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Applicability of Evaluation Models in the PWR Fuel Performance Code, ROPER for CANDU-6 Fuel

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ABSTRACT – The ROPER (ROd PERformance) code is the steady-state fuel performance analysis code developed and licensed recently in Korea for a PWR fuel. Fuel performance predictions generated by ROPER are based on interdependent material response models, manufacturer metrics, and power histories. The predictability of CANDU fuel behaviour by ROPER is investigated based on the comparison with ELESTRES results. In the present study, fuel thermal behaviour is compared with changing thermal conductivity and pellet radial power distribution models in ROPER. From the comparisons, the most appropriate result for the CANDU-6 fuel design is found. The preliminary ROPER analyses demonstrate evaluation model adequacy to the CANDU-6 fuel design.

1. Introduction

The ELESTRES code simulates CANDU-6 fuel behaviour under normal operation conditions (NOCs) [1]. A fuel rod performance analysis and design code, ROPER (Fuel ROd PERformance) has been developed as a principal design tool for evaluating fuel rod performance in PWR (Pressurized light Water Reactor)[2]. ROPER code calculates thermal and mechanical behaviours of UO_2 and Gd_2O_3-UO_2 fuel rods encapsulated with Zirconium base alloy cladding tube under steady-state and transient conditions. ROPER has been developed incorporating updated fuel performance models. The code is appropriately organized to predict the in-reactor fuel rod behaviours based on the currently available database. The incorporation of fuel thermal conductivity models including burnup degradation effect might have impact on fuel rod design analysis.

This study is intended to evaluate the applicability of evaluation models in the PWR fuel performance code, ROPER for CANDU-6 fuel. Code-to-code comparisons between ELESTRES and ROPER are performed. As a first step, the preliminary analyses are done for the fuel thermal behaviour, such as fuel temperatures and fission gas release using typical CANDU-6 fuel design parameters.

2. Analysis Details

The applicability of evaluation models in ROPER is evaluated with the current performance methodology for Wolsong plant. The evaluation is performed on the regular 37 element fuel bundles (37R) composed of Zircaloy-4 and UO_2.

2.1 Analysis Codes

A fuel rod performance and design analysis code predicts fuel rod irradiation performance and is used to show that related design criteria are satisfied. In the current performance evaluations, ROPER is used for the rod thermal calculation. The code performs calculations for the fuel thermal behaviour: fuel temperatures, fission-gas release and rod internal pressure. Thermal-hydraulic conditions are input in the evaluation with ELESTRES. To provide code-to-code comparison between ROPER and ELESTRES, CATHENA thermal-hydraulic boundary conditions are used.

2.2 Analysis Modelling

Table 1 and Figure 1 show a list of input parameters and power history used to represent the 37R design specific aspects of Wolsong plant. The power history shown in Figure 1 is a typical power history for the evaluation of fuel behaviours such as fuel centerline temperature and rod internal pressure. The fuel-coolant heat transfer models in ROPER are modified as input data to match the boundary conditions with ELESTRES. Crud and corrosion models are not considered to match with original ELESTRES simulations. In addition, the governing parameters affecting fuel thermal behaviour are fuel thermal conductivity, gap conductance and radial power distribution models. In this study, analysis on the gap conductance is not done.

The thermal conductivity of the fuel is one of the key parameters that affect the calculations of the fuel temperature, the fission-gas release, the internal gas pressure, and the fuel pellet expansion. For thermal conductivity model, LUCUTA and modified NFI models are considered in [2], [3] and [4]. Similar to most other fuel thermal conductivity models utilized in fuel performance codes, the NFI model consists of a lead term that is inversely proportional to the temperature function(phonon term), with burnup dependence factors in its denominator, plus terms that model the electronic contribution to fuel heat transfer at high temperature. In the ELESTRES calculations, the thermal conductivity of the UO_2 fuel is calculated as a function of temperature, porosity, and burnup [4]. The model takes into account the effects of dissolved and precipitated fission products, pores, and radiation damage on thermal conductivities of UO_2 fuel. Irradiation affects the thermal conductivity of UO_2 fuel. The effects of dissolved and precipitated fission products on thermal conductivity are calculated by using expressions that are recommended in LUCUTA model

And for pellet radial power distribution model, KARMA [2] and TUBRNP [5] models are selected. The KARMA code, a bi-dimensional multi-group neutron transport code for the modeling of the pressurized and boiling water reactor, generates the grid nuclear parameters for reactor core. The radial power distribution data for UO_2 pellet at U-235 enrichment range of 0.75 ~ 9.0 w/o U-235 and burnup range of 0 ~ 90,000 MWD/MTU by KARMA were built-in the ROPER code. TUBRNP (TRANSURANUS burnup) predicts the radial power density distribution as a function of burnup together with the radial profile of plutonium. For this study, TUBRNP model is added in ROPER code to simulate PHWR core. The variation in the heat generation rate is determined based on the HAMMER [4] flux depression look-up table, which is a function of fuel pellet diameter, fuel enrichment, and fuel burnup.

In order to analyze the applicability of ROPER model for CANDU-6 fuel rod design, ROPER code exercise is performed with changing pellet thermal conductivity and radial power distribution. Four cases using combination of various model options are selected as follows:

- Case 1: MODIFIED-NFI, KARMA (ROPER default option)
- Case 2: MODIFIED-NFI, TUBRNP
- Case 3: LUCUTA, KARMA
- Case 4: LUCUTA, TUBRNP

Table 1. Major Input Data

Parameter	Value	Parameter	Value
Pellet Diameter	12.162 mm	Surface Roughness Factor of Sheath	0.5 μm
Dish Depth	0.25 mm	Surface Roughness Factor of Pellet	0.8 μm
Coolant Pressure	10.593 MPa	Coolant Temperature	564.65 K
Density	10.65 g/cm^3	Thermal to Fission Power Ratio	0.925
Stack Length	481.66 mm	Grain Size	10 μm
Diametral Clearance	0.094 mm	Enrichment	0.71 %
Sheath Wall Thickness	0.41 mm	Depth of Pellet Chamfer	0.25 mm
Fraction of He	0.9	Length of Pellet Chamfer	0.06 mm
Heat Transfer Coefficient	53.27 kW/m^2-K	Filling Gas Volume	0.1013 MPa

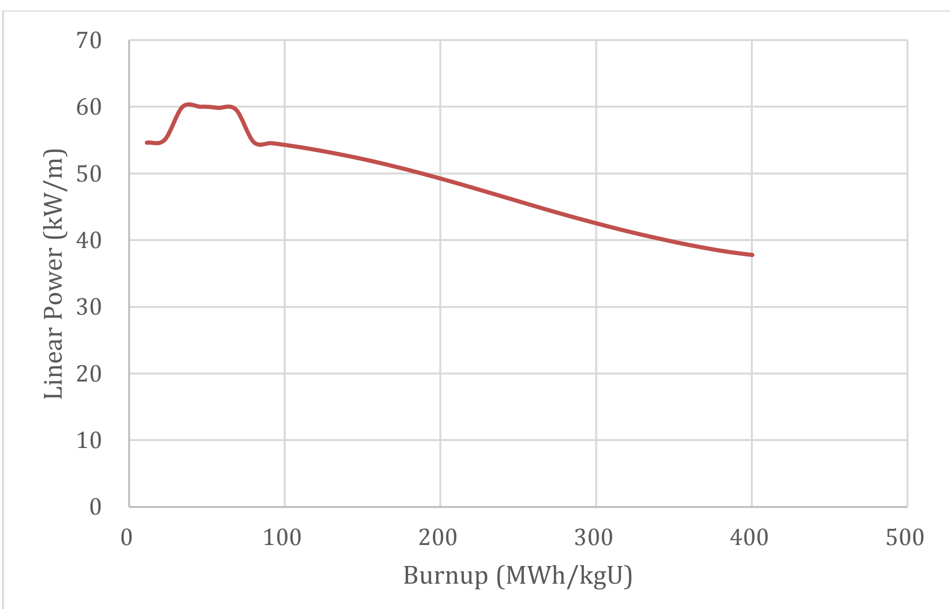

Figure 1. Rod Power History

3. Analysis Result

3.1 Comparison of Evaluation Models

The fuel phenomena governing the thermal-mechanical behaviour are identified and reviewed for understanding fuel performance. The evaluation models used in ROPER are compared to those in ELESTRES for fuel performance simulations. Table 2 shows the application range of between the codes. As shown in Table 3, there are differences between evaluation models of the ELESTRES and ROPER codes. Based on the investigation, it is demonstrated that additional fuel model is required for a best-estimate evaluation of fuel behaviour using ELESTRES in terms of in-reactor fuel rod behaviour based on the currently available database.

Table 2. Range Difference of Application between ELESTRES and ROPER

Parameter	ELESTRES	ROPER
Pellet Material	UO_2	UO_2, UO_2-Gd_2O_3
Clad Material	Zry-4	Zry-4, ZIRLO
Enrichment (%)	0.71~6.0	0.75~5.0
Density (g/cm^3)	10.50~10.80	10.14~10.58 (92.5~96.5 %TD)
Burnup (MWh/kgU)	< 480	< 1440 (60 GWD/MTU)
Linear Power (kW/m)	< 83	< 63.96 (19.5 kW/ft)

Table 3. Difference between Evaluation Models of ELESTRES and ROPER

Evaluation Model	ROPER	ELESTRES
Cladding Temperature	1-D conduction (thermal conductivity and cladding geometry)	1-D conduction (thermal conductivity and cladding geometry)
Pellet Relocation	Function of burnup and linear power	Not considered
Pellet-Cladding Gap Heat Transfer	Open/Closed gap conductance (solid-contact/gap-gas/radiation)	Closed gap conductance (solid-contact/gap-gas/radiation)
Pellet Radial Power Distribution	Input data or Look-up tables from KARMA physics code as a function of enrichment and burnup	Bessel function type fitted HAMMER physics code as a function of burnup

Pellet Temperature Distribution	1-D conduction with thermal conductivity (temperature, porosity, burnup) Finite difference method using energy balance	1-D conduction with thermal conductivity (temperature, porosity, burnup) Finite difference method using parabolic function
Fission Gas Release	Steady-State and Transient semi-mechanistic model based on Forsberg-Massih algorithm (athermal, diffusion, equiaxed grain growth, grain boundary re-solution and saturation, cracking)	Steady-State intra-granular diffusion based on Booth equations (athermal equiaxed and columnar grain growth, grain boundary saturation)
Densification	Empirical equation as a function of burnup and initial density	Empirical equation as a function of porosity and temperature
Swelling	Solid fission product as a function of burnup	Solid and gaseous fission products
Void Volume	Pellet dish & chamfer, crack, surface roughness, gap, open porosity, plenum	Axial & radial gap, pellet dish/chamfer, open porosity, surface roughness, crack
Cladding Growth	Irradiation growth as a function of fast neutron fluence	Not considered
Pellet Deformation	Rigid pellet model (neglect the stress-induced deformation of the fuel) Deformation due to pellet thermal expansion, swelling and densification	Thermal-elastic-plastic-creep deformation 2-D finite element method
Cladding Deformation	Thermal-elastic-plastic-creep deformation at open and closed gap Classical equation using successive iteration on cylindrical geometry	Thermal-elastic-plastic-creep deformation 2-D finite element method

3.2 Prediction of Fuel Thermal Behaviour

With the combination of each model described above, the results of the code-to-code comparison are as follows.

Cladding Temperature (Figure 2)

Same results in all case dut to the fixed boundary condition.

Pellet Temperature (Figure 3)

Over prediction for most cases (ELESTRES < Case 4 < Case 3 < Case 2 < Case 1). But it shows similar trend.

Fisson Gas Release (Figure 4)

For all cases, FGR fractions predicted by ROPER do not match with those of ELESTRES. It may be due to the different FGR modeling concept between two codes.

Rod Internal Pressure (Figure 5)

Over prediction for most cases (ELESTRES < Case 4 < Case 3 < Case 2 < Case 1). But it shows similar trend.

From Figure 3, it can be inferred that more conservative predictions for fuel thermal behaviors are originated from lower thermal conductivity and steeper radial heat generation rate (Figures 5 and 7).

Based on the comparison results, it can be concluded that the calculation results with LUCUTA and TUBRNP models (Case 4) have come close to those of ELESTRES.

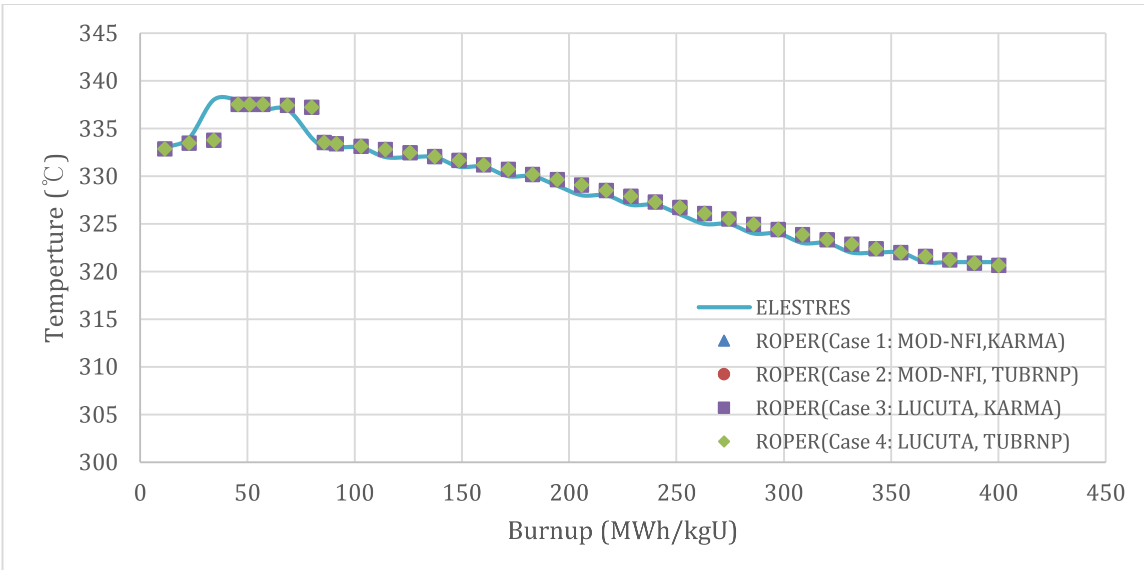

Figure 2. Clad Inner Temperature as a Function of Burnup

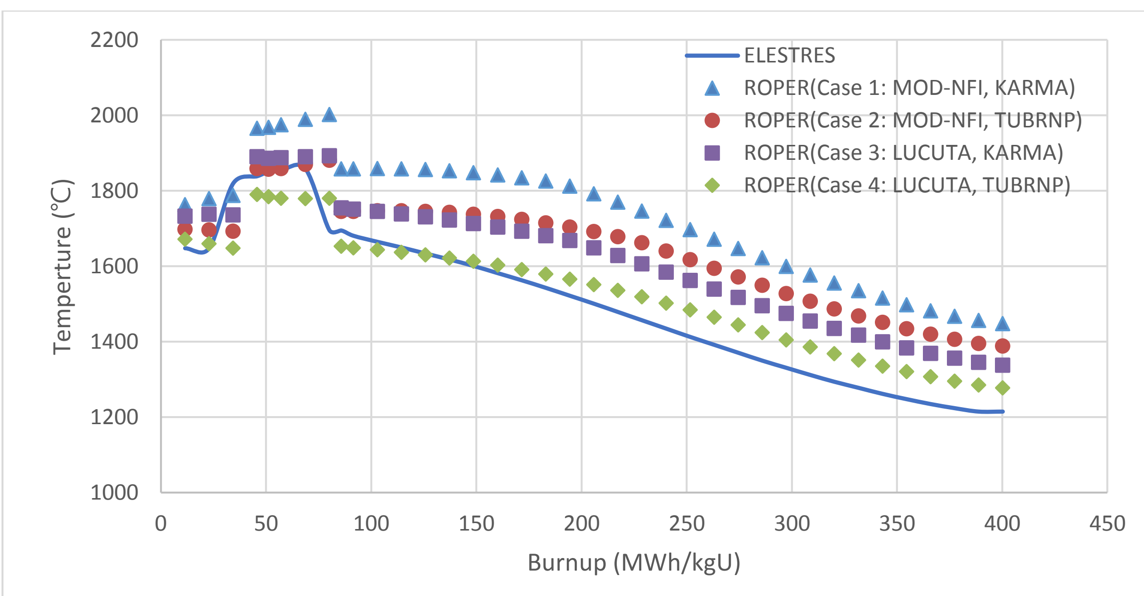

Figure 3. Pellet Center Temperature as a Function of Burnup

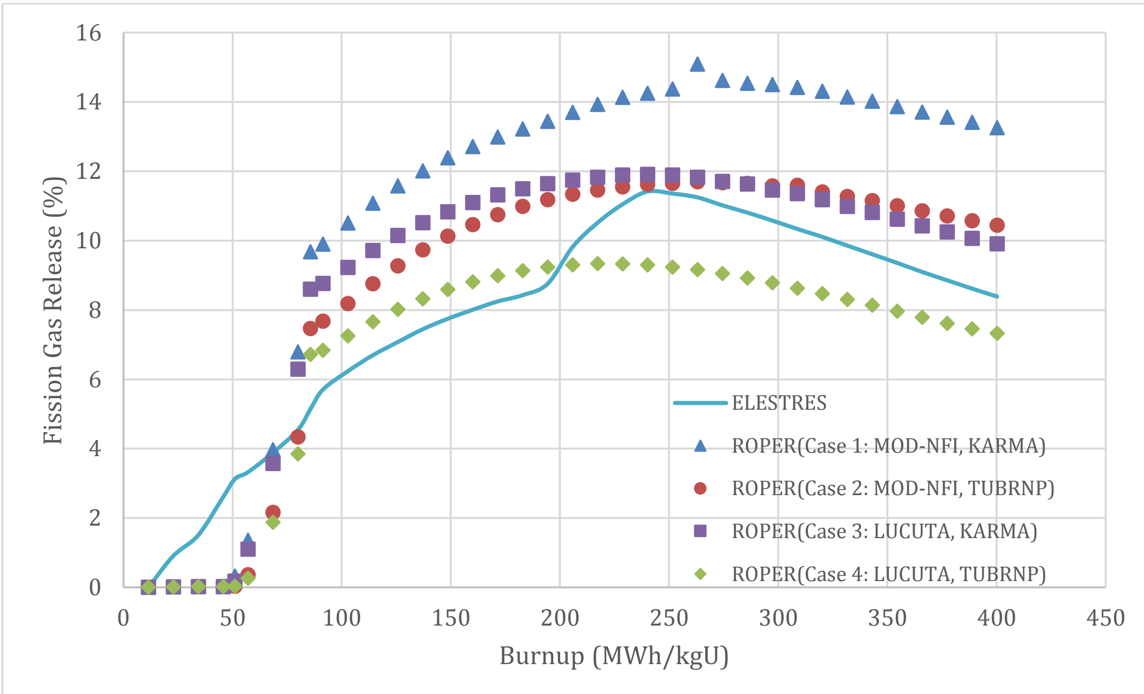

Figure 4. Fission Gas Release as a Function of Burnup

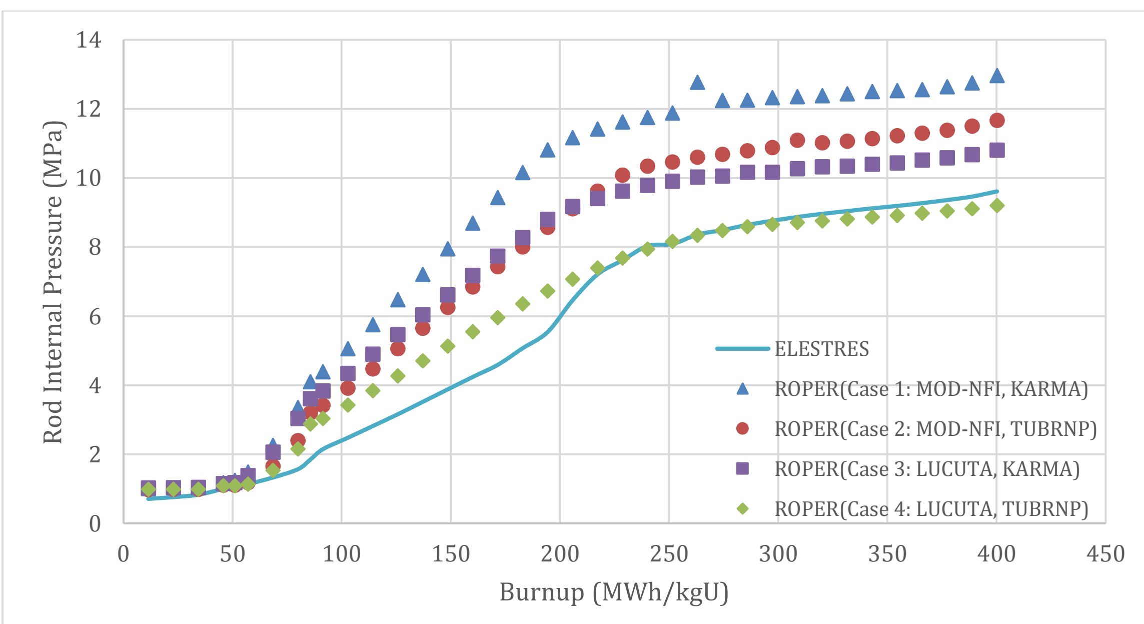

Figure 5. Rod Internal Pressure as a Function of Burnup

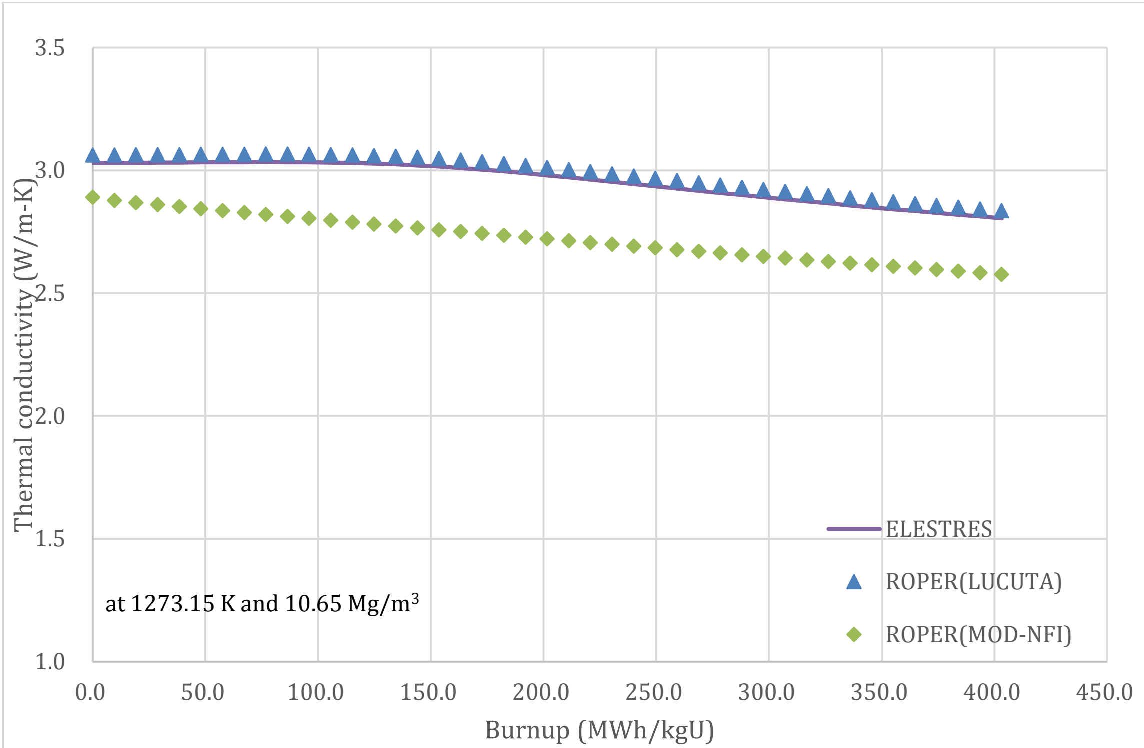

Figure 6. Pellet Thermal Conductivity as a Function of Burnup

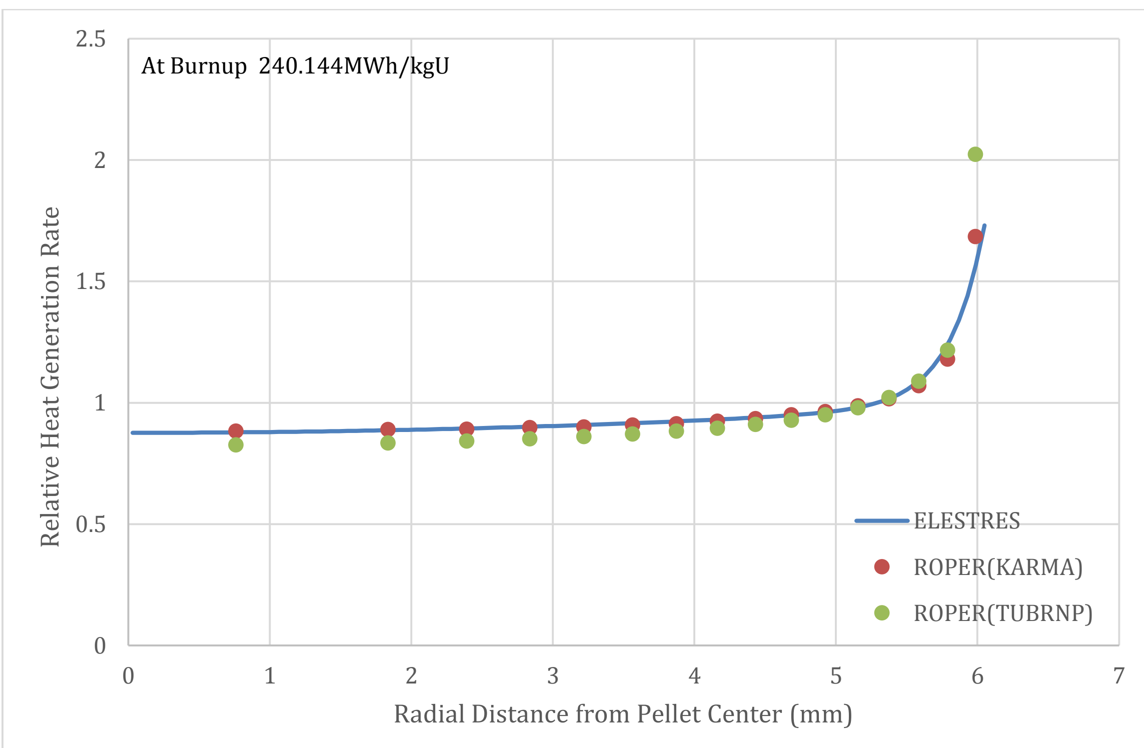

Figure 7. Radial Distribution of Heat Generation

4. Conclusions

Code-to-code comparisons between ELESTRES and ROPER are performed in order to investigate the predictability of CANDU fuel behaviour by ROPER. In the present study, fuel thermal behaviour is compared with changing pellet thermal conductivity and pellet radial power distribution models in ROPER. From the comparisons, ROPER demonstrates the applicability of PWR fuel performance analysis code to the CANDU-6 fuel design.

5. References

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