ANALYSES OF HOT CHANNEL FUEL CONDITIONS AND LOSS OF REGULATION ACCIDENT FOR CANDU-SCWR FUEL CHANNELS

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Abstract
Safe reactor operation relies on remaining below certain thermal limits during normal operation, anticipated operating occurrences and during accidents. With the very high temperature and pressure conditions proposed for the supercritical water reactor (SCWR), ensuring adequate cooling of fuel is of paramount importance. This study focuses on determining the pin temperatures, namely peak clad and fuel centerline temperatures, during normal operation conditions and reactivity induced accidents (RIA) in the most limiting fuel channel. The analysis has been performed using the FUELPIN point kinetics and heat transfer code which has been previously used in CANDU safety and licensing. The study was performed using proposed CANDU-SCWR conditions and operating parameters. Examined is the effect of various reactivity insertion rates on hot channel temperatures. As well, current CANDU neutronic trip coverage setpoints are examined to see how adequately current shutdown systems would perform in the CANDU-SCWR. The results of this analysis shows the response of the key parameters to reactivity insertion as well as the sensitivity to fuel pin diameter, normal operating power, sheath thickness and fuel-clad gap.

Keywords: Reactivity Initiated Accidents, Loss of Regulation, Fuel, Safety Analysis, Point Kinetics, Reactor Physics.

1. Introduction

The supercritical water cooled reactor (SCWR) is a Generation IV reactor design being developed by Canada. The potential benefits from this reactor are low cost electricity generation resulting from a higher thermal efficiency, improved safety and improved proliferation resistance.

The SCWR is essentially a light water-cooled reactor using coolant that is above the thermodynamic critical point (647 K and 22.1 MPa) during part of the thermodynamic cycle. The SCWR will bring considerable plant simplification through removing all the components related to the use of steam, i.e. steam generator, steam dryers, pressurizer, etc. Using, supercritical water for electricity generation is a common practice in many modern fossil stations, thus the turbine technology is available at present. Both fast and thermal neutron spectrum concepts exist, as well as pressure vessel and pressure tube designs. The thermal spectrum pressure-tube design with a heavy water moderator is the focus of Canada's Generation IV research. This Gen-IV research program is collaborative between many countries that aims to leverage resources in order to design an advanced reactor in a suitable time frame.

Using a supercritical water coolant presents some unique challenges. The higher operating temperatures and pressures required, as well as the corrosive nature of supercritical water introduce materials selection issues. Also, strong gradients in many important properties of water are seen around the pseudo-critical point. This makes the neutronics of the reactor strongly coupled to the thermalhydraulic behavior since the proposed coolant inlet temperature is below the critical temperature. The CANDU-SCWR has a unique advantage in that the moderator is separate from the coolant and hence some of the large effects of coolant density variations are less severe than in designs without a separate moderator system.

The current CANDU-SCWR proposed design differs dramatically from the design of current CANDU pressurized heavy water reactors. Due to the high operating pressures, online refueling is unfeasible and it is thus proposed that the core be batch fueled. This fact, combined with the use of light water coolant necessitates the use of enriched fuel. Further, to assist in fuelling, and to take advantage of potential thermalhydraulic safety benefits, it is proposed to place the calandria vessel in a vertical orientation as opposed to the horizontal calandria in current CANDU reactors. Some of the main features of the CANDU-SCWR are presented in the following table.

Parameter	Value
Operating pressure	25 MPa
Coolant inlet/outlet temperature	350 / 623 °C
Cladding material	Stainless steel
Fuel material	LEU or Th/Pu option
Thermal Power	2540 MW
Thermal efficiency	40 - 50%
Number of channels	300

Table 1: Proposed SCWR Parameters

This work examines the preliminary CANDU-SCWR concept by determining the steady state fuel and cladding temperature distributions and during reactivity induced accident (RIA) conditions. This work is performed parametrically by examining reactivity rate transients using a point-neutron-kinetics code, FUELPIN.

2. Description of FUELPIN code

FUELPIN is a computer code designed to predict fuel and clad temperatures during reactivity transients. The thermal conduction model within FUELPIN is based on a “lumped parameter” modeling approach that involves representing distributed temperatures by their average values [1]. Temperature dependent material properties, e.g. thermal conductivity, are accounted for in the code. Power transients can be specified from direct input of power versus time, neutron flux versus time or from an input of reactivity transient where the power is then calculated from point kinetics. As well, neutronic reactor trips can be simulated for the CANDU reactor shutdown systems SDS1 and SDS2 by entering the trip setpoints of log rate, linear rate or neutron flux and manual trip, as well as defining the characteristic reactivity insertion of the shutdown device. Within these calculations the code determines neutron detector response based on the neutron flux, the detector construction and materials, and appropriate time response functions for the associated electronics. The FUELPIN code has been used extensively in the safety and licensing of existing CANDU power plants. For the conservatism in this analysis, we assume the same basic detector design and electronics as for existing CANDU units as well as assuming the same reactivity insertion characteristics for the shut-off rods. In all likelihood, the CANDU-SCWR design will employ improved detector and shut-down systems and hence the analysis performed below is deemed conservative from that standpoint.

3. Description of problem

The operating conditions of the CANDU-SCWR will present challenges never before seen in nuclear reactors in Canada. This paper investigates the response of the highest power density fuel pin in the CANDU-SCWR to reactivity transients and in particular the determination of margins to fuel sheath temperature limit and fuel centerline melting. Previous work [2], using as reference a 43 element ACR-700 bundle design, has determined that the hottest fuel channel will have coolant temperatures exceeding 600°C and peak clad temperatures exceeding 700°C under normal operating conditions. More recently, a new 54 element fuel design has been proposed [3] which may provide additional thermal margins for the fuel. The purpose of this study is to provide some insight into the sensitivity of the fuel and clad temperature response to fuel and coolant parameters such as changes to fuel element geometry and linear element rating. The temperatures examined here are the fuel centerline temperature and maximum clad temperature. The goal for the centerline temperature is to remain below centerline melting. This study is performed assuming UO_2 fuel which has a melting point of approximately 2840°C. The sheath temperature limit is more ambiguous, due mostly to uncertainties in the design and materials of the cladding. Here it is assumed that the clad is stainless steel; an assumption based on the poor resistance of zirconium based alloys to the corrosive nature of supercritical water and to the fair transparency of stainless steel to neutrons. Recommended values for the temperature limit of stainless steel clad are 740°C for maximum inner surface clad temperature in the peak channel, 850°C for normal operating transients and 1260°C for design basis accidents [5].

The design variables examined in this study are: linear element rating (LER), fuel element radius and clad thickness. It is first necessary to estimate the LER for the hottest fuel element in the core. Based on a thermal power of 2540 MW and 300 fuel channels [4], we arrive at an average channel power of approximately 8.5 MW, in agreement with [2]. Assuming a core peaking factor of 1.2 and a typical channel power uncertainty of 5%, the peak channel power is approximately 10.6 MW. Further, given a bundle design containing 54 identical power producing fuel elements [3], and a channel length of 5 meters, it is calculated that the average linear element rating for this high power channel is approximately 39 kW/m. To compute the hottest fuel element LER, we assume additional peaking factors to account for the axial and radial power distributions in this peak channel (a factor of 1.2 is applied to account for the bundle radial peaking while and axial flux factor of 1.2 is applied for the channel peaking factor) this gives the maximum LER for the hottest fuel element in the core to be around 56 kW/m. For consistency to the existing CANDU power limits and to bound the projected LER of 56 kW/m, the reference LER used here is 60 kW/m. A corresponding coolant temperature of 600°C is selected at this location which is conservative since the peak bundle power likely occurs near the middle of the fuel channel where the coolant temperature at this location is significantly below this value.

The heat transfer coefficient is another significant input to the code. Numerous papers exist in literature on the determination of this coefficient. It is noted for supercritical water reactor conditions that the heat transfer coefficient is generally in the range from 5 – 20 kW/m^2°C [2,6,7]. For simplicity, the heat transfer coefficient used throughout this work is 12 kW/m^2°C, which is approximately the median value expected near the center of the fuel channel.

The fuel pellet radius chosen is 0.6 cm: however at this point in the design stage no information is available on the clearance between the fuel pellet and cladding material (i.e. gap thickness or gap conductance). Current CANDU reactors utilize a collapsible zirconium alloy sheath, which produces good contact conductance between fuel and sheath during operation until an event occurs such that fission gas pressure builds up inside the element and the sheath lifts off of the fuel. It is not known whether this will be featured in the CANDU-SCWR, so the gap size selected here is an estimate of 0.25 mm (comparable to that in [5]). The sensitivity to variation of the gap size is also examined.

The final part of the study looks at times to initiate reactor trips and associated temperature increases during various positive reactivity insertions. The shutdown system is initiated by trips that can be modeled in the FUELPIN code by specifying trip setpoints. Included are neutron overpower trips (NOP) with setpoints of 106% full power (this represents the minimum margin to NOP trips in existing CANDU plants), and two log-rate trips with setpoints 0.10 s^{-1} and 0.15 s^{-1} respectively representing SDS1 and SDS2 shutdown systems in current CANDU reactors. The reactivity insertion rates looked at were 0.01 milli-k (mk)/second, 0.1 mk/second and 1 mk/second (1 mk = 100 pcm).

4. Results of FUELPIN calculations

4.1 Comparison of FUELPIN result with FlexPDE software

To test the heat transfer result of the FUELPIN code, a check was first done using the FlexPDE, finite element partial differential equation software. A simplified finite element model was made consisting of a single fuel element with cladding surrounded by coolant at 600°C. The fuel and clad thermal conductivities used in FlexPDE were the average values used in FUELPIN. The dimensions chosen were the same in both cases: 0.6 cm radius for the fuel pellet with a 0.2cm thick sheath. In this simplified model, there is assumed to be no gap between fuel and sheath, and is input into the FlexPDE model using a very low contact resistance (in FUELPIN as a very large contact conductance). For these conditions, the fuel centerline temperature reported by FlexPDE is 2529°C while FUELPIN reports 2542°C. While the fuel surface temperatures are 824°C and 822°C in FUELPIN and FlexPDE respectively. For these typical operating conditions the finite element solutions demonstrate that the lumped methods employed in FUELPIN are sufficient.

4.2 Temperature sensitivities to LER, fuel radius, clad thickness, gap size

The parameters used in the reference FUELPIN case are shown in Table 2.

Parameter	Value
Outer fuel radius	6 mm
Initial coolant temperature	600 °C
Gap thickness	0.25 mm
Linear element rating	60 kW/m
Fuel Density	10.12 g/cm^3
Clad Density	7.9 g/cm^3
Clad Thickness	2 mm
Heat transfer coefficient	12 kW/m^2 K
Gap Conductance	10 kW/m^2 K
Initial Power Level	100% full power

Table 2: FUELPIN reference case parameters

Running this reference case in FUELPIN gives the following temperatures at normal operating power:

- Clad average temperature: 748.1°C
- Fuel average temperature: 1831°C
- Fuel centerline temperature: 2684°C

It is noted that the result FUELPIN provides for the clad temperature is for the clad average temperature and not the maximum temperature. While the recommendation of 740°C for the maximum clad temperature [5] during normal operation has been exceeded slightly, it is observed that the clad surface temperature remains reasonably close to this limit. For this case the fuel centerline temperature is below the melting point of UO_2 (2840°C) but is also relatively high. It is expected that further fuel bundle design refinement and improved heat transfer assumptions will increase the margins during normal operating conditions. The remainder of this section focuses on the changes to these temperatures as a result of adjusting the parameters in Table 2.

4.2.1 Temperature sensitivity to fuel radius and linear element rating

Figures 2 shows the FUELPIN results for clad temperature with respect to changes in fuel radius, and for various linear element ratings under stead-state normal operating conditions. As seen, the clad temperature is much more sensitive to fuel pellet size than the centerline temperature is. Both show a fairly large response to change in linear element rating. Furthermore, for the clad temperature, a larger change is seen for the smaller fuel pellet and increasing LER, than for the larger pellets. This is thought to be due to a higher power density in the smaller pellets for a given LER. For the case of a linear element rating of 70 kW/m, it is seen at 100% full power, the fuel centerline is always above the melting point. The melting point is also exceeded for the case of 60kW/m for the smaller 3 and 4 mm radius fuel pellets. Based on this parametric evaluation, a reduction in the LER for the CANDU-SCWR should be considered to ensure sufficient thermal margin to clad and fuel limits during normal operating conditions. Alternatively annular fuel pencils, similar to the VVER may need to be considered.

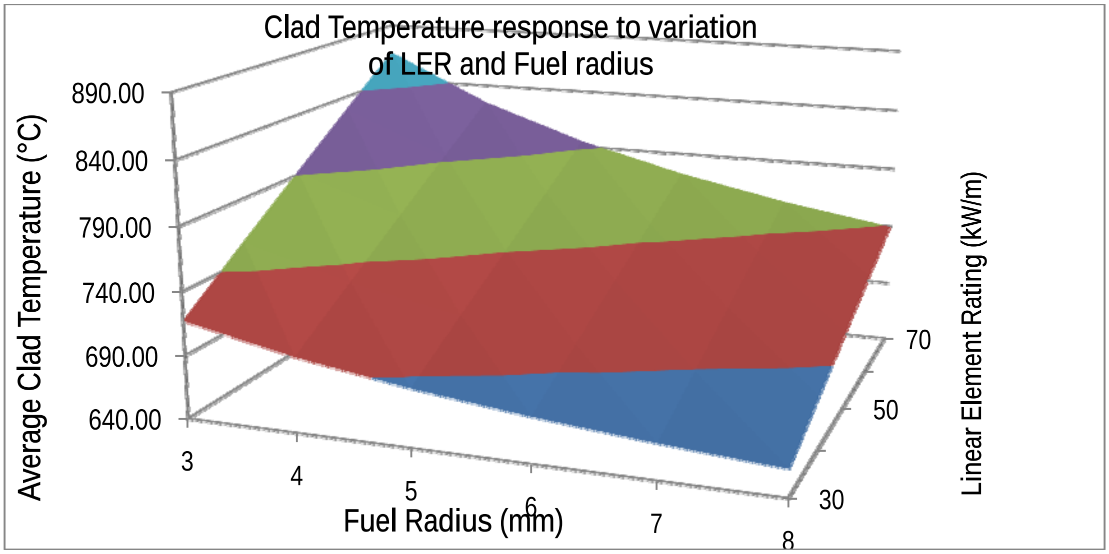

Figure 2 Clad Temperature with variation in LER and Fuel pellet radius

4.2.2 Temperature sensitivity to clad thickness and linear element rating

Seen below is the effect of varying clad thickness on fuel and clad temperatures. Overall there is very little effect on either clad or fuel centerline temperature by varying the clad thickness. There is a slight increase in clad temperature as the clad is thickened due to the added thermal resistance.

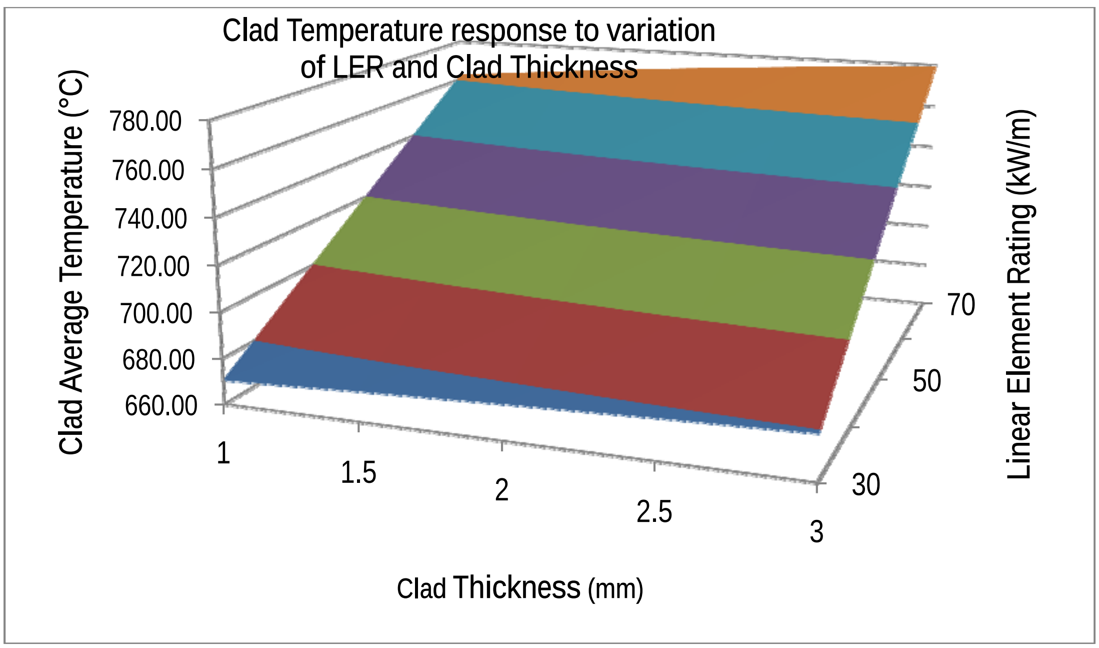

Figure 3: Clad Temperature with variation in LER and clad thickness

4.2.3 Temperature sensitivity to fuel-sheath gap thickness

For the analysis of the temperature sensitivity to fuel-sheath gap thickness, the fuel pellet diameter was adjusted along with the gap size such that the total fuel element size was equal to the reference case (8.25mm). This was done since by increasing the gap size only, the total heat transfer surface is increased non-monotonic results due to the competing effects of added thermal resistance from the gap size increase, and the increased heat transfer area from the larger sheath. A number of gap sizes were modeled ranging from 0.1 mm to 0.5 mm. Overall the gap size has little effect on either fuel centerline or clad temperature. It is noted that for the LER of 70 kW/m, the fuel has exceeded the melting temperature; the corresponding clad temperature an LER of 70 kW/m is 771.9°C, much higher than the limit of 740°C for normal conditions.

4.3 Loss of regulation transient analysis

For the loss of regulation (LOR) analysis, the reference fuel element using both 60 kW/m and 50 kW/m linear element ratings were simulated. The 50 kW/m rating was used here due to the fact that the 60 kW/m case has a steady state clad temperature in excess of the 740°C recommended limit for normal operating conditions. In this situation, the 50 kW/m rating is deemed a more appropriate limit for normal operation. In either case, simulations were run subjecting the element to reactivity insertion rates of 0.01 mk/s, 0.1 mk/s and 1 mk/s. The range of reactivity insertions was selected based on the reactivity mechanism worth in existing CANDU reactors and their speed of insertion. FUELPIN was provided with typical point kinetics data of delayed neutron fractions and decay constants for CANDU U-235 based fuel specified in the FUELPIN documentation. Due to the use of heavy water as a moderator, the delayed photoneutron groups are also included. The prompt generation time used was 10^{-4} seconds, a value roughly one order of magnitude shorter than existing CANDU reactors at 0.9 milliseconds. This was chosen to provide a conservative estimate for the CANDU-SCWR and to ensure the results bound the expected reactor physics behavior.

Each case was simulated with the reactor trip enabled and again with trip disabled. In the trip enabled case, two trips are required to initiate the reactor “shutdown”. Four reactor trip setpoints were used. They are based on the SDS1 and SDS2 shutdown systems in current CANDU reactors. The aim is to assess the applicability of current CANDU trip coverage applied to the CANDU-SCWR. The first two trips represent the neutron overpower trips (SDS1 and SDS2 in CANDU) both with a setpoint of 106% full power. Although both systems have the same setpoint, the design of the SDS1 detector gives prompt response while the SDS2 responds with a slight delay. This feature is included in FUELPIN and is seen in the results as the SDS1 neutron overpower trip always occurs prior to SDS2. The second two trips are neutron log rate trips with setpoints 0.10 s^{-1} and 0.15 s^{-1} for SDS1 and SDS2 respectively. The characteristic shutdown reactivity insertion used in the simulations [1] is given in Table 3. An interpolation is performed by the code for times between the points listed in the table. Overall it is assumed that
-63 mk can be inserted within 2.3 seconds. With the trip enabled, this rapid introduction of negative reactivity is shown to rapidly reduce reactor power. Each simulation was run for times up to 25 seconds and it was found in all cases the trips occur well before 25 seconds.

Time (seconds)	Reactivity insertion (mk)	Time (seconds)	Reactivity insertion (mk)
0	0	1.4	-13.1
0.2	0	1.53	-21.9
0.67	-0.57	1.67	-35.7
0.84	-1.7	1.82	-53.7
0.99	-2.9	2.3	-63
1.14	-4.9	3	-63
1.27	-7.9	10000	-63

Table 3: Characteristic shutdown reactivity insertion

4.3.1 Case 1: 0.01 mk/s insertion rate

Figure 4 shows the increase in fuel power over time for a 0.01 mk/s reactivity insertion rate for the case of no reactor trip and the case in which the trip was enabled.

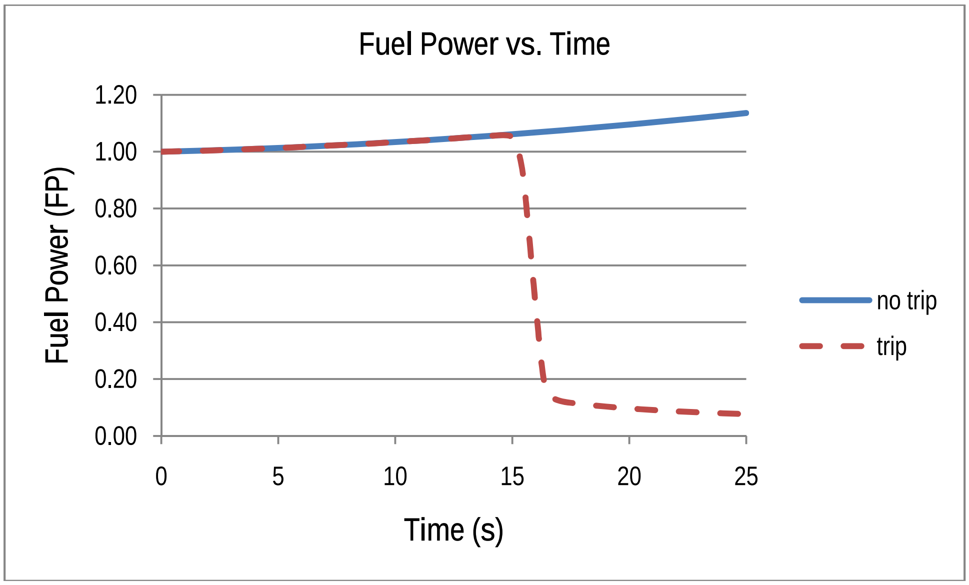

Figure 4: Fuel Power vs. Time for 0.01 mk/s reactivity insertion rate

The corresponding change in average clad temperature and fuel centerline temperature is shown in Figures 5 and 6 for both the 50 kW/m LER case and 60 kW/m LER case. The first, SDS1, neutron overpower trip occurs at 14.28 seconds while the second, SDS2, neutron overpower trip occurs at 14.74 seconds, initiating shutdown. The log rate trips do not occur here as the rate of neutron flux increase is too low. The maximum clad temperature and fuel centerline temperatures predicted by FUELPIN for both the enabled and disabled trip cases at this point are given in Table 4.

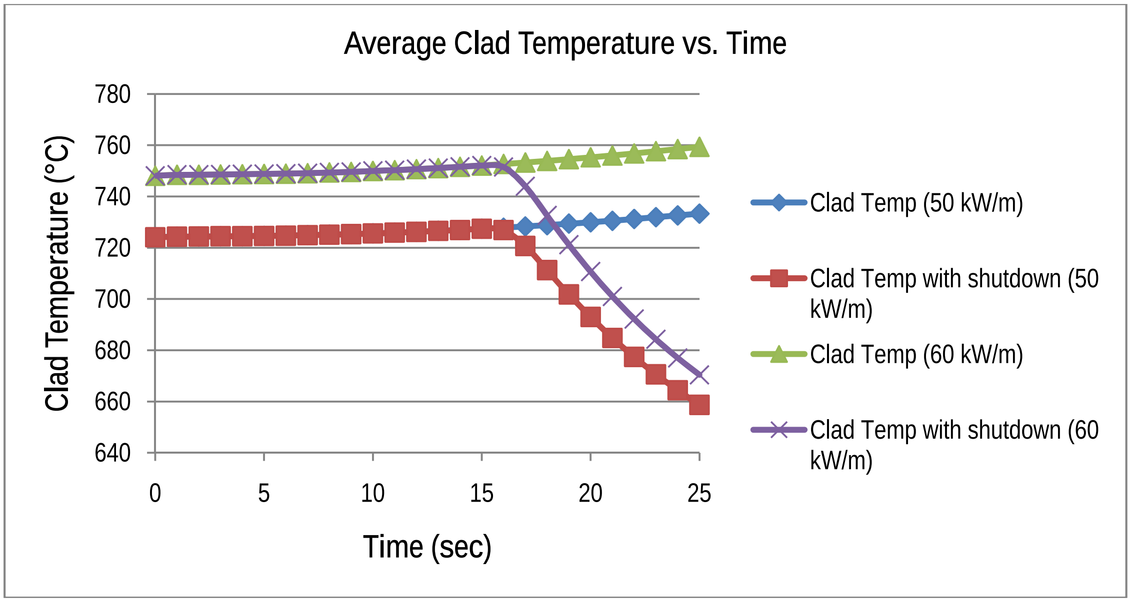

Figure 5: Average Clad Temperature vs time for 0.01 mk/s insertion rate

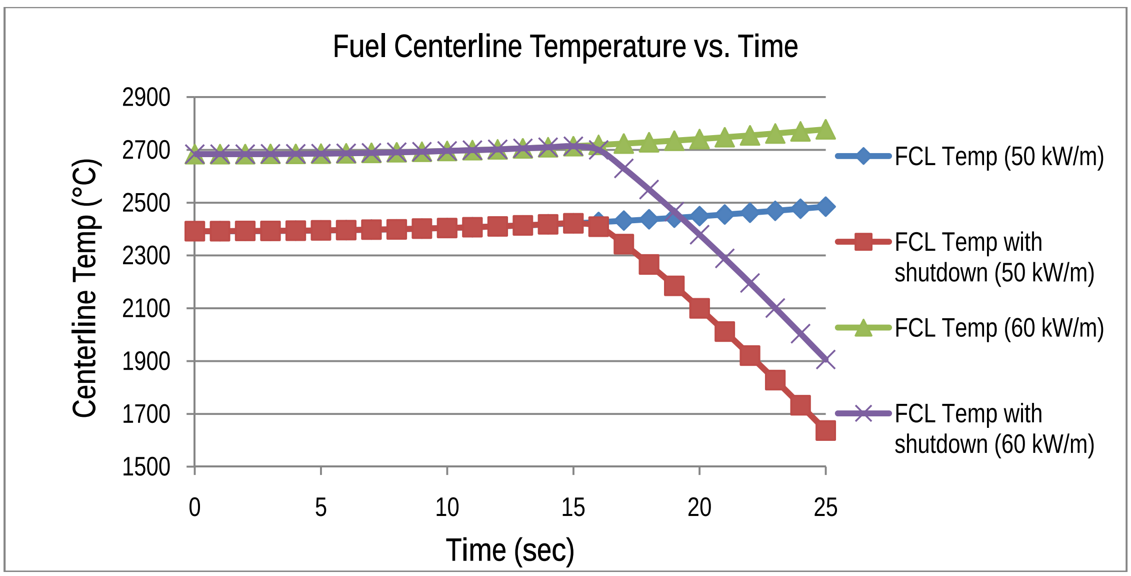

Figure 6: Fuel centerline temperature vs time for 0.01 mk/s insertion rate

	Maximum Clad Temperature (°C) (trip enabled)	Maximum Fuel Centerline Temperature (°C) (trip enabled)
50 kW/m	727.5 (at 15.3 sec)	2422.00 (at 15.0 sec)
60 kW/m	752.3 (at 15.3 sec)	2714.00 (at 14.9sec)

Table 4: Maximum Temperatures for 0.01 mk/s case

4.3.2 Case 2: 0.1 mk/s insertion rate

As for Case 1, the power versus time plot is shown below. This transient was not run to 25 seconds as the FUELPIN code stops calculations when fuel centerline melting occurs. The two neutron overpower trips occur at 2.53 seconds and 2.77 seconds, initiating shutdown. The SDS1 log rate trip would have occured at 17.3 seconds. In this case, without the trip enabled, centerline melting occurred at 17.81 seconds for an LER of 50 kW/m and 13.75 seconds for an LER of 60 kW/m. It is seen that when the trip is present, the maximum clad and fuel centerline temperatures (shown in Table 5) are well below the previously defined limits.

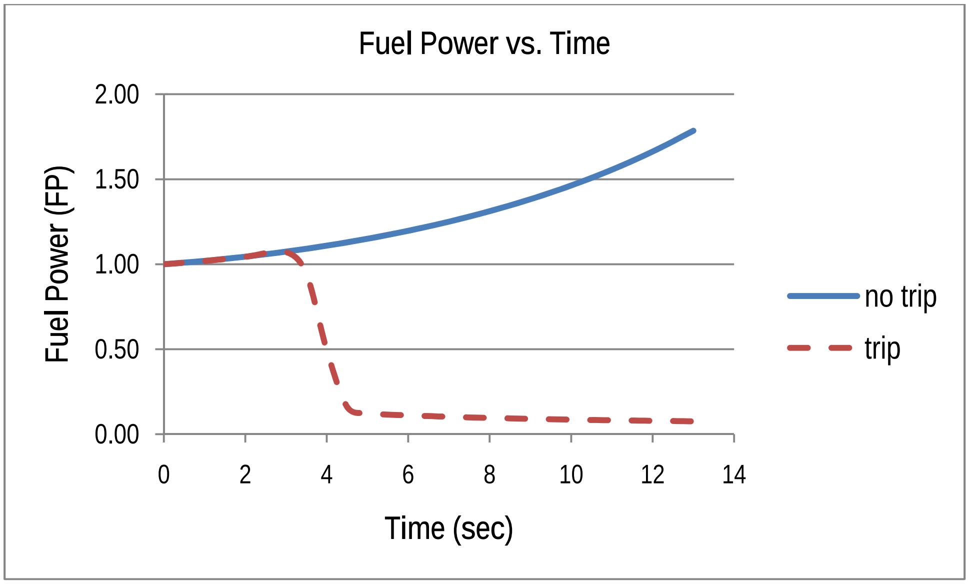

Figure 7: Fuel Power vs. Time for 0.1 mk/s reactivity insertion rate

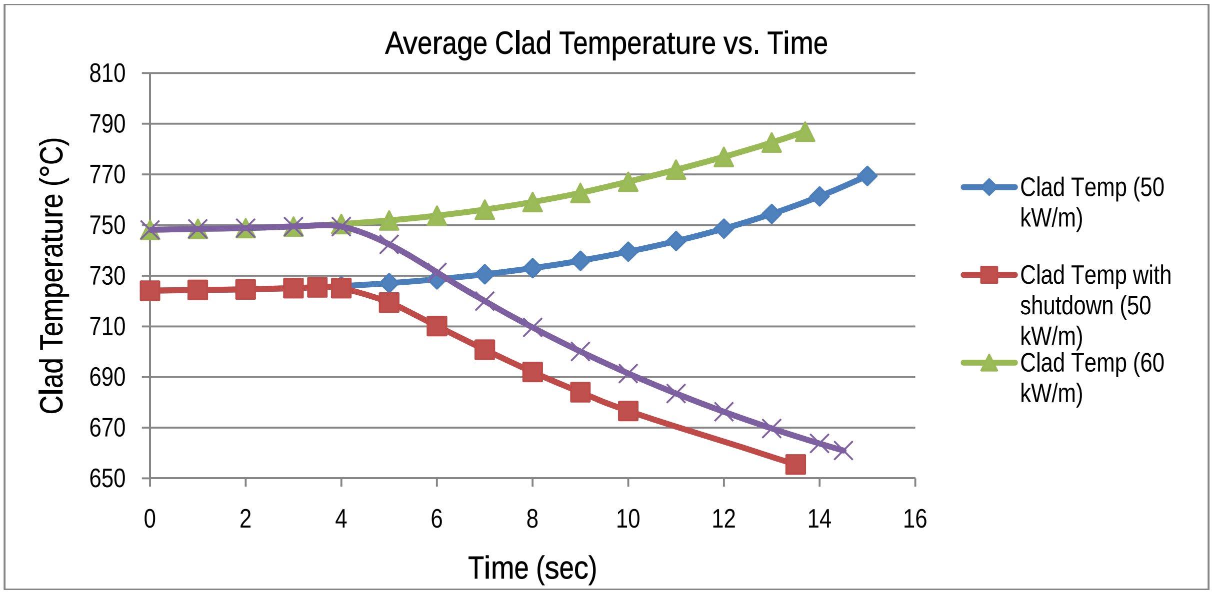

Figure 8: Average Clad Temperature vs. time for 0.1 mk/s insertion rate

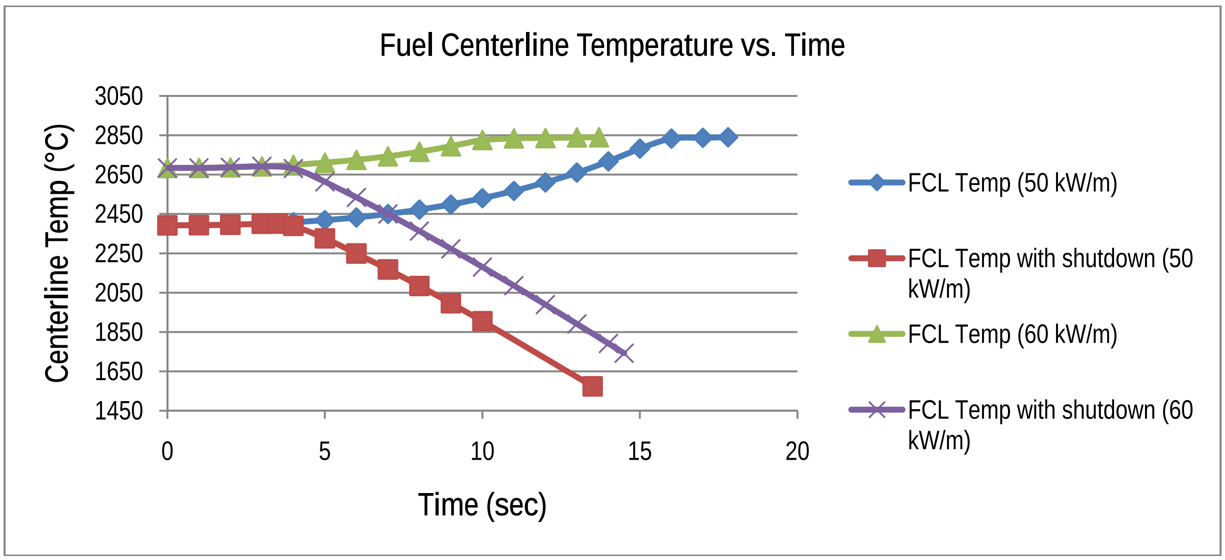

Figure 9: Fuel centerline temperature vs. time for 0.1 mk/s insertion rate

	Maximum Clad Temperature (°C) (trip enabled)	Maximum Fuel Centerline Temperature (°C) (trip enabled)
50 kW/m	725.4 (at 3.4 sec)	2401 (at 3.1 sec)
60 kW/m	749.8 (at 3.5 sec)	2693 (at 3.1 sec)

Table 5: Maximum Temperatures for 0.1 mk/s case

4.3.3 Case 3: 1 mk/s insertion rate

This case represents the most severe reactivity insertion. Power is seen to double in about 2.7 seconds. In this case, FUELPIN reports fuel centerline melting at 4.49 seconds in the 50 kW/m LER case and 3.87 seconds in the 60 kW/m LER case. Here we see four reactor trips occurring: the first, SDS1 high neutron flux trip occurs at 0.426 seconds, followed by the SDS2 high neutron flux trip at 0.475 seconds. The two log rate trips also occur in this case, due to the extremely fast flux increase, slightly after the neutron overpower trips, at 0.472 seconds for SDS1 and 0.653 seconds for SDS2. In all cases, with the reactor trip enabled, the transient is seen to be arrested before any of the temperatures under consideration reach their limits.

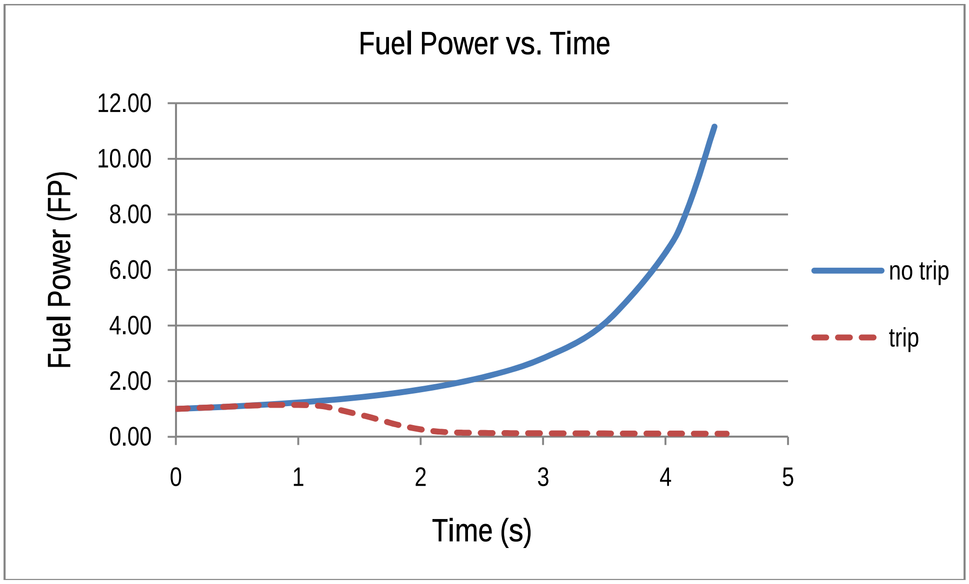

Figure 10: Fuel Power vs. Time for 1 mk/s reactivity insertion rate

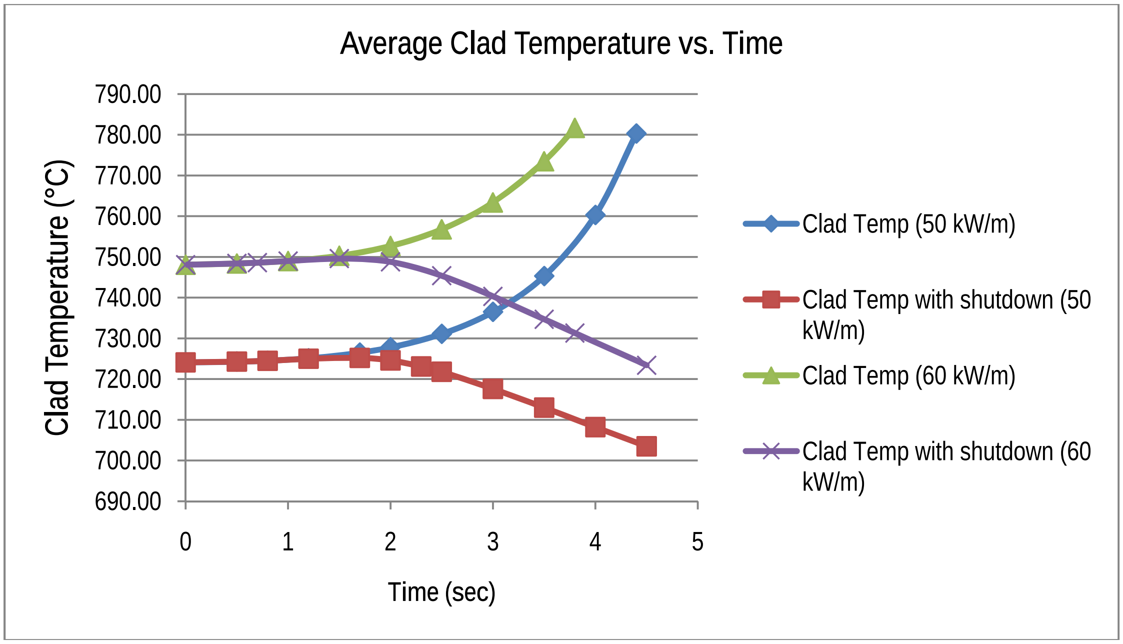

Figure 11: Average Clad Temperature vs. time for 1 mk/s insertion rate

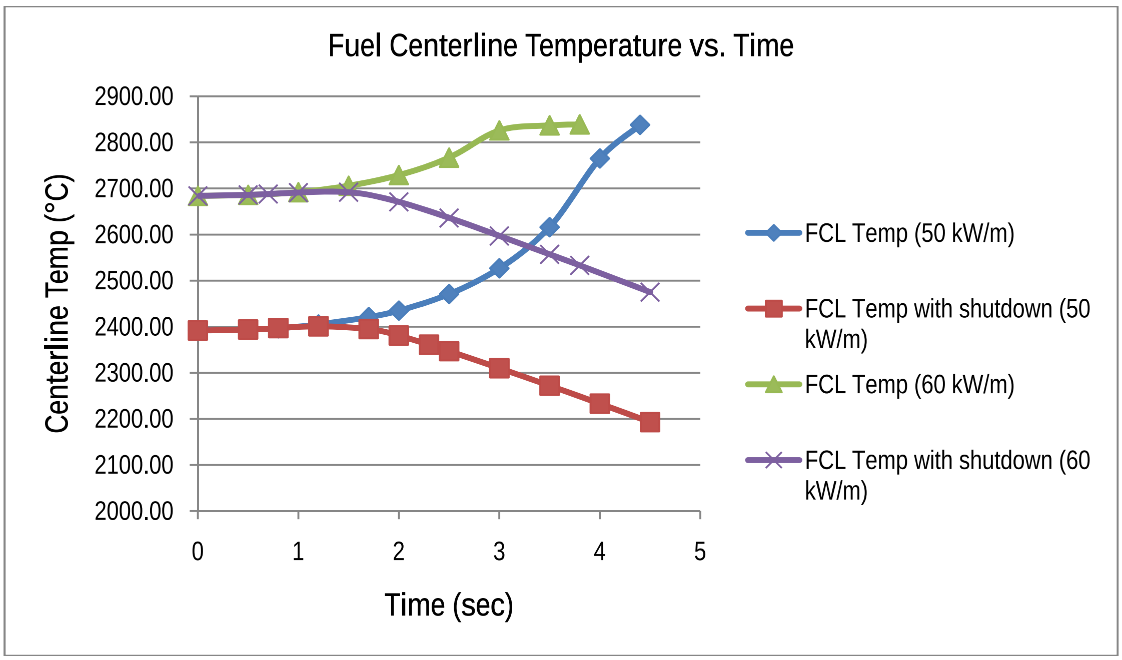

Figure 12: Fuel centerline temperature vs. time for 1 mk/s insertion rate

	Maximum Clad Temperature (°C) (trip enabled)	Maximum Fuel Centerline Temperature (°C) (trip enabled)
50 kW/m	725.3 (at 1.5 sec)	2402 (at 1.3sec)
60 kW/m	749.6 (at 1.5 sec)	2694 (at 1.3 sec)

Table 6: Maximum Temperatures for 1 mk/s case

4.3.4 Case 4: Limiting case: Slow reactivity insertion rate with increased trip setpoint

In considering the case of a positive reactivity insertion, it is found that both the clad and fuel centerline temperature increases lag slightly behind the power increase (often referred to as power to coolant lag). Thus, the limiting case in this analysis, that is, where the highest temperatures will be seen, is with a very “slow” reactivity insertion rate. Further, with a slow reactivity insertion rate, the only reactor trip capable of arresting the transient will be the neutron overpower trips for SDS1 and SDS2. For this case, these have been increased to have setpoints of 112% full power as opposed to the previous value of 106%. Both fuel pins with 50 and 60 kW/m linear element ratings have been simulated here with a reactivity insertion rate of 0.001 mk/s.

The result for this case is presented in the table below. The reactor trip occurs at 23.1 seconds. It is noted that the fuel centerline temperature is affected more than the clad temperature. In the 60 kW/m case, the margin to fuel centerline melting is only 73°C.

	Maximum Clad Temperature (°C)	Maximum Fuel Centerline Temperature (°C)
50 kW/m	732.4 (at 23.9 sec)	2473 (at 23.5 sec)
60 kW/m	758.3 (at 23.9 sec)	2766 (at 23.5 sec)

Table 7: Maximum Temperatures for 0.001 mk/s limiting case with increased trip setpoint

5. Conclusions

In this paper, the heat transfer/point kinetics code FUELPIN has been used to assess the clad temperature and fuel centerline temperature for various fuel geometries and power ratings, as well as determine response to various loss of regulation transients. The temperature predictions from FUELPIN have been found to be consistent with analysis done using finite element software FlexPDE.

It has been found that the use of a fuel element containing a 6 mm fuel pellet, will produce acceptable temperatures for both clad and fuel centerline if kept below a linear element rating of 60 kW/m. For a LER of 60 kW/m, it is found that the clad temperature during normal operation exceeds the recommended limit for maximum clad temperature of 740°C. It should be noted that this LER recommendation is based only on temperature limits. Other constraints on LER may be imposed from other factors such as planned fuel burnup, meaning further reduction in LER may probably be required for safe operation. Fuel radii between 3-5 mm show small margin to thermal limits and appear non-practical for the CANDU-SCWR. Little variation on temperatures is found when adjusting the clad thickness or gap size.

The loss of regulation analysis shows the temperature response to various positive reactivity insertions. In all cases it is found that trip setpoints for current CANDU shutdown systems appear adequate in arresting even the most severe of reactivity induced transients without compromising temperature limits. In the case of a very slow reactivity insertion, low margin to fuel centerline melting is found in the case of a 60kW/m LER, providing more evidence to support a lower maximum LER in the CANDU-SCWR.

6. References

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