Conference Paper

THERMAL-MECHANICAL BEHAVIOR OF FUEL ELEMENT IN SCWR DESIGN

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THERMAL-MECHANICAL BEHAVIOUR OF FUEL ELEMENT IN SCWR DESIGN

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Abstract

This paper presents a study on thermal-mechanical behaviour of a fuel element proposed for the Canadian Supercritical Water Cooled Reactor (SCWR). In the Canadian SCWR, the coolant pressure is 25 MPa, and the temperature is 350°C at the inlet and 625°C at the outlet of the reactor core. Critical design decisions for fuel design will be the selection of the fuel sheath material and details of the fuel element design options (sheath thickness, pellet-clad gap, internal pressure, etc.). The analysis presented in this paper predicted temperature, stress and strain in the fuel element of the Canadian SCWR with a collapsible sheath using ANSYS. Typical conditions for the evaluation of the fuel behaviour, such as linear heat generation rate, coolant temperature and sheath surface heat transfer coefficient, were extracted from core and fuel channel designs. The temperature distribution in the fuel element is predicted by a thermal model and then the thermal model is coupled sequentially with a structural model to predict fuel sheath deformation under the predicted temperature distribution and external (coolant) pressure. Nonlinear thermo-mechanical simulations include nonlinear buckling with elastic-plastic deformation. Three sheath collapse phenomena are considered: (1) elastic collapse by buckling, (2) longitudinal ridging and (3) plastic collapse by yielding. The numerical models are validated against analytical and experimental data. The presented results show the temperature distribution, deformed shape, stress and strain of the fuel element, allowing the designers to select appropriate sheath material and element design options for the SCWR fuel element design.

Keywords: SCWR, thermal-mechanical behaviour, fuel element, temperature distribution, deformation, sheath material.

Introduction

Canada has been focusing on the pressure-tube type Supercritical Water-cooled Reactor (SCWR) with the selection of a coolant pressure of 25 MPa, a temperature of 350°C at the inlet, and a temperature of 625°C at the outlet of the reactor core as the operating conditions. Since the proposed operating conditions are significantly different than the CANDU operating conditions which are about 10 MPa and below 310°C, the fuel sheath design for the Canadian SCWR cannot simply rely on the success of the CANDU design. However, these past experiences can be utilized in fuel element design for the Canadian SCWR.

The current CANDU fuel sheath is designed to collapse onto the fuel pellet, ideally with full sheath-pellet contact. This feature results in good pellet/sheath contact throughout the operation, enhances heat transfer between the pellet and the sheath, and thus lowers pellet temperatures. There are two types of collapse: circumferential collapse and longitudinal ridging. Circumferential collapse is an elastic collapse, while longitudinal ridging is a plastic collapse. When circumferential collapse occurs, the sheath deforms into an oval shape and the sheath contacts the pellet partially. As pressure rises further, the contact area between sheath and pellet increases. Longitudinal ridging can be considered as an extension of circumferential collapse. Collapse is affected by sheath material properties, operating conditions (applied pressure and temperature), sheath dimensions (diameter, wall thickness, and ovality), and pellet-to-sheath diametral gap. Longitudinal ridging is considered unacceptable as it can produce or lead to fuel failures.

In the CANDU fuel design, the analytical model and empirical models were used to determine the critical pressures for circumferential collapse and longitudinal ridging for various fuel designs. Those empirical models were developed in 1970s based on a large number of collapse tests for a specified range of sizes of fuel elements under CANDU operating conditions. However, such empirical models may not be applicable to fuel operating under Canadian SCWR conditions. Therefore, it is desirable to develop a predictive methodology that is valid at SCWR conditions.

Previous work investigating cylinder collapse by circumferential buckling under external pressure [1], [2], [3], [4] with analytical solutions, experimental studies and numerical simulations were considered. Effect of cylinder geometric imperfections on the buckling behaviour were also studied [3], [4], although, in these studies, only hollow cylinders were considered. Very little research has been conducted on numerical simulations of a fuel element in which the sheath collapses onto the fuel pellet.

This paper presents an analysis of thermal-mechanical behaviour of the proposed Canadian SCWR fuel element with collapsible sheath. In this analysis, a thermal model predicted temperature distributions in the fuel. Typical conditions for the evaluation of the fuel behaviour, such as linear heat generation rate, coolant temperature and sheath surface heat transfer coefficient, were extracted from core and fuel channel designs. Then the thermal model was coupled sequentially with a structural model to predict fuel sheath deformation under the predicted temperature distribution and external (coolant) pressure. A linear buckling model was used to calculate the critical pressure of the elastic circumferential collapse. A buckled mode shape calculated from linear buckling analysis was used to create a small asymmetric initial deflection for use in nonlinear buckling analysis. The nonlinear thermo-mechanical model was used to simulate elastic-plastic deformation and possible longitudinal ridging. The numerical models are validated against an analytical model and an empirical model. The model will allow for the selection of an appropriate sheath material and sheath element design options for the Canadian SCWR fuel element design.

1. Design Considerations of Fuel Sheath

In the CANDU design of the fuel sheath, the sheath thickness is determined by ensuring circumferential collapse of the sheath while preventing longitudinal ridging and axial collapse. The following assessments are required:

- Circumferential collapse: the coolant pressure must be higher than the critical pressure for circumferential collapse.
- Longitudinal ridging: the coolant pressure must be lower than the critical pressure of longitudinal ridging.
- Axial collapse: the coolant pressure must be lower than the critical pressure of the axial collapse.

The CANDU fuel sheath is designed to be thin enough to collapse into full contact with the UO_2 pellet at normal operating conditions of temperature and pressure. An analytical model [1] was used to determine the circumferential collapse pressure of the fuel sheath. The collapse pressure of fuel sheath is given by Bryan's equation:

$$\boldsymbol{P_c = \frac{E}{4(1-\gamma^2)}\left(\frac{t}{r}\right)^3} \qquad \text{Eq. (1)}$$

where, t is sheath wall thickness, r is sheath radius, E is Young's modulus of elasticity, and γ is Poisson's ratio.

The behaviour of the sheath under external pressure is quite sensitive to geometric imperfections. When the initial imperfection is in the form of ovality, the critical collapse pressure (q_{cr}) of a sheath is lower than that for a sheath with a perfectly circular shape, and can be determined by the following equation:

$$\boldsymbol{q_{cr}^2 - \left[\frac{\sigma}{(r/t)} + \left(1 + 6\varepsilon(r/t)\right)P_c\right]q_{cr} + \frac{\sigma}{(r/t)}P_c = 0} \qquad \text{Eq. (2)}$$

where, σ is yield stress for the sheath, ε is ovality ratio ($\Delta r/r$), and P_c is critical collapse pressure for a sheath with zero ovality.

Longitudinal ridging is plastic collapse of the sheath in those parts of the sheath length that are supported by the pellets. This occurs when the sheath inside diameter is larger than the pellet outside diameter and the "excess" material of the sheath bends to form a longitudinal ridge during plastic collapse when the critical pressure for longitudinal ridging is exceeded. Longitudinal ridging is assessed to ensure that the coolant pressure is below the critical pressure of longitudinal ridging.

An empirical model based on collapse tests was available for calculating the critical pressure for the formation of severe longitudinal ridging. The correlation has been expressed in the form of a critical collapse pressure and this is the pressure that would cause the ridge strain to become unstable.

$$\boldsymbol{P_c = \frac{E}{10^7}\left[-1560 + 80600\frac{t}{d} + 29.1\left(\frac{d}{100\varphi}\right)^2\right] + 0.03\sigma} \qquad \text{Eq. (3)}$$

where t is sheath thickness, d is sheath outside diameter, σ is sheath yield strength, E is elastic modulus, and $\varphi = \delta - \frac{P\delta^2}{2Et}$, where δ is pellet-to-sheath diametral gap and P is operating pressure.

In the CANDU fuel element design, the fuel sheath thickness was determined by performing circumferential collapse and longitudinal ridging assessments. The same design considerations are being adopted for the Canadian SCWR fuel design. However, the test data used to obtain the correlation of critical pressure for longitudinal ridging were for CANDU operating conditions and for CANDU sheath material, which are significantly different from those proposed for the Canadian SCWR reactor. Therefore, the correlation may not be suitable for the fuel design of the Canadian SCWR. With the advance of computational modelling, a numerical model is possible to simulate the thermal-mechanical behaviour to predict circumferential collapse and longitudinal collapse of the fuel sheath.

2. ANSYS Modelling of Thermal-Mechanical Behaviour of Fuel Element

The fuel element was modeled in a two-dimensional domain. Both heat transfer and deformations in the axial direction were assumed negligible. The fuel was modelled with a gap between the fuel pellet and the sheath. The element type of PLANE55 and PLANE182 were used [5] and ten elements were used through the thickness of the sheath and 640 elements were used along the circumferential direction. The current reference fuel for the Canadian SCWR is thorium-plutonium dioxide but all the necessary properties were not available and so uranium dioxide was used as a surrogate. Inconel 625 is one of the sheath material candidates and was used in this analysis. Temperature-dependent material properties of the sheath and fuel were used and the properties between two temperatures were linearly interpolated by the code.

For boundary conditions in the thermal model, convective heat transfer was given on the external surface of the sheath, and heat generation rate was specified on the fuel pellet. Linear heat generation rate, coolant temperature and sheath surface heat transfer coefficient, were extracted from core and fuel channel designs. A uniform gap between fuel pellet and the sheath was filled with helium with a temperature-dependent heat transfer coefficient. Then the thermal model predicted the temperature distribution in the fuel element.

Linear buckling analysis predicts the theoretical buckling strength of an ideal elastic structure. It computes the structural eigenvalues for the given system loading and constraints. Displacement constraints were specified on selected nodes. The node at the pellet centre was fixed. For the sheath, the nodes on the x-axis were constrained to be only free to move in the x-direction, and the nodes on the y-axis were constrained to be only free to move in the y-direction. These constraints were used to prevent rigid body motion problem in ANSYS. They were valid for the perfectly symmetric geometry. With the presence of the eccentricity in the geometry, the constraints on the sheath reflected the cases with high friction between the pellet and the sheath. Thermal-mechanical coupling occurs by applying load terms from the thermal analysis to the stress analysis across a node-to-node similar mesh interface. The coolant pressure was applied on the sheath external surface. After the load and boundary conditions were set up under a Static Structural analysis branch, a second analysis branch, called Linear Buckling, was added. The buckling mode shapes and critical pressure for circumferential collapse can be obtained as the simulation results. The predicted critical pressure for circumferential collapse can be compared with the analytical solutions (Eq. (1)).

The nonlinear model was used to simulate the more realistic situation of a fuel element, that is, one with non-perfect circular geometry. The same mesh, initial conditions and boundary conditions as in the linear model were used. In addition, plastic behaviour, initial imperfections, large-deflection response and material plastic properties were included in the model. The approach in this analysis was to constantly increase the applied loads until the solution began to diverge.

Buckling will not occur if the modelled geometry is perfectly symmetric. In the numerical modeling, a perturbation is necessary to initiate buckling. Imperfections in the sheath geometry exist in reality. In this work, an oval shape of the sheath geometry was considered as a perturbation to stimulate the buckling response, as shown in Figure 1. The applied load, representing the coolant pressure, is gradually increased until a load level is found whereby the structure becomes unstable or suddenly a very small increase in the load causes very large deflections. The simulation results including temperature, displacement, hoop stress, strain and time-histories of those parameters were extracted from data files. When examining how the radial deflection of the fuel sheath varied with the pressure increase, it can be seen that the radial deflection increased slowly as the pressure increased, up to a certain pressure, then, the radial deflection of the sheath increased dramatically representing the formation of a longitudinal ridge. That pressure is the critical pressure of longitudinal ridging.

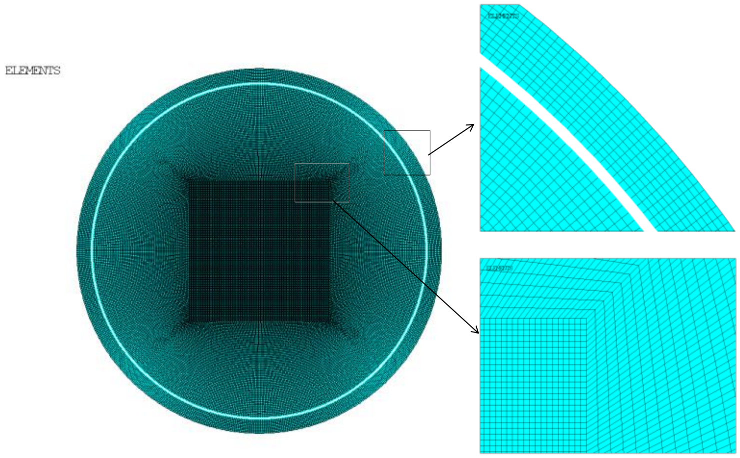


Figure 1 Meshes in ANSYS Model with Sheath Ovality

A validation was necessary to ensure the ANSYS analysis models were built correctly and able to predict the thermal and mechanical behaviour of a known fuel sheath before it could be confidently applied to the fuel sheath design for the Canadian SCWR. With the past successful experiences in the CANDU fuel sheath design, the CANDU fuel sheath was used for validation.

The material properties of UO_2 as the fuel material and Zircaloy as the sheath material are temperature dependent. Heat generation was assumed homogeneous and linear heat generation rate of 40 kW/m was used for the case. The convective heat transfer coefficient was estimated by using empirical correlations [6] resulting in a value of 29.8 kW/(m^2K) being used. The bulk fluid temperature was 310°C and was assumed to be constant throughout the simulation. An external pressure of 10 MPa was applied on the sheath surface. Temperature distributions in the fuel element under CANDU operating conditions were predicted by the ANSYS thermal model. Since the boundary conditions are uniform along the circumferential direction, the thermal case is simply a one-dimensional problem, in which the analytical solutions are available. A comparison of temperatures between the prediction of the ANSYS analysis model and the analytical solutions is shown in Figure 2 with good agreement. It indicates that the ANSYS thermal model is able to predict the fuel element temperature distributions correctly.

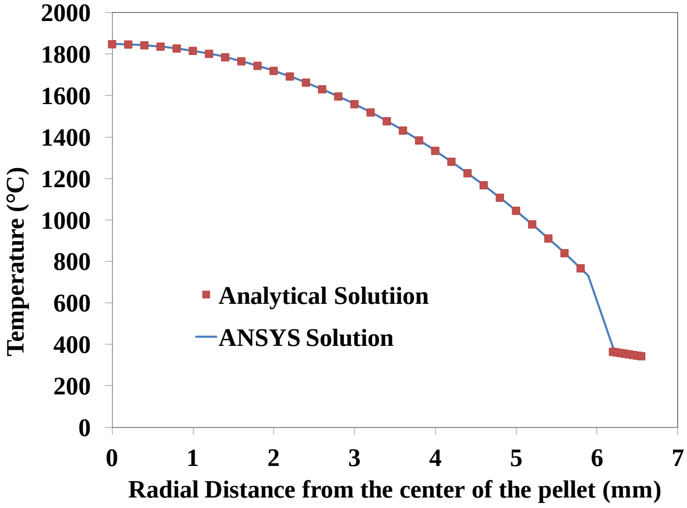


Figure 2 Comparisons of Temperature Distributions between the ANSYS Model and Analytical Solutions

The critical pressure of circumferential collapse for the CANDU fuel sheath with nominally round geometry was predicted by the linear buckling model. Five cases were tested by varying the sheath thickness to compare the ANSYS predicted critical pressures for circumferential collapse and the theoretical ones (Eq. (1)). Figure 3 shows a good agreement between the ANSYS model's prediction and the theoretical predictions.

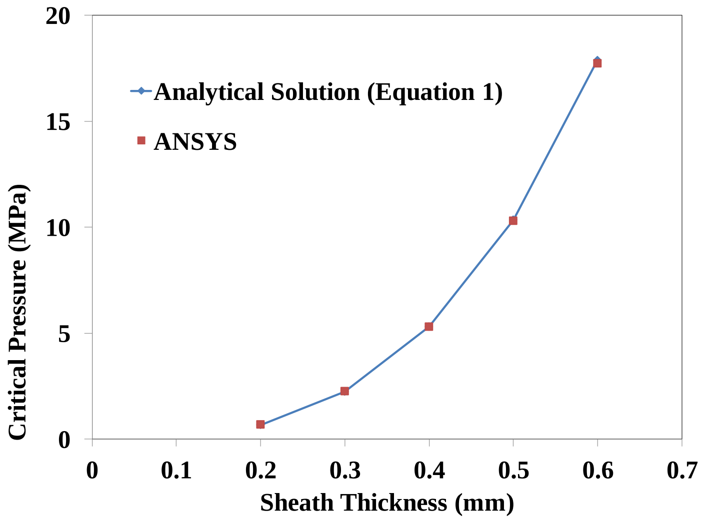


Figure 3 Comparisons of Critical Pressure of Circumferential Collapse between the ANSYS Model and Theoretical Solutions

The critical pressure of longitudinal ridging for the CANDU fuel sheath was predicted by the nonlinear model. Four cases selected from the WCL (Westinghouse Canada Limited) collapse test data, which used Pickering elements, were used for validation. Figure 4 shows the ANSYS predicted critical pressure and the empirical correlation predicted critical pressure versus the measured critical pressure. It appears that the ANSYS predictions agree well with both of the measurements in the WCL collapse tests and the predications using the empirical correlation.

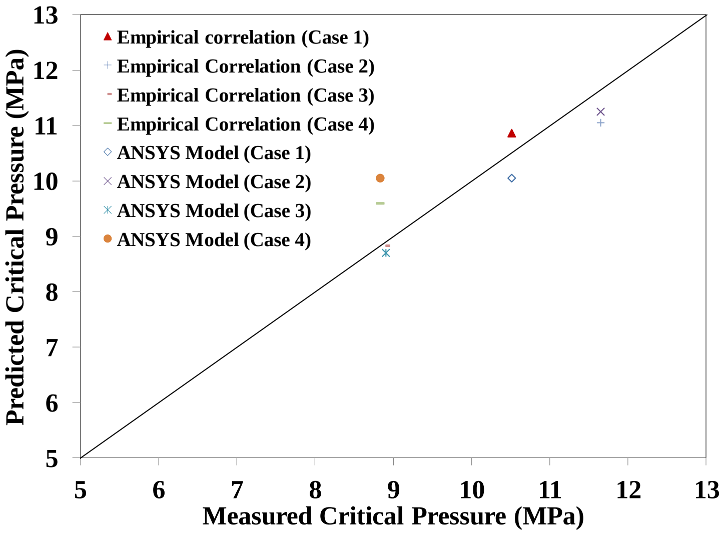


Figure 4 Comparison between the ANSYS Predicted and the Measured Critical Pressure of Longitudinal Ridging in WCL Tests

3. Results for Canadian-SCWR Fuel Element

Following validation of the ANSYS models, these models were used to simulate the Canadian SCWR fuel element. Two cases with different conditions were selected from a thermalhydraulic analysis of the fuel channel for the investigations. The cases represent the locations that experienced maximum and minimum sheath temperatures (referred to here as the high and low sheath temperature cases). The conditions for these two cases are summarized in Table 1. The fuel element geometry was modelled with a pellet diameter of 9.5 mm, sheath thickness of 0.4 mm and radial gap of 0.05 mm between the sheath and pellet.

Table 1 Boundary Conditions for the Selected Cases in Canadian SCWR Design

Cases	Unit	High Sheath Temperature Case	Low Sheath Temperature Case
Linear Heat Generation Rate	kW/m	28.35	29.31
Convective Heat Transfer Coefficient on the Sheath Surface	kW/m^2K	5.193	22.001
Coolant Temperature	°C	625	385
Initial Temperature	°C	625	385
Coolant Pressure	MPa	25	25

The maximum temperatures appeared at the center of the fuel and the minimum temperature appeared at the outer surface of the sheath as shown in Figure 5. Temperature was distributed uniformly along the circumferential direction. The maximum temperatures for the high and low sheath temperature cases were 1989°C and 1584°C, respectively. The minimum temperatures for the high and low sheath temperature cases were 792° and 426°C, respectively.

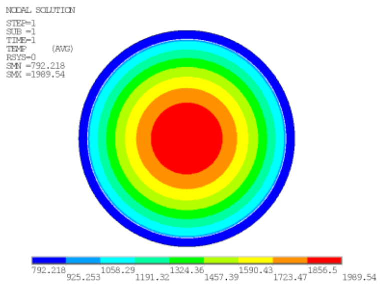
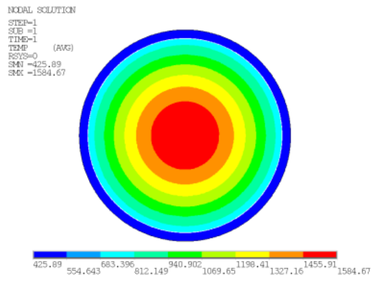
<table>
<tr><th></th><th>High Sheath Temperature Case</th><th>Low Sheath Temperature Case</th></tr>
<tr><td>Temperature (°C)</td><td>
</td><td>
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FIGURE 5 Temperature Distribution of Fuel Element in Canadian SCWR Design

The results of the linear buckling analysis show that the critical pressures for circumferential collapse are 22.4 MPa and 25.8 MPa, while the theoretical results calculated by Eq. (1) are 22.3 MPa and 26.0 MPa for the high and low sheath temperature cases, respectively. The linear buckling model prediction agrees very well with the theoretical predictions.

The shape of the first mode from the linear buckling analysis was used as an initial condition for the nonlinear buckling model with ovality specified as 0.9%. The maximum gap was 0.095 mm and the minimum gap was 0.005 mm. Under predicted temperatures and an external pressure of

25 MPa on the sheath external surface, the simulated results extracted from the nonlinear buckling model include the distributions of displacement, stress and strain as shown in Figure 6. For the high and low sheath temperature cases, the maximum displacements were 0.1005 mm and 0.0697 mm; the hoop stresses were between -346 and -283 MPa, and between -385 and -242 MPa; and the maximum strains were 1.54% and 0.77%, respectively. The negative stress indicates that hoop stress was compressive.

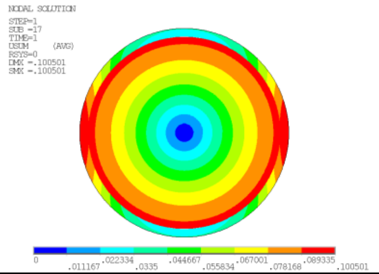
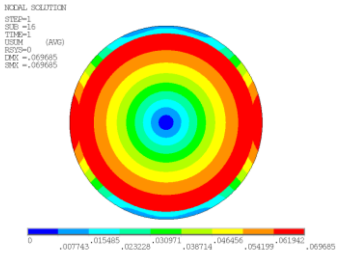
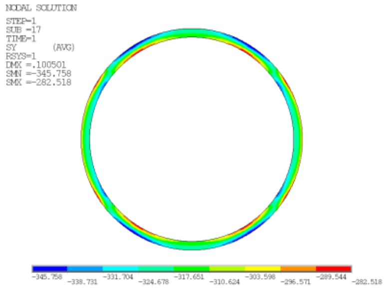
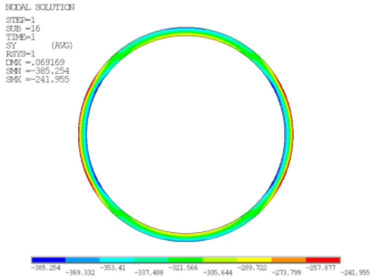
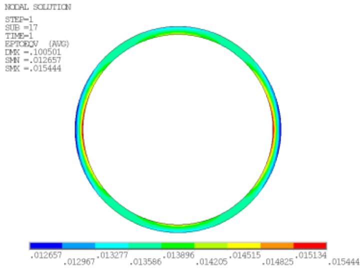
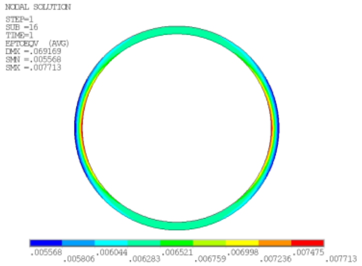
	High Sheath Temperature Case	Low Sheath Temperature Case
Displacement (mm)		
Hoop Stress (MPa)		
Strain		

Figure 6 Simulated Distributions of Displacement, Hoop Stress and Strain of SCWR Fuel Element

Figure 7 shows the variation in displacements of points on the sheath surface at the maximum and the minimum gap locations with pressure for the high sheath temperature case. The displacement at the maximum gap location increases at low pressure as the sheath is compressed into contact with the pellet on the minimum gap side. This contact provides support to the sheath and the displacement increases linearly due to the thermal expansion of the pellet. (Pressure and temperature were increased in step with each other in the model.) The maximum gap location displacement continued to increase with a lower slope. As the pressure increased to 23.2 MPa, the displacement started to decrease due to the material yielding as indicated by a stress level greater than the yield stress. Up to a pressure of 25 MPa, there was no dramatic increase in the slope, therefore the critical point for longitudinal ridging was not reached. The displacements at the minimum gap locations decreased slowly at beginning due to the external pressure.

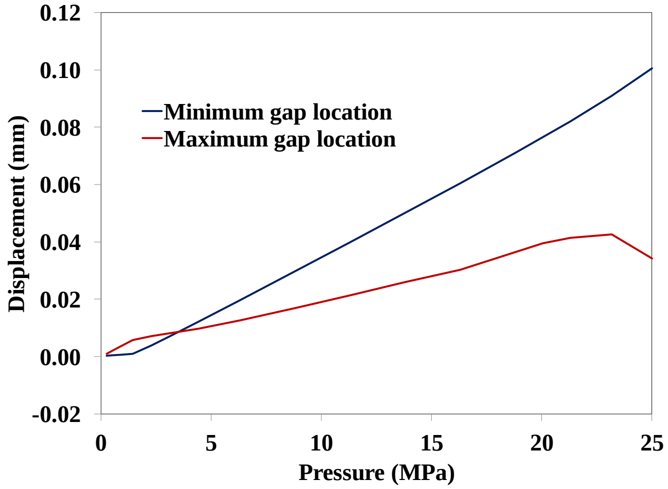


Figure 7 Simulated Displacement of the Canadian SCWR Fuel Sheath Varied with Applied External Pressure for High Sheath Temperature Case

4. Effect of Select Element Design Options

The ANSYS models developed provide the capability to analyze the thermo-mechanical response of the fuel to a number of variables and thus provide justification for fuel design choices. The results of displacement, hoop stress and strain on the fuel sheath for different sheath thickness (0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm and 0.6 mm) and radial gaps (0.05 mm and 0.1 mm) were examined as shown in Table 2. When the radial gap was 0.05 mm, the maximum displacement was approximately 0.1 mm; all the hoop stresses were compressive; and the maximum strains remained low, for all sheath thickness. When the radial gap was 0.1 mm, the maximum displacement decreased as the sheath thickness increased. The hoop stress on the sheath changed from tension to compression as the sheath thickness increased and maximum strain decreased significantly as shown in Figure 8. When the sheath was thicker than 0.4 mm, the maximum strain change was insignificant. When the sheath thickness was less than 0.4 mm, the maximum strain on the fuel sheath changed dramatically, indicating the onset of longitudinal ridging.

Figure 9 shows the variation in radial deflection with pressure for the extreme case of a sheath thickness of 0.2 mm and radial gap of 0.1 mm. The slope changed dramatically at approximately 5.5 MPa, indicating the onset of longitudinal ridging.

Table 2 Maximum Displacement, Hoop Stress and Strain on the Sheath for Different Sheath Thicknesses and Different Radial Gaps of Canadian SCWR Fuel Element

	Sheath Thickness	Maximum Displacement	Hoop Stress	Maximum Strain
	mm	mm	MPa	%
Radial Gap=0.05 mm	0.2	0.09313	-239 to -88	1.7158
	0.3	0.115406	-425 to -101	1.149
	0.4	0.100501	-346 to -283	1.5444
	0.5	0.099728	-303 to -210	1.4433
	0.6	0.101068	-281 to -151	1.3881
Radial Gap=0.1 mm	0.2	0.146686	-570 to 374	13.5777
	0.3	0.148048	-485 to 321	6.7615
	0.4	0.119596	-421 to -114	1.856
	0.5	0.101296	-358 to -114	1.4862
	0.6	0.098152	-312 to -121	1.362

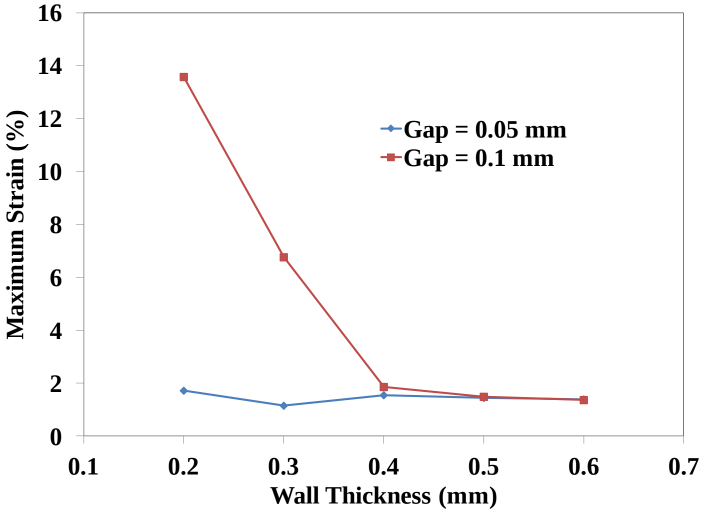


Figure 8 Simulated Maximum Strain Variation with the Thickness for Canadian SCWR Fuel Sheath

It is likely that the centres of the sheath and the pellet are not at the same point. Figure 10 shows the results of temperature, displacement, hoop stress and strain on the fuel sheath for eccentricities (defined as the distance between the sheath center and the pellet center) of 0.02 mm, 0.03 mm, 0.04 mm, and 0.05 mm for the high sheath temperature case with a radial gap of 0.1 mm and the sheath thickness of 0.2 mm. This case was used as an extreme case in order to demonstrate the model's capabilities of simulating ridging phenomena. The constraints imposed on the sheath as the structural boundary conditions made the model more representative to a case with high friction between the pellet and the sheath. In this case, as the eccentricity increased from 0.02 mm to 0.05 mm, the maximum displacement increased linearly, the maximum hoop stress increased insignificantly, and the maximum strain for all cases increased linearly. Figure 11 shows the variation in radial deflection with pressure for different eccentricities. In general, eccentricity skews the maximum displacement to the side of the pellet with the largest starting gap resulting in asymmetry in the deformed shape of the fuel sheath. A comparison between the simulated deformed shape of the aforementioned fuel element and a typical longitudinal ridge from an experiment shows good similarity (Figure 12).

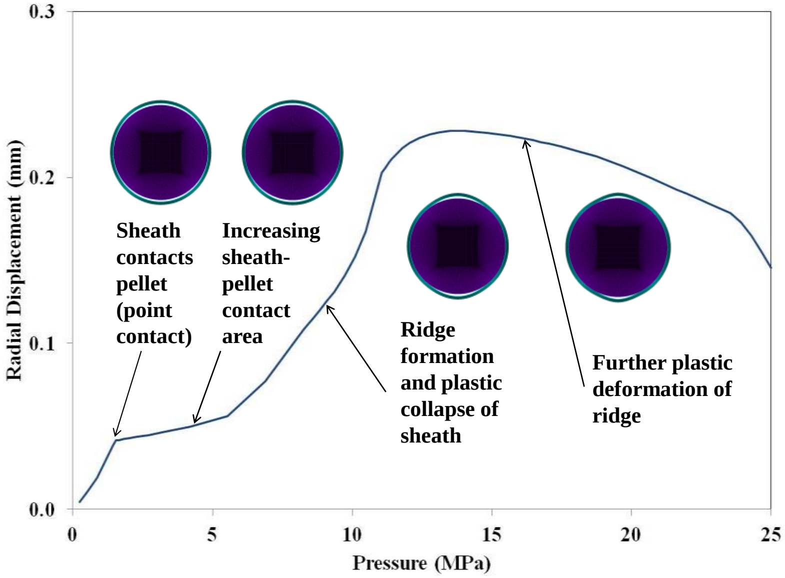


Figure 9 Simulated Displacements at the Maximum Gap Location Varied with External Pressure for Canadian SCWR Fuel Sheath

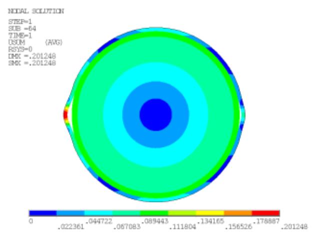
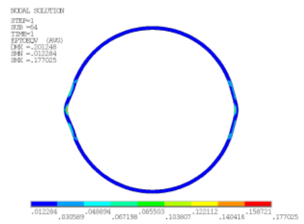
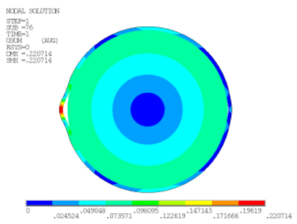
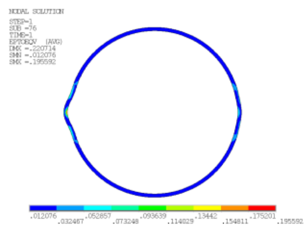
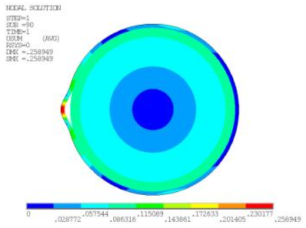
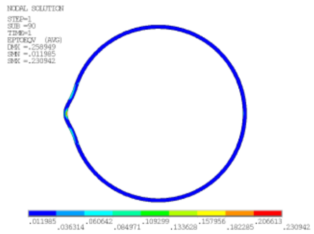
Eccentricity	Displacement (mm)	Strain
0.02 mm		
0.03 mm		
0.05 mm		

Figure 10 Simulated Distributions of Displacement and Strain of Canadian SCWR Fuel Element with Different Eccentricity

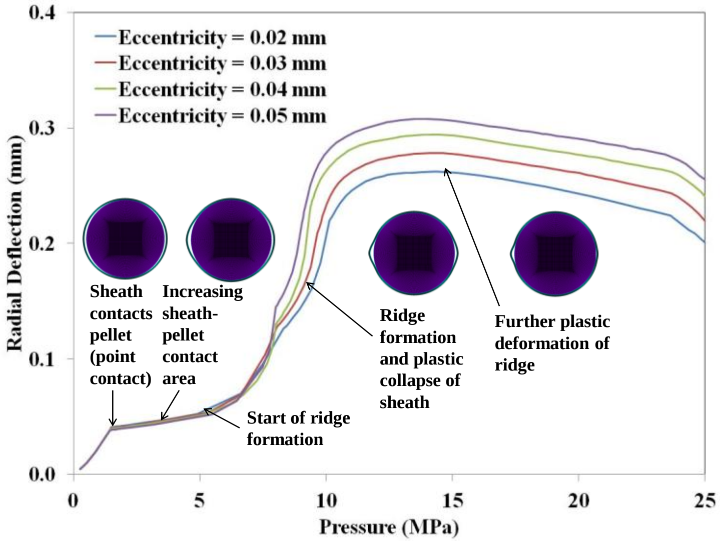


Figure 11 Simulated Radial Deflection at the Maximum Gap Location as a Function of External Pressure for Canadian SCWR Fuel Sheath with Different Eccentricities

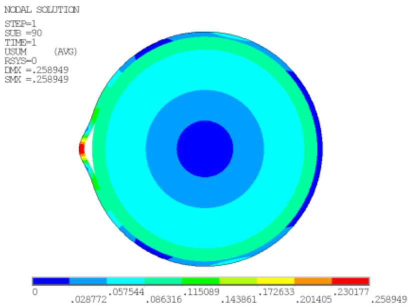
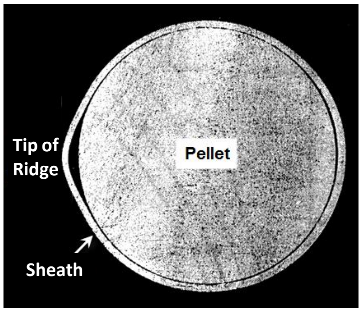
Deformed Shape of Fuel Element in ANSYS Model	A Photo of A Typical Longitudinal Ridge
	

Figure 12 Comparison of the Simulated Deformed Shape of Fuel Element and a Typical Longitudinal Ridge

5. Conclusion

This paper presents a study on thermal-mechanical behaviour of fuel elements operating under the conditions expected in the Canadian SCWR. Finite element models using ANSYS were developed to perform the analysis and evaluate the feasibility of using fuel with a collapsible sheath under such conditions. To test the models, Alloy 625 material was used as the sheath material in all SCWR calculations. The models were able to simulate sheath collapse phenomena including elastic collapse by buckling, longitudinal ridging and plastic collapse by yielding. Before this numerical model was used for the Canadian SCWR fuel, it was validated against the analytical solutions and the empirical correlations developed for CANDU fuel. The results allowed for the prediction of sheath circumferential collapse and longitudinal ridging as a function of element design options. A Canadian SCWR sheath with a thickness of 0.4 mm and a radial gap of 0.05 mm, under the proposed operating conditions, at the selected high and low sheath temperature locations in the fuel bundle, was examined. Under both conditions, the fuel sheath collapsed onto the pellet and made full contact with the pellet circumferentially with compressive hoop stress and no longitudinal ridging.

A set of simulations were performed considering the design options of sheath thicknesses and pellet-sheath gaps. As the sheath thickness decreases or the gap increases, longitudinal ridging is more likely to occur. When the radial gap is 0.05 mm, the sheath can collapse on the pellet and longitudinal ridging does not occur for sheath thickness of 0.2 to 0.6 mm. When the radial gap is 0.1 mm, the sheath can collapse on the pellet but longitudinal ridging was predicted to occur when the wall thickness was less than 0.4 mm under the conditions for the high sheath temperature case.

6. References

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