ASSESSMENT OF FUEL AND FUEL CHANNEL BEHAVIOUR AT HIGH TEMPERATURE DURING A POSTULATED LOCA/LOECC EVENT

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ABSTRACT – To demonstrate defence in depth, an assessment of fuel and fuel channel behaviour at high temperature during a postulated large loss-of-coolant accident coincident with loss of the emergency core cooling system has been performed. The assessment of this beyond design basis accident in a CANDU®[2] core is based on recent regulatory requirements [1] for safety analysis and industry guidance for limit of the operating envelope/realistic operating envelope analysis methodologies. Utilising the best understanding and knowledge of fuel and fuel channel behaviour at high temperature, the assessment has demonstrated that the moderator water surrounding the fuel channels acts as an effective heat sink, together with other CANDU safety features and measures, to successfully mitigate the consequences of this postulated event.

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1. Introduction

To demonstrate the adequacy of safety design, a loss-of-coolant accident (LOCA) due to a break in the large-diameter piping of the primary heat transport system is postulated. For CANDU reactors, the results of LOCA analysis have shown that the consequences of the accident can be effectively mitigated by key safety features, including dual, independent reactor shutdown safety systems, each with high reliability and redundant design, and the emergency core cooling (ECC) systems which provide high-pressure coolant injection for the core makeup and establishes long-term recirculation/recovery for long-term fuel cooling.

Historically, a dual failure event is also postulated of a large break LOCA coincident with loss of the ECC systems (LOCA/LOECC). A postulated large break LOCA/LOECC has a very low probability, in the range usually associated with severe core damage events. In the CANDU design, the presence of moderator water surrounding the fuel channels is expected to act as an effective heat sink (Figure 1), together with other safety features, to prevent severe core damage following a postulated LOCA/LOECC. Therefore, the LOCA/LOECC event has been analyzed as a legacy safety case for CANDU reactors (References [2] and [3]). This event is re-analyzed

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here to assess the consequences and to demonstrate adequate defence in depth for a beyond design basis accident as specified in Canadian regulatory document (REGDOC-2.4.1, Reference [1]) given the CANDU reactor's inherent safety features and fail-safe design, and additional equipment and procedures to mitigate the consequences of such accidents.

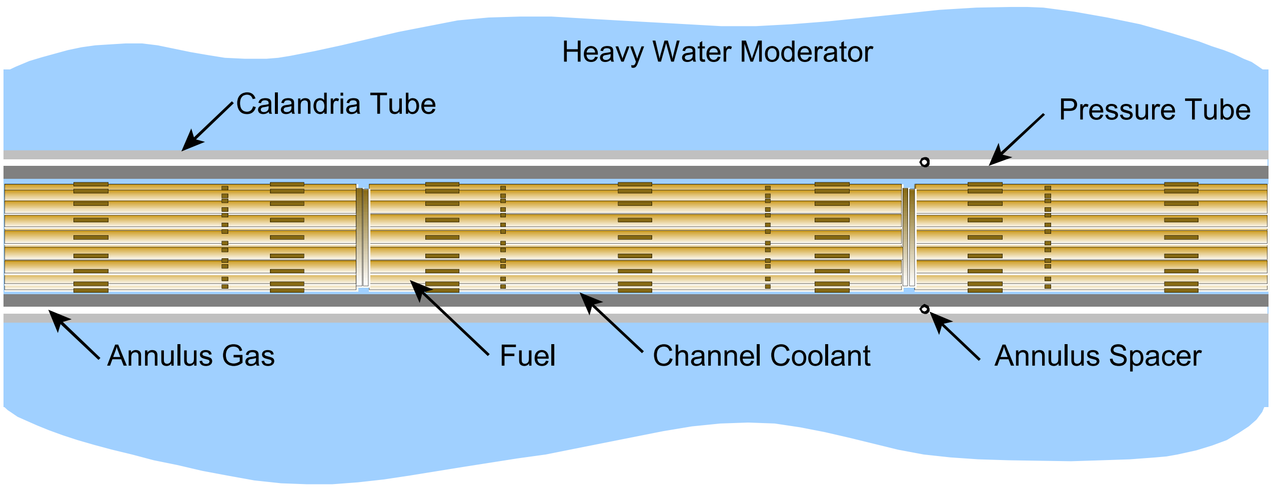


Figure 1 Moderator Surrounding Channels Acts as a Heat Sink

2. Beyond Design Basis Accidents and Analysis Approach

For a typical CANDU reactor, the frequency of large break LOCA (single failure) events is about 1.0×10^{-5} per reactor year. The large break LOCA with LOECC (dual failure) has a frequency well below 10^{-5} per year and is hence classified as a beyond design basis accident (BDBA) according to REGDOC-2.4.1 (Reference [1]).

According to REGDOC-2.4.1, the analysis of a BDBA can use best estimate analysis codes and assumptions that reflect the likely plant configuration and the expected response of plant systems and operators following the accident. As per CANDU industry guidance, the realistic operating envelope (ROE) approach is defined as a deterministic safety analysis methodology for BDBA events that assumes a realistic approach in setting key parameters and credited equipment performance, consistent with the reasonable and necessary degree of conservatism for these events as per REGDOC-2.4.1 (Reference [1]). BDBA analysis is performed in a realistic fashion, different from the limit of operating envelope (LOE) approach applied to design basis accidents (DBAs). In general, BDBA analysis is performed in a more realistic manner than DBA analysis under best estimate conditions with realistic assumptions for performance and operating configurations of structures, systems, and components.

For ROE application to BDBA analysis, the plant representation is generally based on design-centred values. The ROE analysis methodology applies realistic initial and boundary conditions and assumptions on availability reflecting the likely plant configuration and the expected response of plant systems and operators. The important initial and boundary parameters are set at realistic values reflecting normal operating ranges. Operational parameters and assumptions are best estimate with appropriate conservatism applied to account for normal operating ranges. BDBA analysis is performed in a realistic manner and, although the results retain a level of conservatism, there is no requirement for BDBA analysis results to bound all uncertainties in operational and modeling parameters. However, sensitivity analyses should be performed for ROE application in a manner similar to LOE, as considered necessary, to examine if there are cliff-edge effects where a relatively small change causes a significant change in the consequences.

3. Key Phenomena during Postulated LOCA/LOECC Events

For the postulated LOCA/LOECC events, any available core coolant makeup is not credited in the analysis. Hence, once the coolant inventory is nearly depleted in the affected channels, the fuel bundles and pressure tubes of these channels are subject to steam cooling conditions and start to heat up due to decay power. The calandria tubes of the affected channels remain cooled by the surrounding moderator water. It is expected that these fuel bundles experience high temperatures for an extended period of time. The figures of merit parameters relevant to the LOCA/LOECC event include fission product release from the affected fuel and channel integrity.

The important phenomena for the figures of merit are identified. At low steam flow conditions, fuel temperatures would be high. Under the high temperature conditions, the major heat transfer mechanism is radiation from the fuel to the pressure tube. Radiative heat transfer is the primary means of heat transfer from the fuel (impacting the sheath strain and fuel sheath temperature parameter) for the large break LOCA/LOECC event when the core is highly voided. Radiative heat transfer is the primary mechanism of heat transfer to the pressure tube (impacting pressure tube strain parameter). Zircaloy/steam thermal chemical reaction is the primary mechanism for production of hydrogen in the heat transport system (impacting on concentration of hydrogen parameter) and increasing fuel sheath temperature and in turn, radiative heat transfer (impacting sheath strain, fuel temperature and pressure tube strain). Fuel channel deformation is the most important fuel channel and system thermalhydraulics phenomenon (impacting pressure tube/calandria tube strains) and results in pressure-tube/calandria-tube contact (impacting the heat transfer path forming toward the moderator heat sink). These phenomena are modelled in the assessment of large break LOCA/LOECC, similar to the analysis of the large break LOCA.

Furthermore, fuel bundle deformation under the sustained high temperature conditions relevant to this postulated LOCA/LOECC event is inevitable. The fuel bundle is structurally formed with four components: end plate, end cap, sheath tubes and beryllium brazed-joints (Figure 2). The fuel is in the form of natural uranium dioxide pellets, sheathed and sealed in zirconium alloy tubes (sheath, Figure 2). CANDU fuel bundles perform well, retaining their configuration with insignificant deformation, during normal operating conditions and can be considered fit for service even after withstanding any effect induced by an anticipated operational occurrence. However, with fuel heat-up during the postulated LOCA/LOECC event, each of the four components of fuel bundle can deform structurally, resulting in significant fuel bundle deformation. The fuel bundle deformation with sustained high temperature conditions is discussed in the following sections based on the realistic operating envelope approach.

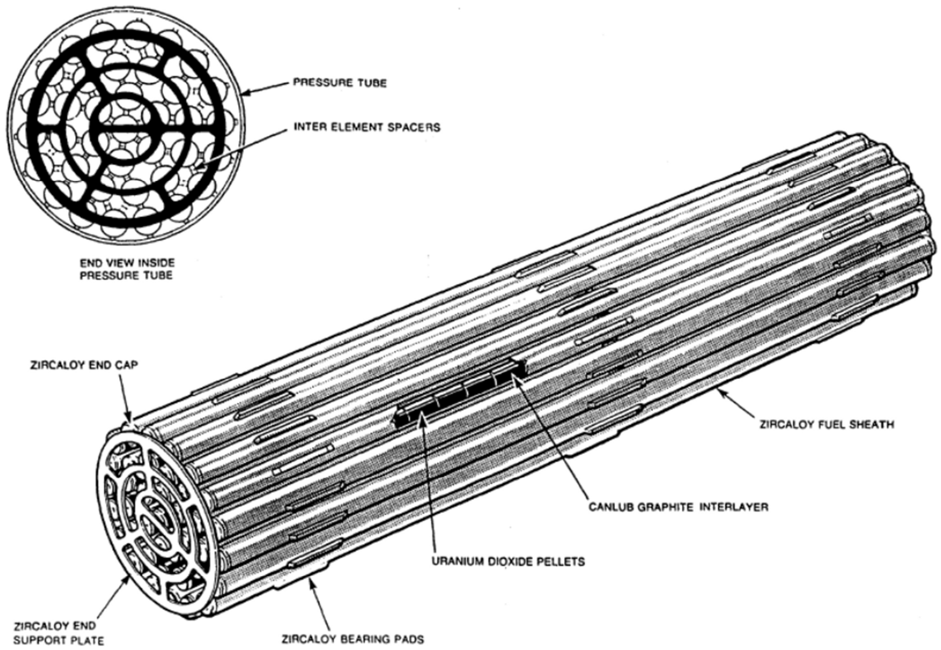


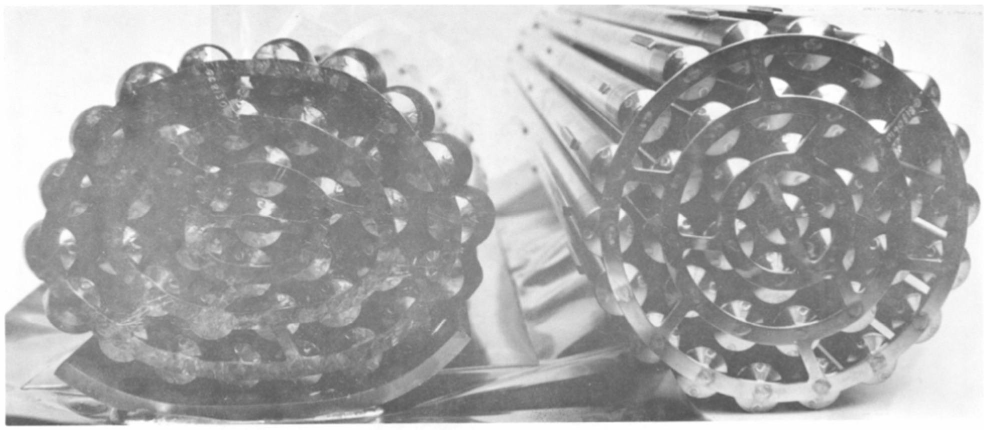
Figure 2 37-Element Fuel Bundle

4. Bundle Deformation with Sustained High Temperature

4.1 Bundle Slumping Observed in Experiments

Based on experimental results (References [4] and [5]), the end plate begins to collapse due to the elements' weight (in-plane deformation) when the Zircaloy temperature exceeds 1000 °C, and bundle "slumping" occurred in both of the tests with maximum temperatures of 1400 °C and 1600 °C, respectively. The test with the end plates showed that they have no structural strength above 1400 °C (References [4] and [5]). The end plates are squashed into an elliptical shape by the weight of the fuel elements (Figure 3). The results of the experiments conducted at 1400 °C are the same as those at 1600 °C, with only slightly less slumping of the bundle (References [4] and [5]). Fuel bundle slumping is accompanied by contacts among fuel elements, and between fuel elements and the pressure tube.

To better understand bundle slumping, a stylized computer simulation (References [6] and [7]) was performed with the focus on end plate in-plane deformation caused by the fuel element weight when the end plate is heated at a rate of about 120 °C/min from its normal operating temperature around about 300 °C. The simulation results indicated that with increased temperature, subjected to the same dead load (gravity of element weight); a large number of plastic spots appear on the end plate when its temperature increases beyond 1000 °C. The onset of the end plate local buckling is expected to occur by the time the Zircaloy-4 material changes into its β-phase at temperatures near 1000 °C.



(Slumped Bundle) (Un-deformed Bundle)
(From Figure 5 in Reference [4])

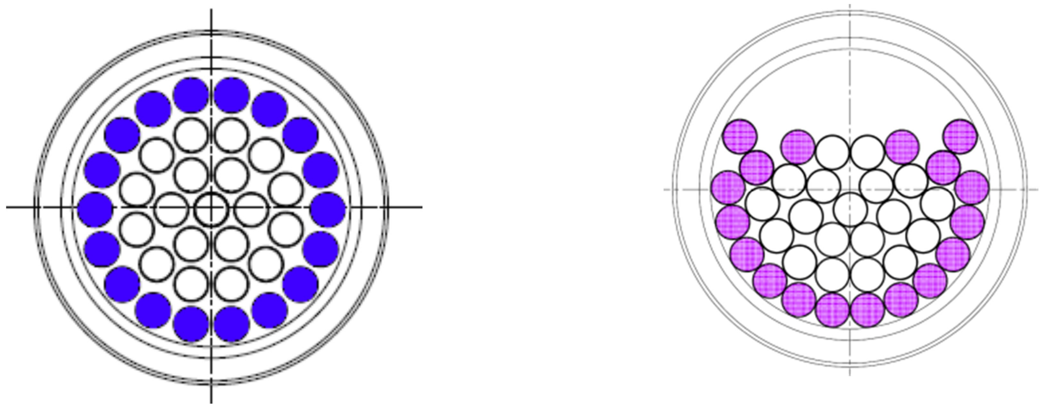
Figure 3 End View Comparing Un-deformed Bundle to Slumped Bundle in Bundle Heat-up Tests at Whiteshell Nuclear Research Establishment

4.2 Bundle Slumping Model

Based on experimental and stylized simulation results, bundle slumping is expected to occur at or prior to temperatures reaching 1400 °C. With local failure of end plates, the bundle collapses, settles down and contacts the pressure tube, similar to that shown on the left side of Figure 3. A slumped bundle (not necessarily disassembled) with the packed elements, would enhance the heat transfer toward the moderator by solid-solid contact in-between elements, as well as between elements and the pressure tube (at the bottom). Bundle slumping can be taken into account in the LOCA/LOECC analysis, as was done in Reference [3].

Bundle slumping affects the contact heat transfer within the fuel bundle, and between the fuel bundle and the pressure tube. Bundle slumping is assumed to occur when the maximum fuel land temperature reaches 1400 °C, which also ensures the bundle temperature is high enough for the onset of loss of end plate structural strength (above 1000 °C) and element sagging (above 1200 °C). The slumped bundle configuration used in the analysis is shown on the right side of Figure 4. The contact conductance can be assumed taking account for the contact heat transfer effect after the bundle slumping temperature is reached.

The slumped bundle affects the radiation heat transfer within the fuel bundle and between the fuel bundle and the pressure tube. This effect is accounted for in this analysis via the radiation view factor matrices for the assumed initial shape and slumped shape, respectively, as shown in the schematics in Figure 4. Radiation heat transfer occurs on the sheath outer surface. Radiation heat transfer with slumping is assumed once the sheath temperature reaches 1400 °C.



Left: fuel channel cross-section under normal operating conditions (initial shape)
Right: Fuel channel cross-section with slumped bundle at high temperature

Figure 4 Fuel Channel Cross-Section and Bundle Shapes

The slumped bundle would have some effect on channel flow. The heat removal rate depends on the convection due to coolant flow, heat conduction and thermal radiation. For a slumped bundle, convective cooling tends to be enhanced for the outer elements due to increased bypass flow while convective cooling for the inner elements tends to be reduced. A slumped bundle enlarges the bypass flow area above the fuel bundle; however, the net flow area remains about the same along the bundle length. With the trace flow assumed in LOCA/LOECC, the bypass flow area does not significantly change the overall trace flow rate. Hence, it is assumed the channel flow resistance remains the same as with the initial bundle shape. It is also expected that the bypass flow is mainly filled with lighter hydrogen gas during LOCA/LOECC and flow will be mixed with the remaining steam along the bundle, typically at the bundle middle plane and at the ends. Therefore, modelling of a packed bundle with multi sub-channels to obtain detailed trace channel flow and hydrogen concentration calculations within the fuel bundle is deemed unphysical and unnecessary.

4.3 Pressure Tube Deformation and Moderator Heat Sink

At the initial stage of a postulated LOCA/LOECC event, the core has a rapid depressurization while the coolant discharges out of the core. Due to the imbalance between power generation and fuel cooling, the deposited energy in the fuel increases fuel temperature prior to re-establishing fuel cooling. With degradation of the channel flow and increase of fuel temperature, the pressure tube temperature also increases. Pressure tube heating is by convective heat transfer from the hot coolant steam as well as thermal radiation from the overheated fuel. If the pressure tube becomes sufficiently hot while the channel pressure is still relatively high, the pressure tube may deform radially and fully contacts its calandria tube (pressure-tube/calandria-tube ballooning contact). Pressure-tube/calandria-tube ballooning contact challenges channel integrity, since the channel pressure is still relatively high. This has extensively been studied experimentally and analytically [8]. Moderator heat sink effectiveness is required to be demonstrated to ensure fuel channel integrity after pressure-tube/calandria-tube ballooning contact. The effectiveness of the moderator heat sink is primarily influenced by the moderator temperature distribution at the time at which the contact occurs. Assessments have shown that

CANDU reactors designed with a large amount of subcooled moderator water can passively provide a sufficient and effective heat sink by the time contact occurs, in particular for reactors with glass-peened calandria tubes [8]. When the coolant inventory of an affected channel approaches depletion, the channel pressure approaches atmospheric pressure; hence, the driving force for the pressure tube ballooning diminishes. It is worth noting that the CANDU core is designed with an effective ECC system for core inventory makeup to cool the channels and to terminate any further channel deformation. However, the ECC makeup effect is not credited in postulated LOCA/LOECC events.

Later in the transient, if the pressure tube becomes sufficiently hot, the pressure tube tends to deflect downwards (sagging) due to the load exerted by its own weight and that of the fuel bundles. If the high temperature conditions persist, the pressure tube may sag and contact the calandria tube along the bottom of the channel. The pressure-tube/calandria-tube sagging is due to axial strain (bending strain), which is relatively small at the time of pressure-tube/calandria-tube sagging contact (about 1% for the pressure tube strain) and is perpendicular to the hoop strain. Hence, pressure-tube/calandria-tube sagging and pressure-tube/calandria-tube ballooning have little influence on each other in terms of pressure tube local strain accumulation. The calandria tube is designed to support the full channel weight under normal operating conditions through its end rolled joints fixed on the calandria tubesheets. With pressure-tube/calandria-tube sagging contact, the calandria tube is subject to load conditions similar to the normal operating conditions, which is an order of magnitude below the calandria tube capacity (bending), even if a small bottom strip of the calandria tube is in film boiling, as shown in the sagging contact boiling tests [9]. Based on sagging contact boiling experiment results [9], there is no concern for fuel channel integrity regardless of whether or not the local sagging contact area is in the film boiling regime as long as moderator water covers the calandria tube outside surface. In the tests, the film boiling patches on the calandria tube that did occur all quenched, while the power was on and the water temperature was hotter than that used in operating reactor [9]. Therefore, a full inventory of moderator ensures that all channels are submerged to assure channel integrity in case of pressure-tube/calandria-tube sagging contact.

Both pressure-tube/calandria-tube ballooning and sagging contact help to establish a channel heat transfer path to the moderator, which is a low pressure, low temperature closed circuit. This has been considered in the assessment of LOCA/LOECC events. The major equipment in the moderator cooling circuit consists of the calandria vessel, two 100% capacity pumps, two 50% capacity heat exchangers, the associated piping, and two pony motors fed by Class III electrical power to drive the pumps when the main motors are stopped following the loss of Class IV electrical power. The moderator design heat load is about 5% of the core full power, which is significantly higher than expected decay heat in the affected channels if they are all transferred into the moderator. With a large amount of inventory (over one hundred cubic meters), the moderator temperature remains cool even if the circulation were to temporarily stop until automatic or operator manual recovery action would re-start circulation.

5. Example of Assessment Results after a Postulated LOCA/LOECC Event

An assessment of a postulated LOCA/LOECC event has been performed following the ROE approach for a typical CANDU 6 reactor with the focus on the fuel and fuel channel behaviour at high temperature.

The assessment results show that after the large-break LOCA the reactor is automatically shut down immediately by either of the two independent reactor shutdown systems. Reactor loop isolation is automatically and timely completed, which effectively limits the affected channels to within a half of the core (i.e., the broken loop) and isolates the channels in the other half of the core (i.e., the intact loop) from the break. Class III electrical power is automatically available for the scenario with assumed loss of Class IV electrical power following reactor trip. Hence, moderator circulation is recovered within a short period (less than three minutes), which ensures the availability and effectiveness of the moderator heat sink for channel integrity and channel heat removal. Circulation for the secondary heat transport system also recovers to provide the steam generator heat sink for the channels in the intact loop. Containment is automatically isolated which effectively retains the majority of the fission products released from the core and limits the release of non-condensable gases only to the public by leakage through the containment building. The ECC system for core inventory makeup is also atomically available by design; however, it is not credited in this assessment.

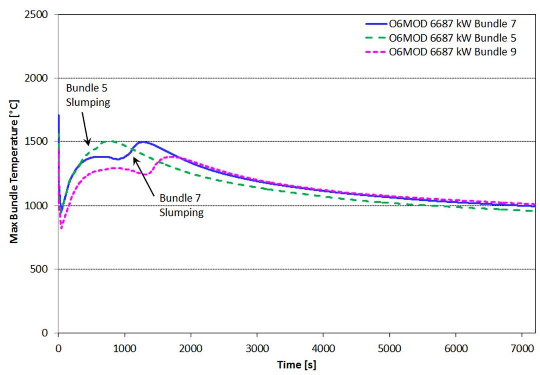


Figure 5 Maximum Bundle Temperature During a Postulated LOCA/LOECC Event

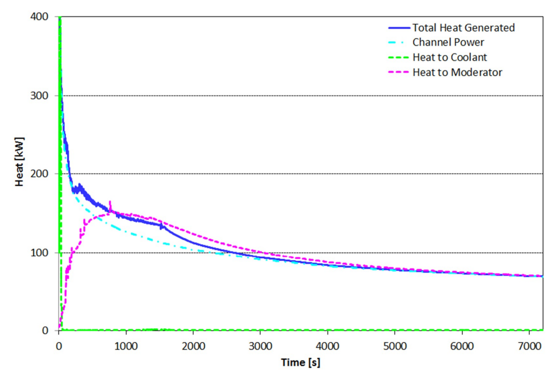


Figure 6 Heat Generation and Transfer to the Moderator for a High Power Channel during a Postulated LOCA/LOECC event

During the postulated LOCA/LOECC event, the assessment results show that severely degraded cooling conditions appear in some fuel channels where the fuel temperature gradually increases and remains at a sustained high level (Figure 5 and Figure 6) for a prolonged period (about 30 minutes). With near steam only conditions, the channel heat removal by the coolant is insignificant compared with the total channel heat generated (Figure 6). The total channel heat generation in the assessment includes the fuel decay power and extra heat induced by Zircaloy/steam exothermic reaction (the portion between the channel power curve and total heat generation curve in Figure 6). The fuel temperature tends to decrease following the decay power trend when channel heat generation is balanced by moderator heat removal through either radiation heat transfer or conductive heat transfer between the pressure-tube/calandria-tube or both. Taking into account bundle slumping, the peak fuel temperature (Figure 5) is below the fast reaction temperature for the Zircaloy/steam exothermic reaction (around 1850 °C), which would be overestimated if the bundle is unrealistically assumed to remain intact, as one case shown in Figure 7.

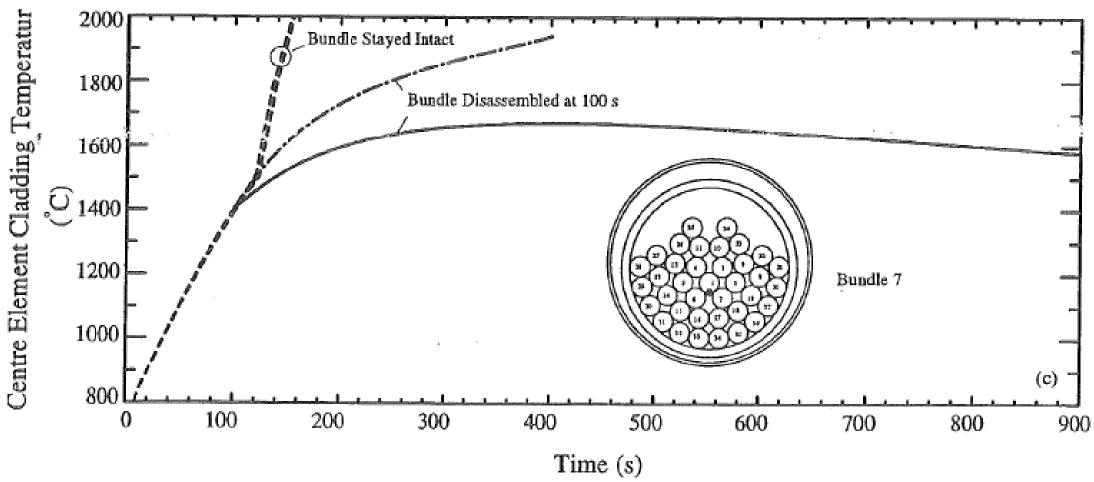


Figure 7 Comparison of Fuel Temperatures with/without Bundle Deformation Consideration During a Postulated LOCA/LOECC Event from Reference [3]

Overall, the moderator water acts as the backup heat sink to remove the heat generated in affected channels which would be almost fully voided during the postulated LOCA/LOECC event. Hence, the core remains intact as the fuel gradually cools down, which significantly reduces the risk for the fission product release to the public.

6. Remarks

Utilising the best understanding and knowledge of fuel and fuel channel behaviour at high temperature, the assessment has demonstrated that the presence of moderator water surrounding the fuel channels acts as an effective heat sink, together with other CANDU safety features and measures, to successfully mitigate the consequences of the postulated events. Hence, while the postulated LOCA/LOECC event is classified as a beyond design basis accident, the consequences are unlikely to progress into severe accident conditions. The results of this fuel and fuel channel assessments can be used as input to subsequent containment and dose analyses to ensure that the public is provided a level of protection with no significant risk to the life and health of individuals.

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