Development of a Fuel Performance Model for the Canadian SCWR

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Summary

The development of a finite element model for the Canadian SCWR fuel pellet and clad geometry has begun. An initial test model has been developed using the expected coolant conditions, element linear power and the material properties of UO_2 and 310 stainless steel. This work is to gain insight into the general fuel performance behavior and to establish the modeling requirements for the SCWR fuel. Development work is still ongoing to stabilize the model and input the material properties of the thorium-based ceramic fuel pellets that have been proposed for the SCWR design.

1. Introduction

To address the ever growing need for electrical power, the Generation IV International Forum (GIF) was established to encourage collaboration in the research and development required for the technology that is essential for the next generation of nuclear energy systems [1]. The GIF is mandated to promote reactor designs that improve on the current reactor types in terms of sustainability, improved economics, safety/reliability and proliferation resistance. Canada's contribution to GIF is being led by Atomic Energy of Canada Limited in the development of a pressure tube based Super-Critical Water cooled Reactor (SCWR).

The proposed fuel for the Canadian SCWR is made of a Th-Pu mixed oxide ceramic pellets (13% PuO_2 by weight) housed within fuel elements of approximately 5 m long, with clad made of zirconium modified 310 stainless steel [2]. The expectant coolant temperature range of Canadian SCWR is about 315-625^{o}C, with a pressure of 25 MPa. The Linear Element Rating (LER) has been set to be below 40 $kW \cdot m^{-1}$ and a projected target fuel burnup of approximately 40 $MWd \cdot kg^{-1}$ [2]. The supercritical water clad-to-coolant heat transfer coefficient that is heavily dependent on coolant flow rate is expected to range anywhere between 3500-17000 $W \cdot m^{-2} \cdot K^{-1}$ [3].

Using similar irradiation and coolant information, previous work done at the Royal Military College of Canada (RMCC) has successfully produced CANDU fuel performance models using COMSOL Multiphysics that a finite element methods solver [4]. The premise behind this work is that a similar fuel performance model of the Canadian SCWR can be produced and used as a means to support fuel design and subsequent qualification. The fine details of the SCWR fuel pellet and sheath have yet to be established. By setting acceptance criteria based on in-reactor fuel safety requirements, the fuel performance model can be used as a fuel design assessment tool for determining an acceptable range of pellets and sheath thicknesses. The safety limits to be used as the acceptance criteria are three limits imposed by the U.S. Nuclear Regulatory Commission on fuel behaviour, that: 1) There is to be no fuel melting, 2) The internal gas pressure of an element must be below the coolant pressure during NOC and 3) there is to be 1% or less diametral strain occurring within the clad [6]. This work will present the initial modelling efforts in the development of a Canadian SCWR fuel performance model.

2. Model Development

At this point within the reactor design phase, the geometry of the fuel assembly is iterating through various designs. This work will present the initial efforts in the development of a fuel performance model, using fuel elements of two different sizes from a 77-element fuel assembly design (cross section shown in Figure 1) [2]. In this initial test for a SCWR fuel performance model, clad made of 310 stainless steel and a pellet comprised of UO_2, with coolant conditions representative of the expected temperature and heat transfer properties of the supercritical water coolant were examined. The physical properties of a Th-Pu dioxide mixed ceramic pellet are not well known, however the irradiation behaviour of UO_2 has been extensively examined. This model will not be representative of the actual SCWR fuel. However it will give insight into the general fuel performance behaviour as well as establish what modelling requirements for the SCWR fuel will be.

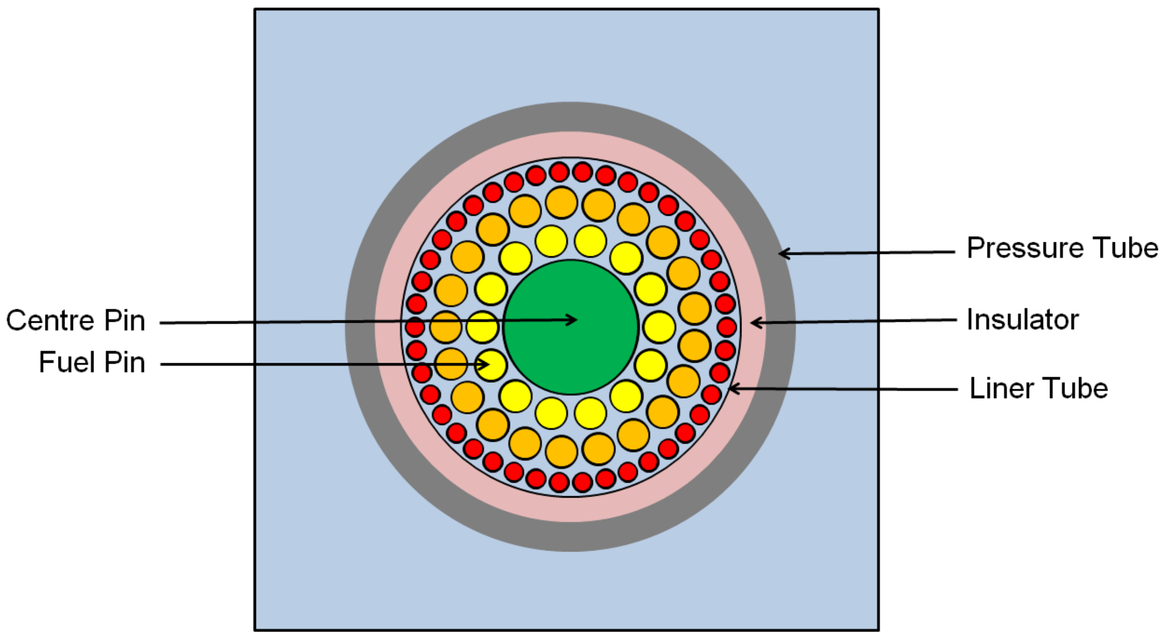

Figure 1 Cross-sectional view 77- element Canadian SCWR Fuel Assembly, with the element radii of the fueled elements being 0.68 cm for the two inner rings and 0.41 cm for the outer ring [2].

Finite element analysis is a way of estimating the solution of differential equations. The idea is that the differential equations that describe the heat transport and deformation of a fuel pellet and clad could provide an estimate for the temperature and strain while the fuel is in the reactor. A full detailed description of the fuel performance model is beyond the scope of this abstract. Further details of this model were presented at the 6th International Symposium for Super-Criteria Water Reactor paper [7].

3. Results and Discussion

The initial modeling efforts examined the two proposed fuel element dimensions within a 77 element assembly (as per Figure 1). The following modelling parameters were assumed: a clad-to-coolant heat transfer coefficient of 10000 $W \cdot m^{-2} \cdot K^{-1}$, a coolant pressure of 25 MPa, two temperatures within the supercritical fluid phase of 384 ^{o}C (657 K) and 600 ^{o}C (873 K) and at a constant LER of 25 $kW \cdot m^{-1}$. These sets of conditions, although within the expected ranges, are arbitrary, and are used as initial test cases.

The results of the heat transport calculation for the inner ring element geometry are displayed in Figure 2.

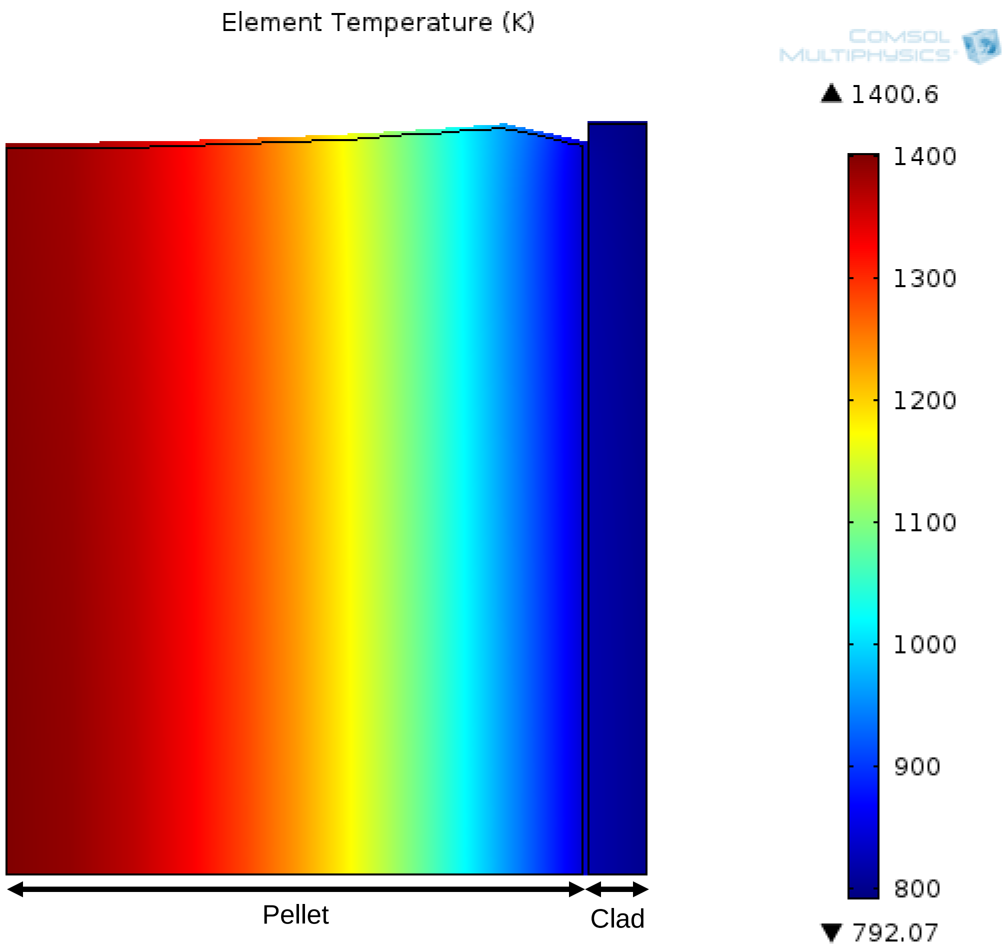

Figure 2 Temperature of an inner ring fuel element after 21 days irradiation with a LER of 25 $kW \cdot m^{-1}$

Since we have confidence in the modelling treatment of UO_2, based on previous models implemented at RMCC and based on the coolant conditions, the pellet centerline temperature of 1400 K is not unexpected. Inner ring fuel elements are similar in size to an element from CANDU 37-element fuel bundle. At an LER of 25 $kW \cdot m^{-1}$and a coolant temperature of 557 K for CANDU fuel, the centerline temperature calculated by the industry standard toolset code ELESTRES is approximately 1023 K [4]; this pellet temperature difference can be explained by the differences in the clad/sheath-to-coolant heat transfer coefficient. The heat-transfer coefficient has a value of 10000 $W \cdot m^{-2} \cdot K^{-1}$, which is 5 times less than the 50000 $W \cdot m^{-2} \cdot K^{-1}$ used in modelling the CANDU fuel. Temperatures in the pellet are below the melting temperature of UO_2. Table 1 lists the acceptance criteria for inner elements examined at both temperatures.

Table 1 Inner ring elements safety parameter values

Irradiation Time	**Coolant Temperature [K]**	**Maximum Pellet Temperature [K]**	**Internal Gas Pressure [MPa]**	**Max. Clad Strain %**
21 days	657	1401	0.476	0.016
7 days	873	1799	0.726	0.523

Results from both simulations indicate that the pellet geometry and clad thickness would meet the acceptance criteria for the proposed reactor conditions. The results also demonstrate that the modeling approach is able to track the changes for those acceptance criteria as set by Reference [6].

As a first approximation, the pellet geometry used in an outer ring element was assumed to be the same length to diameter ratio as the inner ring pellets. The same LER and coolant conditions were applied to the model as test case #2. Table 2 lists the acceptance criteria for outer elements examined at both temperatures.

Table 2 Outer ring element safety parameter values

Irradiation Time	**Coolant Temperature [K]**	**Maximum Pellet Temperature [K]**	**Internal Gas Pressure [MPa]**	**Max. Clad Strain %**
2 days	657	1499	0.394	-1.36
69 minutes	873	1849	0.531	-0.994

These results indicate that further changes in the pellet geometry are required; even within such a short time frame as the strain limit is exceeded. Optimizing the length-to-diameter ratio and clad thickness may limit the amount of compressive strain and provide a greater surface for heat transfer to lower the pellet centerline temperature. The future of this work is to establish fuel designs that meet the proposed acceptance criteria, including burnup and LER requirements.

The irradiation times that these models represent are many orders of magnitude shorter than the targeted burnup of 40 $MWd \cdot kg^{-1}$. At this point in the model development, it has been observed that the set of equations are extremely non-linear. Non-linear systems are computationally expensive to solve and often lead to program failure due to non-convergence, the results presented here are only an illustration of the modeling approach. Further work is required to perform a series of convergence studies with the goal of optimizing mesh and time step sizes to best account for the complexity of the system and allow the analysis to be performed for the expected burnup range.

There is a considerable amount of work remaining before this fuel performance model for the Canadian SCWR is complete. The inclusion of the plastic deformation of the 310 stainless steel will likely be the next step following the convergence studies. Beyond that, a literature review of the irradiation behavior of thoria-based ceramic pellets will need to be done to generate a model for the proposed Th-PuO_2 SCWR fuel. Once all of that is in place, simulations of varying pellet and clad geometries will be undertaken under the expected coolant conditions, LER ranges and times that reflect the targeted burnup.

4. Conclusion

Work has begun in the development of a fuel performance model for the Canadian SCWR. The model is being developed in support of the fuel element design, by developing a tool that can be used to examine variations in clad thickness and pellet geometry. This work will provide insight into what element geometries will meet safety criteria. It has been found that the simulation of UO_2 within the SCWR environment produced reasonable results and that the model is capable of tracking the acceptance criteria that have been selected to guide model development.

5. References

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