicting channel failure. This conclusion can be confirmed by performing simplified calculations using values measured in CSCB2.

Modelling of contact conductance can therefore be a source of main uncertainty in code predictions of fuel channel behavior following PT-CT contact.

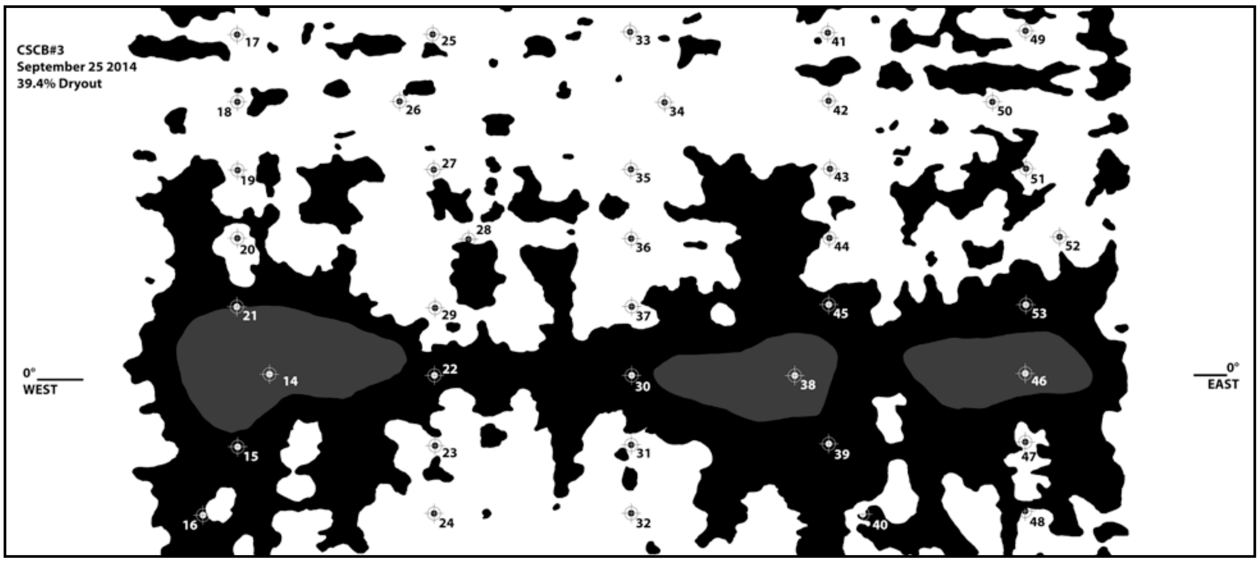


Figure 7 Map of dryout pattern in the heated zone on the CT surface in test CSCB3 (Black colour indicates oxidation on the calandria tube surface. Grey colour indicates bulged regions on the caladnria tube.)

### 4.2 Possible Existence of Hot Spots

As discussed in section 3.2, hot spots on the CT surface are random by nature and cannot be predicted by computer codes (refer to Figure 7). If they are large enough, they can lead to FC failure. Current computer codes conservatively assume the whole surface to be in dryout once CHF is reached. CHF is however based on predicted average surface temperature with no account for hotspots.

### 4.3 Cliff Edge Effects

Cliff edge effects may exist in this transient due to non-linearity in both:

1. The set of heat transfer and creep equations solved for this transient;

2. The PT and CT material properties around 800°C due to phase change.

The existence of cliff edges is apparent in Figure 4, showing code predictions for CT strain in relation to test conditions of PT heating rate and moderator subcooling.

## 5. Conclusions

Even though the CSCB test series is not yet completed, some preliminary conclusions may be attempted on the basis of the first three tests. It appears that CT material can sustain 2% plastic strain without failure, if the straining is arrested by timely rewet. It also appears that the conditions leading to 2% CT strain may be too close to channel failure conditions and too close to the region of cliff edge effects, where operation is not recommended.

These conclusions may change when the remaining CSCB tests are carried out and systematic analysis of the entire set is completed.

## 6. Acknowledgements

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