Modeling Background for Thermal-hydraulic Analysis Tool of CANDU Fuel Channel

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1. Introduction

The two pressure tube rupture events have been reported so far from CANDU reactors at the early 80s [1, 2]. When rupture of a pressure tube in a high power channel G-16 at Pickering Unit 2 occurred at full power in August 1983, approximately 1000 kg/min of fluid was reported lost through the two end fitting bellows at the two ends of the surviving calandria tube. Since the 2 m crack was located at the downstream end, all upstream fuel bundles saw increased flow and there was no fuel heat-up. However, an upstream crack would have caused reduced fluid flow past fuel bundles and would have had different consequence. In the case of pressure tube rupture from N-06 fuel channel of Bruce Power during a cold pressurization, calandria tube did not survive. In this type of failure when simultaneous ruptures of pressure tube and calandria tube occurred, large coolant flows may initiate from the two headers towards the break. These flows may cool the fuel bundles remaining in the channel. On the other hand, with calandria tube surviving the pressurization transient potential exists for local flow degradation and fuel heat-up.

The magnitude of fluid discharges through the PT/CT annulus onto the end fitting bearings and the following rupture of the end fitting bellows essentially define the break in terms of total fluid loss from the increased channel inlet flow. A pressure tube crack with calandria tube intact can result in channel response from benign to catastrophic. If the calandria tube survives the bellows downstream of the end fittings will likely rupture instead to relieve the pressure in the PC/CT annulus. Depending on the size and location of the crack, a degradation in fuel cooling may occur in fuel bundles under the crack or downstream of the crack. The magnitude of the discharge would be a function of the clearance within the end fitting bearings and may be limiting fluid loss from the fuel channel. The discharge into the feeder cabinet may not be detected early and the reactor will remain operational until another event like a channel failure due to hot fuel interactions occurs. These accidents have not been analyzed for Wolsong CANDU reactors, although in Canada these were considered within the design basis accident and have been examined in detail for some multi-unit stations.

In this study, a computer code PT-CRACK has been developed to assess the impact of pressure tube cracks with calandria tube intact. A loss of pressure tube geometric integrity due to a break (hole or a long crack) can result in loss or degradation of fuel cooling both in the vicinity of the crack and downstream of it. It will also cause pressurization of the otherwise unpressurized annular space between the pressure and calandria tube and discharge of the fluid through end fitting bearing clearances. In order to analyze this phenomena a special, dedicated methodology was required because the conventional one dimensional thermal-hydraulic methods such as in CATHENA, TUF, RELAP cannot capture the physics of the axial as well as cross flows. PT-CRACK code used a unique flow network analysis methodology to assess the on-power thermal-hydraulic response of fuel bundles in all CANDU fuel channels following onset of a crack or a rupture in pressure tube that causes cross bundle flows and new flow paths in the enlarged flow sub-channel outside the bundle and in PT/CT annulus.

This paper introduces the basic modeling issues of PT-CRACK and the how to model the flow paths in the fuel channel including both axial and cross flows.

2. Governing Accident Parameters

There are five governing parameters that define the accident considered in PT-CRACK.

- channel power
- header condition
- channel hydraulic characteristics
- pressure tube rupture geometry
- discharge through end fitting bellows

2.1 Channel Power

The operating channel power may vary by a certain margin about its time-averaged value. This is dictated by the positions of reactivity control devices, the fuel power and its burnup history. Sensitivity analyses must therefore be undertaken to assess the effect of these changes especially at the time of the pressure tube rupture.

2.2 Header Condition

Reactor power and the corresponding header conditions at the time of the accident determine not only the nominal channel flows but also the channel thermal-hydraulic conditions following a pressure tube rupture.

2.3 Channel Hydraulic Characteristics

The Wolsong feeders were designed to be approximately flow power matched and a significant design effort in sizing and placement was devoted to ensure these characteristics. In order to achieve this, inlet and outlet feeder pipes were fixed accordingly and a number of feeders were orificed, both for flow measurements and flow control. The feeder geometry also influences abnormal flows such as after a pressure tube rupture. In CANDU 6 reactors, the feeders were designed to maintain a design ratio between channel power and nominal channel flow of about 250 kW/(kg/s) with the nominal time averaged channel flows ranging from about 11 kg/s in the peripheral, low power channels to about 27 kg/s in the centrally located, high power channels.

2.4 Pressure Tube Rupture Geometry

The rupture geometry may be characterized by the parameters such as location of rupture (crack), length and shape of rupture, pressure tube geometry changes, fuel geometry changes, and local crushing or displacement of garter springs.

The pressure tube rupture geometry parameters may have the largest variability, for example, the crack may be closer to a hole, or to a through longitudinal crack of a range of widths. In some cases the crack in the pressure tube may represent the dominant resistance to the diversion of flow into the calandria tube annulus while in other cases of a wider crack the cross flow resistance of the rupture may be small compared to the resistance to cross flow across the bundle and into the annulus. Therefore, the crack geometry will affect the flow patterns and hence flow degradation in fuel bundles under and downstream of the crack.

2.5 Discharge through End-fitting Bellows

A pressure tube rupture may quickly (within less than a second) pressurize the space between the pressure tube and calandria tube and a continuum that will be established through the end-fitting bearings and the interconnected annular spaces between the lattice tube and the end fitting body, and through the broken bellows to the containment atmosphere. If the nickel bellows that are tested for only about 40 psig rupture are broken, a flow path to the containment will be established.

The pressurization of the annulus between the pressure and calandria tubes will result in bursting of one or both of the bellows at outside ends of the end fittings. The discharge characteristics are expected to depend not only on the end fitting geometry (mainly the complicated thin annular path between the annulus at the end of the pressure tube and the discharge location) but also on the upstream coolant conditions.

3. Parameters Affecting Channel Flow Pattern

The main modeling challenge is to compute the axial flow and cross flow patterns and the corresponding local coolant boundary conditions at fuel surfaces within the failed channel for a wide range of rupture geometries. Therefore, a steady-state, two phase fluid network model has been developed to estimate the fluid flow and enthalpy conditions which are then used to quantify the extent of dry-out at various fuel rings. Local estimates of maximum fuel sheath temperatures for potential fuel melting and the assessments of radiological consequences are also made.

Following parameters which affect channel flow pattern and hydraulics inside the fuel channel should be considered to develop the PT-CRACK code.

3.1 Flow Patterns in Un-ruptured Channel

Each CANDU fuel bundle consists of 37 fuel elements arranged in four concentric rings. The fuel elements are equally spaced along concentric pitch circles of diameters 29.72, 57.53 and 86.45 mm with 6, 12 and 18 fuel elements in the inner, intermediate and outer rings respectively with one central pin. Each fuel element is a sealed assembly containing natural UO_2 pellets, Zircaloy-4 sheath and Zircaloy-4 end caps. In each fuel bundle, 156 inter-element spacers are brazed to all sheaths at the mid-plane. In addition there are 54 bearing pads brazed to the sheaths of the outer elements at three planes. The ends of the fuel elements are welded to Zircaloy end plates.

Coolant interchange between sub-channels occurs due to a number of factors. These include natural turbulent interchange and mixing due to spacers and bundle end plates. The radial density and enthalpy variations in the fluid paths become minimal and data show that there are essentially one-dimensional sub-channel flows that are predominantly unidirectional along the tightly packed bundles.

Flow region around each fuel pin is geometrically unique and theoretically a large number of flow sub-channels may be defined. For practicality and sensible engineering analyses, two distinctly different annular regions within and around the fuel bundle are considered. An outer sub-channel is defined between the pitch circle of the outer ring of the fuel elements and the pressure tube. The inner region has a similar hydraulic diameter but specific flow area per element is considerably larger in the outer sub-channel. An appreciable fraction of the total channel flow passes through this outer region. We first consider flow distributions in these two sub-channels around the fuel string is the first step towards evaluating the consequences of a pressure tube rupture.

3.2 Effect of PT Creep on Flow Patterns

Effect of an increase in pressure tube diameter (brought about by its circumferential enlargement by rupture, deviation from a circular cross-section by sagging or enlargement by creep or ballooning) on the flow distribution among the two sub-channels is such that while the geometry of the inner of sub-channel is totally unaffected, the changes in outer sub-channel flow area and the wetted parameter are quite pronounced. Even if this occurs only in a small section of the pressure tube, the overall flow into the channel will alter due to a change in channel flow resistance. Locally, flow distribution among the sub-channels changes such that the fraction of flow that passes through the outer sub-channel increases.

When caused by a pressure tube strain, the most obvious effect is that an enlarged pressure tube will result in an increase in overall cross-sectional flow area. An initial channel cross-sectional flow area of about 3480 mm^2 increases to about 4340 mm^2 for a 5% diametrical creep. This 25 % increase in flow area will result in decreased pressure drop and hence an increase in channel flow and hence a feedback effect on pressure tube and fuel behavior.

An estimate of the single phase flow redistribution is presented in Fig. 1 and shows that the inner sub-channel flow which amounts to about 61% of the total channel flow for an un-deformed pressure tube can decrease to about 41% of the total channel flow with a 5% diametrical strain. The inner sub-channel mass flux at 5% diametrical strain would then be about 79% of the mass flux for an un-deformed pressure tube. Under normal conditions the outer sub-channel receives about 60% of flow into the inner sub-channel. For a PT with 5% diametrical strain the outer sub-channel would receive 40% more flow than the inner sub-channel as shown from the upper curve in Fig. 1.

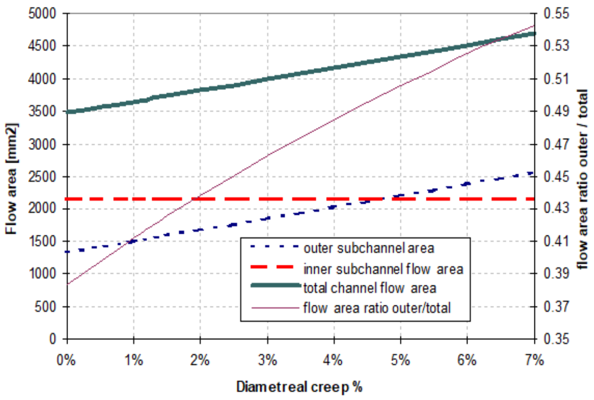

Fig. 1. Effect of diametrical creep on sub-channel flow.

3.3 Annulus between PT/CT

The annulus between the ruptured pressure tube and the intact calandria tube serves not only to feed the discharges through the broken end fittings, but also as a convenient flow bypass to the relatively resistive bundle. The rate and magnitude of flow redirection into the annulus is expected to be a function of the local, radial and axial pressure drop characteristics of the new geometric configuration and will strongly influence the flow distributions inside the pressure tube.

3.4 Effect of Feeder Thinning on Channel Hydraulics

Feeders connect the fuel channel end fittings at each end to common headers. There are about 7 km of 760 feeder pipes whose diameters are from 38 to 75 mm. Wall thickness of the feeder pipes, which is from 5 to 8 mm, is consistent with the 11 MPa design pressure and the total surface area is up to 1700 m^2.

Feeders corrode from inside and rust from outside. Under accident conditions they may oxidize both from inside and outside. The flow accelerated corrosion on the inside surfaces is higher for higher power channels that are least orificed and have larger flow velocities. The unfortunate choice of low carbon steel (ASTM SA106-Grade B) with actual chromium content at the lower end of the 0.04 to 0.4%, is one of the most critical life limiting factors for Wolsong feeders and hence the reactors. This steel is easy to work with but corrodes, erodes and oxidizes easily. Steels with higher Chromium content do not.

These feeder pipes are composed of a number of bends (~3000) and a number of elbows (~1500) that are particularly prone to erosion and flow accelerated corrosion. About 8% of wall thinning already occurs during bending at the manufacturing plant. Eroded iron dust is regularly seen deposited on spent fuel bundles. Flow assisted/enhanced corrosion/erosion leads to thinning of feeders by an average of about 0.1 mm/year and their inaccessibility leads to near impossible comprehensive monitoring.

Thinned feeders can leak, crack or fail catastrophically. The main issue with a gradually developing or sudden loss of coolant after failure of a stressed and thinned feeder under normal operation is that it can result in break discharges into the containment that are not immediately detected. For a leak in an inlet feeder between the header and the inlet end fitting, the remaining flow into the fuel channel can stagnate leading at full power to fuel melting and channel rupture. The rate of fuel heat-up at full power can be of the order of 100^o C/s such that the fuel melting and channel destruction can occur in minutes.

Reference 3 includes data on wall thinning in CANDU feeders and proposes a correlation for ‘remaining life’. From this data, we see that the feeders will thin to less than 50% wall thickness in 30 years and this is beyond its safe operating envelop and code requirements.

4. Modeling of Flow Path between the Headers

Fig. 2 shows the fuel bundle response owing to the pressure tube crack and following degradation of cooling.

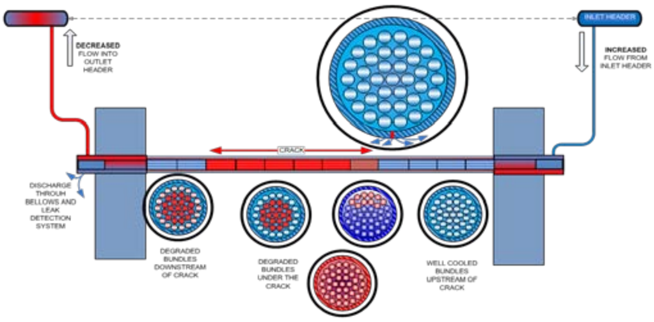

Fig. 2. Fuel bundle responses due to a degradation of cooling caused by a pressure tube crack.

There are 190 distinctly different inlet and outlet feeder geometries. Thus flow path between the headers for each channel offers different flow resistances that must be considered in conjunction with other channel specific parameters like thermal power that affect the fluid behavior driven by the relatively invariant header conditions and the newly formed crack. Therefore the analytical methodology is designed to consider for each fuel channel the following four axial regions.

(1) The flow path upstream of the pressure tube rupture (channel specific inlet feeder, the inlet end fitting and the portion of pressure tube containing fuel upstream of the crack). The length and composition of this path is different for each channel and may include a partial length of the fuel bundle.
(2) The flow paths created within and around the crack in the pressure tube.
(3) The annulus between pressure and calandria tube on either side of the rupture and enveloping the intact portion of the fuel channel and the path to bellows through the end fitting. This path not in direct mass communication with the flow paths within the pressure tube and has unidirectional flows towards the broken bellows. It includes heat transfer surfaces to the moderator and to the intact portions of the pressure tube.
(4) The flow path downstream of the pressure tube rupture (the portion of pressure tube and downstream of the crack, the outlet end fitting and the outlet feeder). The length and composition of this path is also different for each channel.

The fluid thermal and hydraulic behavior in all region except region 2 is adequately represented by a one-dimensional, homogenous equilibrium thermal hydraulic model.

In the region of the rupture, a multi-directional flow pattern will have to be modelled. Within region 2 the axial fluid flow distribution is dictated by the relative axial flow resistances of the three parallel flow paths. The radial redistribution between the three parallel flow paths is influenced by resistance to cross flow across the bundle and through the crack. In addition the fluid discharge through the end fittings dictates the flow in the annulus along with presence of garter springs and any debris. The end fitting discharge on the other hand depends upon the geometric clearances in the bearings surfaces and on the fluid enthalpy and pressure upstream of the end fitting. These are given by the pressure losses and heat transfer in the annular fluid paths from the ends of the crack to the discharge to atmosphere through the bellows as illustrated in Fig. 3.

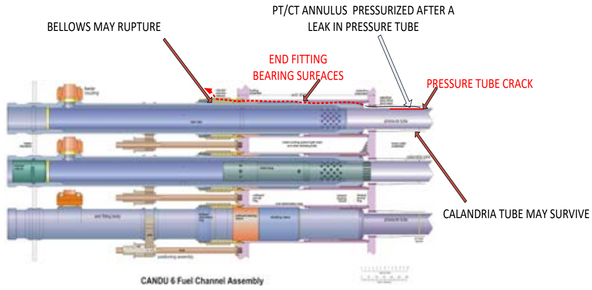

Fig. 3. Illustration of end fitting discharge path after a pressure tube crack.

5. Conclusions

This paper describes the technical background for development of PT-CRACK, which is a TH analysis tool for CANDU fuel channel considering the pressure tube crack with calandria tube intact. Unique flow network analysis methodology was used to assess the axial flow as well as the cross flow. PT-CRACK code will be used to assess the detailed TH phenomena of CANDU fuel channel and also to assess the safety margin such as critical channel power.

Acknowledgments

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