12th International Conference on CANDU Fuel
Holiday-Inn Waterfront Hotel
Kingston, Ontario, Canada, 2013 September 15-18

ANALYSIS OF FUEL END-TEMPERATURE PEAKING

Zhen Xu, Qing Jiang, Liping Lai, and Masoud Shams
Fuel Engineering Department, Candu Energy Inc., 2285 Speakman Drive
Mississauga, Ontario, Canada L5K 1B1

ABSTRACT – During normal operation and refuelling of CANDU®[1] fuel, fuel temperatures near bundle ends will increase due to a phenomenon called end flux peaking. Similar phenomenon would also be expected to occur during a postulated large break LOCA event.

The end flux peaking in a CANDU fuel element is due to the fact that neutron flux is higher near a bundle end, in contact with a neighbouring bundle or close to heavy water coolant, than in the bundle mid-plane, because of less absorption of thermal neutrons by Zircaloy or heavy water than by the UO_2 material.

This paper describes Candu Energy experience in analysing behaviour of bundle due to end flux peaking using fuel codes FEAT, ELESTRES and ELOCA[2].

1. INTRODUCTION

A CANDU reactor has many fuel channels in its core. Each fuel channel is loaded with a fuel string consisting of 12 or 13 fuel bundles (as illustrated in Figure 1). Each fuel bundle is made of a number of fuel elements welded to two endplates. Each fuel element contains a number of UO_2 pellets inside a Zircaloy sheath with two ends sealed by endcaps. A typical as-fabricated CANDU fuel pellet, fuel element, and a fuel bundle are shown in Figure 2.

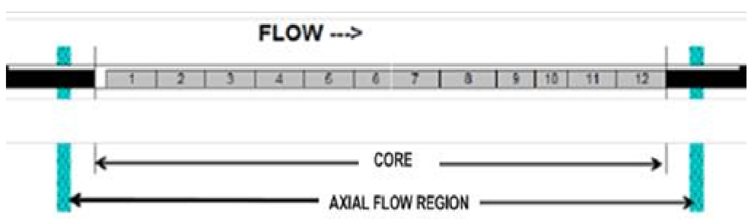

Figure 1 A CANDU Reactor Fuel Channel Loaded with 12 Fuel Bundles (Illustration)

Figure 2 A Typical CANDU Fuel Bundle, Fuel Element and UO_2 Pellet

1 CANDU® (CANada Deuterium Uranium®) is a registered trademark of AECL, used under exclusive license by Candu Energy Inc.
2 FEAT, ELESTRES, ELOCA and FEED are AECL fuel codes, used under exclusive license by Candu Energy Inc.

1.1 Fuel Temperatures during Operation

During operation of CANDU fuel, several factors can affect the fuel temperatures, for example,

- Bundle power and fuel element linear power,
- Bundle burnup and fuel element burnup,
- Coolant conditions (e.g., coolant temperature and pressure, flow rate),
- Heat transfer from pellet stack to sheath,
- Material properties in the pellet stacks and sheath,
- Bundle positions in the channel, and
- Bundle positions during on-power refuelling.

The effects of bundle power, burnup, coolant conditions, pellet-sheath heat transfer, and material properties have been extensively studied in the past. To understand the effects of bundle positions in the channel and during on-power refuelling on fuel temperature, end flux peaking on a fuel element needs to be considered. As described in Section 1.2 below, end flux peaking can cause fuel temperature increases at the end of bundles. During postulated large break LOCA events, end flux peaking phenomenon also exists prior to reactor shutdown.

Maintaining fuel temperatures below certain level is required to meet licensing requirements for operation. Therefore, the assessment of end temperature peaking in a CANDU fuel under both normal operation and postulated events is required. Such assessment is challenge involving a multi-dimensional but very localized thermal-mechanical analysis. This paper describes Candu Energy experience in analysing behaviour of bundle due to end flux peaking using fuel codes FEAT ([1] [2] [3] [4] [5]), ELESTRES [6] and ELOCA [7].

1.2 Effect of End Flux Peaking on Fuel Temperatures

During normal reactor operation, the local heat generation rate (or the local power density) in the nuclear fuel changes with operating power (i.e., linear power) and can also change in the axial directions due to the change in thermal neutron flux along the axial direction.

The thermal neutrons flux is higher near a bundle end, in contact with a neighbouring bundle or D_2O coolant, than in the bundle mid plane (as illustrated in Figure 3). Such phenomenon is caused by the less absorption of thermal neutrons by Zircaloy (in the case of bundle-bundle contact), or by D_2O coolant (in the case of bundle-coolant contact), than by the UO_2 material. This phenomenon is called “end flux peaking”.

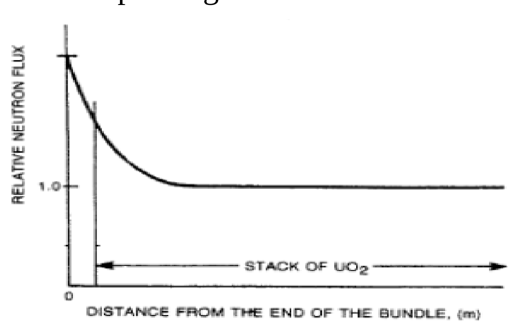

Figure 3 Illustration of End Flux Peaking in a Nuclear Fuel Element

The local heat generation rate (or the local power density) is mainly dependent on the thermal neutrons flux, hence, the end flux peaking causes "end power peaking" (i.e., heat generation rate peaking). The increase in local heat generation rate causes local temperature to increase, therefore, end power peaking in turn causes temperature peaking. The tear drop shape observed from the post irradiation examination (PIE) of an experimental fuel element in the past is the evidence of end temperature peaking, see Figure 4.

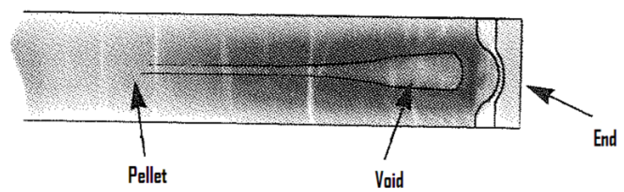

Figure 4 Neutron Radiograph Showing Tear Drop [2]

The neutron radiograph of Figure 4 shows a void near the end of a pellet stack. Such void is associated with temperatures above 2100 °C [2]. However, it is worthwhile to point out that end temperature peaking is very local to the ends of the fuel element due to the relative good cooling at the bundle end, the short range effect of end flux peaking and the poor thermal conductivity of the UO_2.

1.3 Temperature Peaking Analysis Scenarios

Depending on the operating conditions and bundle locations, end flux peaking will be different, which affects fuel temperature peaking and the maximum fuel temperature. To assess fuel temperatures, different scenarios may need to be considered, for example,

- Temperature peaking in a fresh fuel element in a fuel string (bundle-bundle contact)
- Temperature peaking in a fresh fuel element of a upstream bundle in a fuel string (bundle-coolant contact) during refuelling
- Temperature peaking in an irradiated fuel element of a bundle in a fuel string (bundle-bundle contact)
- Temperature peaking in an irradiated fuel element of a upstream bundle in a fuel string (bundle-coolant contact) during refuelling

Also for safety analysis, conditions will be different, e.g.,

- Temperature peaking in a fuel element of a bundle in a fuel string (bundle-bundle contact) during a postulated large break LOCA

Selection of scenarios for an analysis is dependent on the requirements of the analysis.

1.4 Tools Used for End Temperature Peaking Analysis

FEAT (Finite Element Analysis for Temperature) ([1] [2] [3] [4] [5]) is two-dimensional finite-element computer program for modeling and predicting thermal behaviour of CANDU fuel, under normal operating conditions, AOO conditions, and postulated overpower transient conditions such large break LOCA. The FEAT calculation output parameters include temperatures, heat flux, sheath oxidation thickness, and centreline temperatures and profiles.

The following factors are accounted for in the FEAT code:

- Radial distance-dependent heat generation due to flux depression (as a result of self-shielding and skin effect) in the pellet,
- Axial distance-dependent heat generation due to end flux peaking,
- Effect of pellet-sheath radial gap conductance on heat transfer from pellet to sheath,
- Effect of operating conditions (e.g., temperature, burnup) on thermal properties of UO_2 or (U, Dy)O_2 pellet and Zircaloy sheath and on heat transfer in the fuel element,
- Effect of time-dependent boundary conditions on heat transfer,
- Effect of time-dependence in heat generation (e.g., due to power pulse, or time-dependent end-flux peaking) on heat transfer, and
- Effect of pellet geometry (e.g., dishes, chamfers, central hole) on heat transfer in the fuel element.

FEAT is the main code used in end temperature peaking analysis, with use of some output parameters from ELESTRES [6] for normal operation conditions, from ELOCA [7] for postulated overpower transient conditions such as large break LOCA, and the boundary conditions from thermalhydraulic calculations. These output parameters from other calculations are used as additional input to FEAT.

2. ILLUSTRATION OF END TEMPERATURE PEAKING ANALYSES FOR NORMAL OPERATION AND NORMAL REFUELLING

2.1 Input Parameters

End flux peaking, such as illustrated in Figure 3, is used as an auxiliary input to FEAT, other input parameters include geometry, operating conditions (e.g., linear power, burnup, coolant temperatures, sheath-coolant film heat transfer coefficient), pellet-sheath gap conductance, end-pellet to endcap gap conductance (see 2.3), and material properties.

End temperature peaking in each fuel element in a fuel string can be assessed. The key parameters to choose the bounding cases are bundles at highest power positions, element at highest power ring in a bundle, and bundle with the highest end flux peaking ratio.

2.2 End Temperature Peaking

An example in end temperature peaking is described below. The scenario is the temperature peaking in an irradiated fuel element of an upstream bundle in a fuel string (bundle-coolant contact) during refuelling. In this example, the 8-bundle refuelling shift scheme is considered.

During the refuelling process, as the fuel string is moved with the pressure tube, new (fresh) bundles and existing (old/irradiated) bundles enter a region of relatively high thermal neutron flux along the channel which can lead to these bundles briefly experiencing high transient bundle powers. Although these high transient bundle powers are brief as bundles move in and out of the high flux region, the time is sufficient for the bundle to reach the maximum temperature. This is an important factor when assessing temperatures for the most upstream bundle adjacent to coolant (Fresh Bundle 1) during the refuelling operation. In the fuel temperature peaking simulation, FEAT accounts for the effect of the power peaking profile at the end for bundle-to-coolant contact conditions. As shown in Figure 5, the maximum temperature is predicted to occur several millimetres from the end of the fuel stack due to axial heat transfer at the end of the fuel element.

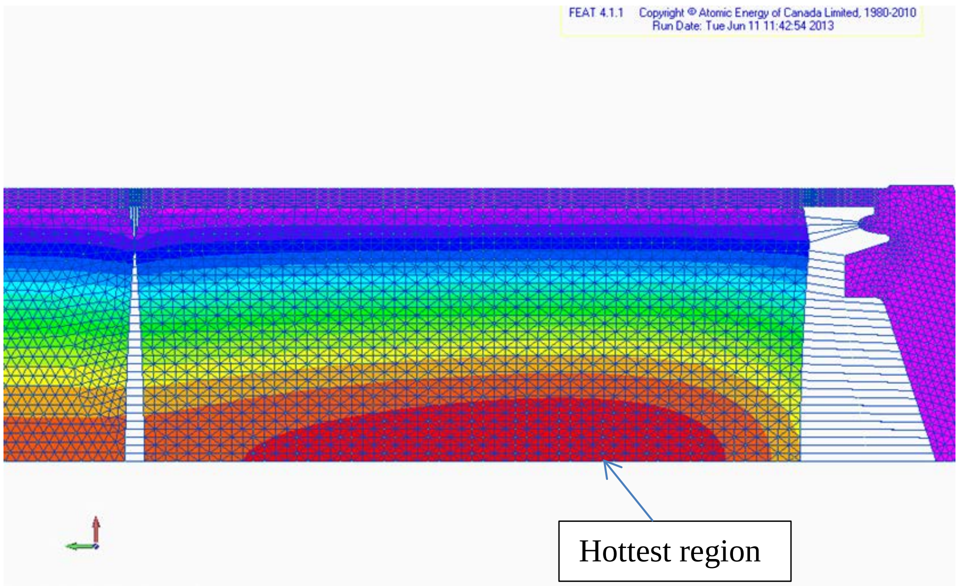

Figure 5 FEAT Calculated Detailed Temperatures near Bundle End

Another example is also the temperature peaking in an irradiated fuel element of an upstream bundle in a fuel string (bundle-coolant contact) during refuelling. However, a two-bundle shift refuelling scheme and H_2O as coolant in fuel channel are considered in this example. Figure 6 shows the temperature profile of a fuel bundle at a high element rating [8].

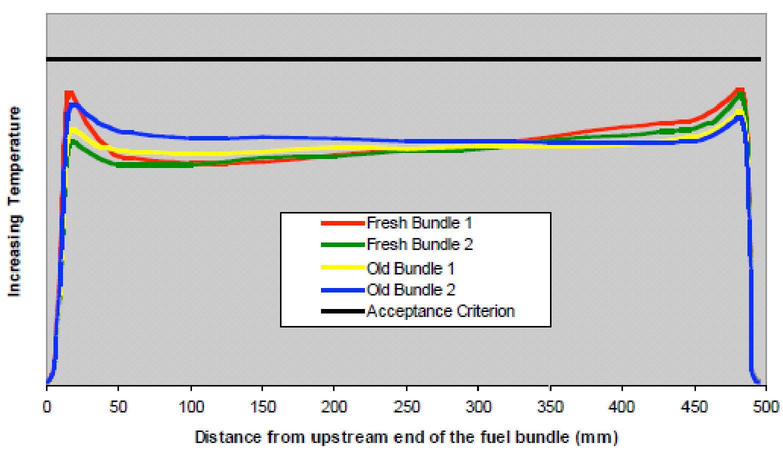

Figure 6 Calculated Outer Element Centreline Temperatures

This figure represents the variation of the fuel bundle centreline temperature for Fresh Bundle 1, Fresh Bundle 2, Old Bundle 1 and Old Bundle 2 where coolant is next to Fresh Bundle 1 at 0 mm. These temperature profiles include temperatures of the endplates, endcaps, pellet-to-endcap clearance, and the fuel stack. Fresh Bundle 1 has the highest peak temperature, and Old Bundle 1 has the lowest peak temperature. Peak temperatures for all bundles occur a few millimetres from the ends of the fuel stack due to axial conduction of heat. The slope of the temperature along the element length is due to the channel axial power profile.

2.3 Determination of End-Pellet to Endcap Heat Transfer

The end power peaking increases the local power in the end region, increasing the pellet temperature, causing end temperature peaking. Although the maximum power peaking occurs at the end of the fuel stack, the maximum temperature will generally occur several millimetres from the end of the fuel stack due to the axial heat transfer from the end pellet to endcap in the end region of a fuel element. The end pellet-endcap gap conductance is one of the key parameters affecting the value and position of the maximum fuel temperature. In past assessments, pellet-endcap gap conductance was applied in FEAT calculations based on the test measurements of CANDU fuel. To estimate the end pellet-endcap gap conductance more accurately, a manual iteration method can be applied.

After several times of manual iteration, the more accurate pellet-endcap gap conductance and maximum temperature can be found. In normal analysis, when difference between the final average surface temperature in the hot zone and that in last iteration is less than a tolerance, the simulation results are considered acceptable.

2.4 Fuel Temperature Change with Power History

Sometimes there is a need to study the effect of operating conditions (power history, burnup etc.), or sheath oxidation layer growth with power history, on detailed fuel temperatures. A utility-function tool (LINKS) can be used. Figure 7 shows an example of the utility-function, which allows the temperatures in a fuel element (entire pellet stack and sheath), as a function of the operating power history, to be predicted.

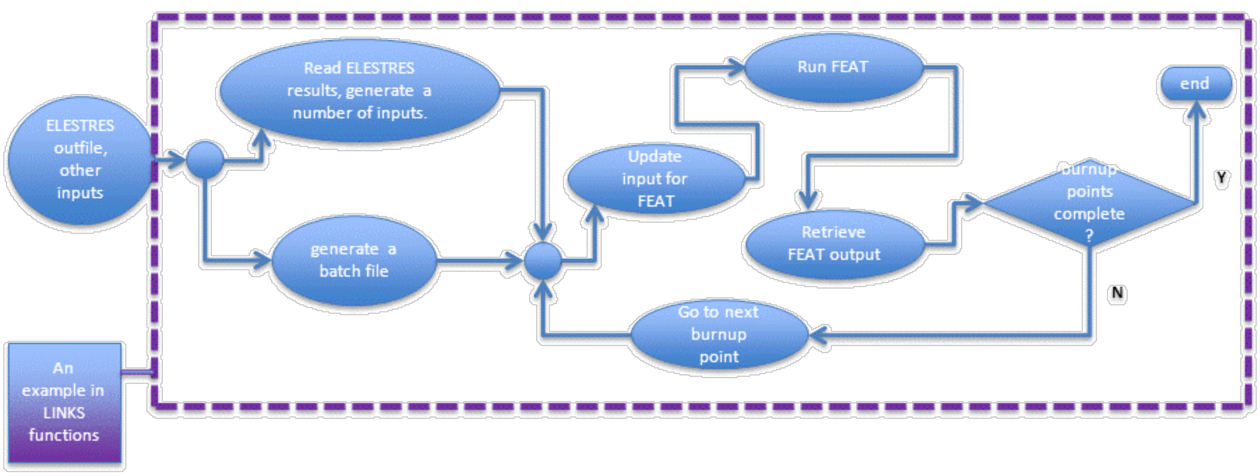

Figure 7 Illustration for Utility-Function Tool (LINKS) to Account for Effect of Operating Conditions on Detailed Fuel Temperatures

2.5 Sheath Oxide Layer Growth with Power History

Sheath oxidation is not significant in current CANDU fuel. For high-burnup fuel it may become significant and its effect on fuel requires consideration. In that case, the capability in FEAT code to calculate sheath oxidation can be activated by user.

When oxidation effect on fuel temperature is modelled, the first aspect to be considered is how the oxide layer thickness grows with operating conditions. The next aspect to be considered is how the heat transfer is affected by the presence of the oxide layer.

FEAT has built-in models to predict the build-up of the coolant-side sheath oxide layer. Figure 8 shows the comparison between FEAT predicted oxide thickness and the results from tests, as described in Reference [1].

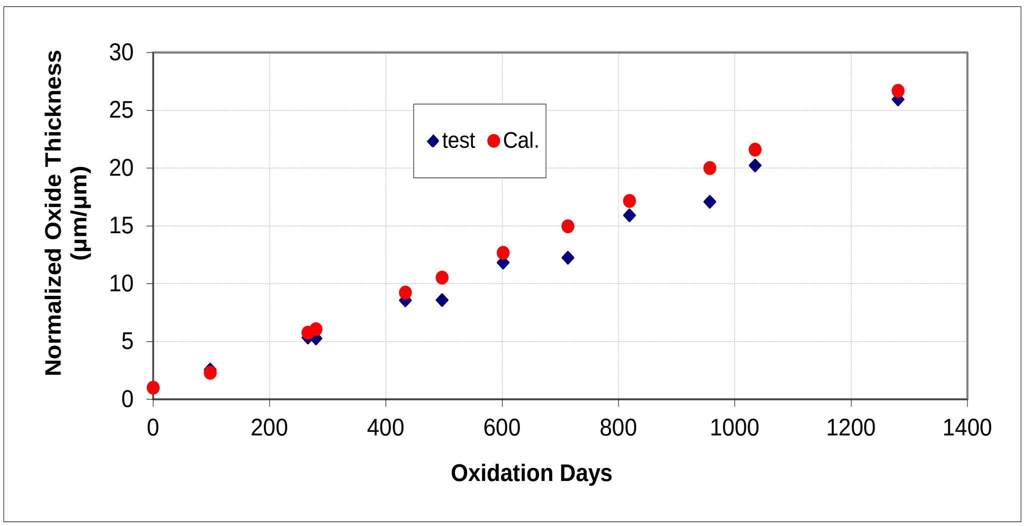

Figure 8 Comparison of FEAT Predicted Oxide Thickness with Test Data

Because of the low thermal conductivity of the oxide layer, the heat transfer through the sheath wall is reduced, which causes the oxidized sheath to have higher temperatures than non-oxidized sheath, as illustrated in Figure 9.

2.6 Sheath Hydride

As sheath oxidation is accompanied by the hydrogen pickup from coolant, the oxidation rate calculated by FEAT is also the key input to the down-stream code FEED[2] ([9] [10]), which is used to predict the following items in Zircaloy components of a fuel element (sheath and endcaps):

- hydrogen pickup under operating conditions;
- local hydrogen concentration as a result of hydrogen diffusion driven by concentration gradients, temperature gradient and stress gradients; and
- hydride formation (hydrogen precipitation).

Detailed descriptions on modelling and analysis of CANDU sheath hydriding are given in References [9] and [10].

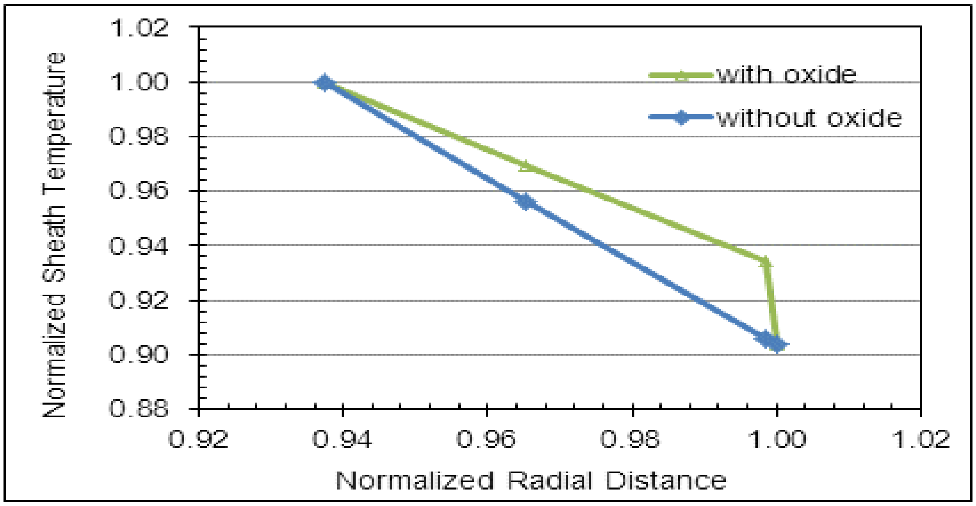

Figure 9 Illustration for Effect of Oxide on Sheath Temperature

3. ILLUSTRATION OF END TEMPERATURE PEAKING ANALYSES DURING A POSTULATED LARGE LOCA

3.1 Power Pulse and other Additional Input Files

The local heat generation rate in a fuel element can be affected by the end power peaking (due to the end flux peaking), and by the change of reactor power with time in some safety analysis scenarios. To describe these detailed variations during a transient, some auxiliary input files (called "Aux Infile" below) are required as additional input to the FEAT code for temperature calculation during transients such as a postulated large LOCA:

- Aux Infile 1: power pulse $p = \frac{P}{P_{nominal}}$, as a function of time, are based on physics calculations.
- Aux Infile 2: end power peaking profile during a postulated large LOCA. This profile is different from the initial end power peaking profile. Such end power peaking profile is from physics calculations.
- Aux Infile 3: initial end power peaking profile before a postulated large LOCA occurs. Such initial end power peaking profile is based on physics calculations.
- Aux Infile 4: film heat transfer coefficient (between the sheath and coolant) and the coolant temperature, as a function of time, are based on CATHENA [11] calculations.
- Aux Infile 5: gap conductances between the pellet stack and sheath, as a function of time, are based on ELOCA calculations.

3.2 End Temperature Peaking during a Postulated Large Break LOCA

End-flux peaking is important because it can affect the thermal-mechanical behaviour of fuel elements during a postulated accident, such as a large break LOCA. Particularly, a large reactor inlet header (RIH) break can cause temporary bundle separation due to channel flow reversal in the broken pass of the broken loop. Bundle separation may also occur in the intact pass of the broken loop during a large reactor outlet header (ROH) break. Such a temporary bundle separation leads to coolant fill-in between the two adjacent bundles and may induce higher end-power peaking for a short time between the break initiation and the time when the reactor is shut down. The end-flux peaking can potentially increase the sheath and fuel temperatures in the fuel end region, resulting in additional sheath failure leading to more fission product release.

An example is given here [12]. The focus of the analysis was on the temperature difference (delta-T) caused by end-flux peaking, rather than the absolute temperatures calculated by FEAT. Using this delta-T method can avoid any detailed assessment of uncertainty in the absolute temperatures calculated by the code. Conditions considered in the analysis include

- End- power profile (power peaking factors at the fuel end region),
- Coolant flow and temperature,
- Fuel and bundle conditions, and
- Heat transfer characteristics at the end region, which includes:
  - Fuel-to-sheath heat transfer coefficient,
  - Fuel-to-endcap heat transfer coefficient,
  - Sheath-to-coolant heat transfer coefficient, and
  - Endcap-to-coolant heat transfer coefficient

In this example (base case - Case 1) end-flux peaking has little effect on the initial sheath temperature (Figure 10) because it is controlled largely by the channel cooling condition when the sheath is in nucleate boiling at normal operation. However, end-flux peaking affects the sheath temperature when the sheath is in film boiling (dryout) during the transient.

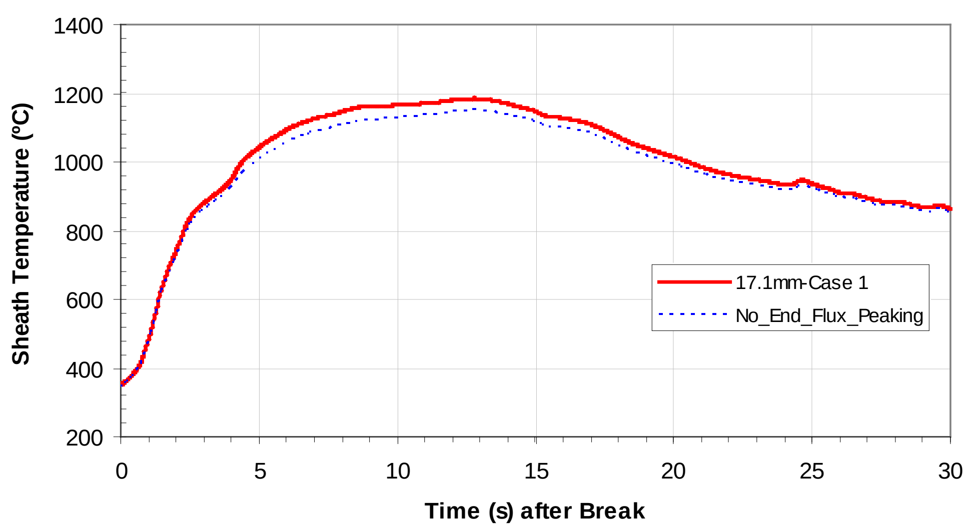

Figure 10 Calculated Maximum Temperatures in Sheath (Case 1)

(Case 1 is with 100% ROH Break Event) [12]

Figure 10 shows the sheath temperature transient is close to the case without end-flux peaking before 2.5 s. After that, although the linear power rate is decreasing following reactor shutdown, the sheath temperature continues to increase because of the degraded channel cooling condition.

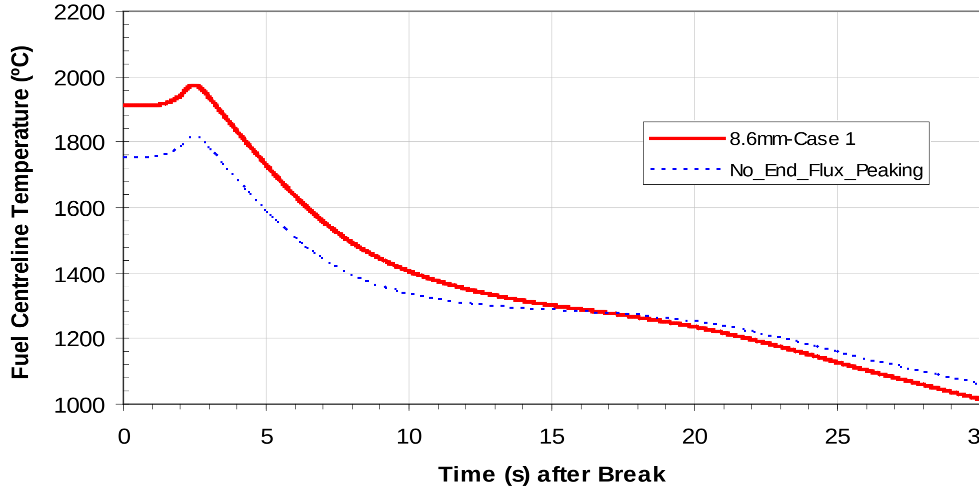

Figure 11 Calculated Maximum Temperatures in Pellets (Case 1)

(Case 1 is with 100% ROH Break Event) [12]

Figure 11 shows that the initial fuel centreline temperature at the fuel end region is much higher than the case without end-flux peaking, indicating that the most significant effect of end-flux peaking on fuel centreline temperature occurs at normal operation or prior to an accident transient. The calculated maximum fuel centreline temperature prior to the transient is 1914 ºC, which occurs at an axial location of 8.6 mm from the end of the fuel stack. Although the reactor trip occurs at about 1.1 s after the break, the short overpower transient leads to the maximum fuel centreline temperature to rise to 1976 ºC at 2.46 s. After that, the fuel temperature decreases in response to the rapid decrease in element linear power after reactor shutdown. After 18 s, the fuel centreline temperature at this particular axial location (8.6 mm) for the case with end-flux peaking becomes lower than that for the case without endflux peaking because continuous fuel-to-endcap heat removal takes place and the end-flux peaking effect at the end fuel region rapidly reduces with reactor shutdown.

Figure 12 shows the axial distributions of the fuel centreline temperature for several sampling times for Case 1. Unlike the sheath temperature change for the first 2.5 s during which the sheath temperature transient is close to that in the case without end-flux peaking (as shown in Figure 10), the pellet temperature changes differently. At the beginning of the transient, there is a large pellet temperature increase due to the deteriorated cooling. The highest fuel temperature occurs at 2.5 s at about 8.6 mm due to the overpower effect. At 30 s, the highest fuel temperature gradually reduces and moves inward to at about 19.6 mm (1.96 cm in Figure 12) and there is no significant end-flux peaking effect because of the pellet-to-endcap heat transfer and power shutdown.

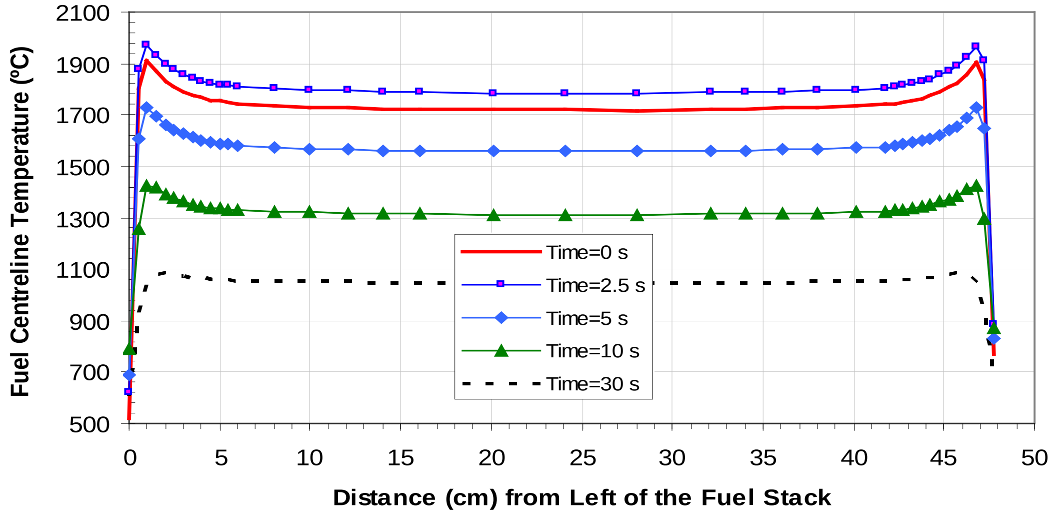

Figure 12 Calculated Centreline Temperatures with Axial Locations

(Case 1 with 100% ROH Break Event) [12]

4. CONCLUSIONS

In this paper, based on recent advancements in fuel modelling and fuel code development, a systematic approach for assessing CANDU fuel temperatures, used in Candu Energy Inc., is described. This approach addresses the needs in accounting of key effects when predicting fuel temperatures. Those effects include, for example, the end flux peaking during normal operation, normal refueling, postulated high temperature events such as large break LOCA; the effect of power history; and coolant-side sheath oxidation associated with high-burnup operations.

5. REFERENCE

[1] Qing Jiang, Liping Lai, Zhen Xu and Uttam Kumer Paul, "FEAT 4.1: Modelling of Sheath Oxidation and Heat Flow in CANDU Fuel Elements", Proc. of 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, Canada, 2010 October 17-20.

[2] M. Tayal, "The Finite-Element Code FEAT to Calculate Temperature in Solids of Arbitrary Shapes", Nuclear Engineering and Design 114 (1989), 99-114.

[3] S. Girgis, N. Singhal and M. Tayal, "Influences of Load Following, Partial Dryout, and End Flux Peaking on Temperature Distribution in CANDU Fuel", Proc. of 11th CNS Annual Conference, Toronto, Ontario, Canada, 1990 June.

[4] M. Tayal, S.D. Yu, C. Manu, R. Aboud, D. Bowslaugh and L. Flatt, "Modelling Transient Two-Dimensional Non-Linear Temperatures in Nuclear Fuel Using the FEAT Code", Proc. of 5th International Conference on CANDU Fuel, Toronto, Ontario, Canada, 1997, 352-363.

[5] Z. Xu, C. Manu, M. Tayal and J. Lau, "Validations, Verifications and Applications of the FEAT Code", Proc. of 19th CNS Annual Conference, Vol. 2, Toronto, Ontario, Canada, 1998 October 18-21.

[6] G.G. Chassie, Q. Jiang, H. Liu, M. Tochaie and Z. Xu, "ELESTRES 2.1 Computer Program for HighBurnup CANDU Fuel Performance Analysis", Proc. of 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, Canada, 2010 October 17-20.

[7] A.F. Williams, "The ELOCA Fuel Modelling Code: Past, Present and Future", Proc. of 9th International Conference on CANDU Fuel, Belleville, Ontario, Canada, 2005 September.

[8] T. Laurie and F. Iglesias, "ACR-1000 Fuel Element Rating and Temperature Analysis", Proc. of 10th International Conference on CANDU Fuel, Ottawa, Ontario, Canada, 2008 October 5-8.

[9] L. Lai, Z. Xu, Q. Jiang and G. Cheng, "FEED 1.6: Modelling of Hydrogen Diffusion and Precipitation in Fuel Bundle Zircaloy Components", Proc. of 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, Canada, 2010 October 17-20.

[10] Liping Lai, Zhen Xu and Qing (Alan) Jiang, "A Method to Model Hydrogen Precipitation", Proc. of 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, Canada, 2010 October 17-20.

[11] B.N. Hanna, "CATHENA: A Thermalhydraulic Code for CANDU Analysis", Nuclear Engineering and Design 180 (1998) 113-131.

[12] F.J. Gao, Q.M. Lei and Z. Bilanovic, "ACR-1000 End-Temperature Peaking Analysis under Postulated Accident Conditions", Proc. of 11th International Conference on CANDU Fuel, Niagara Falls, Ontario, Canada, 2010 October 17-20.

