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Evaluation of Gap Heat Transfer Model in ELESTRES for CANDU Fuel Element Under Normal Operating Conditions

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CANDU형 핵연료봉의 정상상태 계산용 ELESTRES 코드내 간극 열전달 모델 평가

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Abstract

The gap conductance between the fuel and the sheath depends strongly on the gap width and has a significant influence on the amount of initial stored energy. The modified Ross and Stoute gap conductance model in ELESTRES is based on a simplified thermal deformation model for steady-state fuel temperature calculations. A review on a series of experiments reveals that fuel pellets crack, relocate, and are eccentrically positioned within the sheath rather than solid concentric cylinders. In this paper, the two recently-proposed gap conductance models (offset gap model and relocated gap model) are described and are applied to calculate the fuel-sheath gap conductances under experimental conditions and normal operating conditions in CANDU reactors. The good agreement between the experimentally-inferred and calculated gap conductance values demonstrates that the modified Ross and Stoute model was implemented correctly in ELESTRES. The predictions of the modified Ross and Stoute model provide conservative values for gap heat transfer and fuel surface temperature compared to the offset gap and relocated gap models for a limiting power envelope.

요 약

핵연료 소결체와 피복관 사이의 간극 크기에 크게 좌우되는 간극 열전도도는 연료봉내 초기 저장에너지 양에 중요한 영향을 끼친다. 정상상태 계산용 ELESTRES 코드에서 사용 중인 수정된 Ross-Stoute의 간극 열전도도 모델은 단순한 열적 변형 모델에 기초한다. 최근의 실험에서 핵연료 소결체가 연소됨에 따라서 균열, 소결체 재배열 등이 발생되고, 피복관 내부의 편심에 위치하게 된다는 것이 알려졌다. 본 논문에서는, 최근에 제안된 편심형 간극 모델과 소결체 재배열형 간극 모델 등이 기술되었고, 실험 조건과 중수로 핵연료봉의 운전조건 하에서의 소결체와 피복관 사이의 간극 열전도도를 계산하는데 이용되었다. 실험치와 계산치가 잘 일치됨으로써, 수정된 Ross-Stoute 모델이 ELESTRES 코드 내에서 사용된 열전달 관련 가정들과 잘 부합됨을 보여 주었다. 출력 경계곡선을 따라서 수정된 Ross-Stoute 모

델로 계산된 간극내 열전달과 핵연료 표면 온도 등이 편심형 간극 모델과 소결체 재배열형 간극 모델에 의한 예측치보다 보수적이었다.

1. Introduction

In CANDU safety analysis, ELESTRES [References 1, 2] which models fuel element thermal and mechanical behavior during irradiation under normal operating conditions is used to provide fuel conditions (such as UO_2 temperature distribution, sheath temperature, sheath strain, internal gas pressure) at the time of a postulated accident.

The amount of stored energy in the fuel at the start of a reactor transient plays an important role in the response of the fuel element during the transient. The amount of stored energy is directly related to the fuel center-line temperature and the temperature gradient from the fuel center to the fuel surface. The initial stored energy for fuel element primarily controls the sheath temperature rise after dryout. The fuel center-line temperature and the temperature gradient are functions of thermal conduction within the pellet, heat transfer through the fuel-sheath gap, and conduction through the sheath under the same element power, coolant temperature and sheath-to-coolant heat transfer coefficient.

The fuel-sheath gap is a major resistance to the heat transfer from the fuel pellets to the coolant. The primary heat transfer mechanisms within fuel-to-sheath gap are conduction through the fill gas, radiation, and solid-solid contact conduction. The total heat transfer through the fuel-sheath gap can be considered to consist primarily of contributions arising from contact conductance (fuel and sheath are in contact) and gap conductance (fuel and sheath are separated). The fuel-to-sheath radiation heat transfer only contributes significantly to the gap conductivity under the conditions of sheath ballooning.

The mechanism that governs heat transfer across the fuel-sheath gap has been well understood [Reference 3]. One significant trend in steady-state thermal calculations in the past ten years has been a steady reduction in calculated values for fuel temperatures and stored energy [Reference 4]. This perspective permitted data interpretation and fuel element modeling to focus on effective gap size rather than on the gap conductance mechanism itself.

U.S. NRC Regulatory Guide [Reference 5] recommends that the calculation of the gap width during reactor operation (hot gap size) take into account UO_2 fuel swelling, densification, creep, thermal expansion and fragment relocation, and sheath creep. The recently-proposed models such as offset gap conductance model [References 6, 7, 8] and relocated gap conductance model [Reference 9] include the above essential phenomena and are based on in-pile and out-of-pile test data. As a result, the heat transfer across the fuel-sheath gap is significantly greater than what is calculated with fuel pellet modelling as solid concentric cylinder. However, the ELESTRES dynamic gap conductance model assumes a modified Ross and Stoute model [References 10, 11] based on a simplified thermal deformation model. In the case of CANDU fuel, the sheath is collapsed into contact with the pellet at the beginning-of-life (BOL). At higher burnups a gap may exist so that the effects of fuel relocation and cracking should be considered to estimate the gap width correctly.

In this paper, the two recently-proposed gap conductance models (offset gap and relocated gap conductance models) are described along with the modified Ross and Stoute model. For the comparison purpose, the models are applied to calculate the fuel-sheath gap conductances under the conditions of experiment and in a fuel element during CANDU reactor operations.

2. Gap Conductance Model

Measurement of UO_2-zircaloy conductance at Pacific Northwest Laboratory (PNL) yielded the conclusion that the previous understanding of gap heat transfer mechanisms had been incomplete [References 3, 12]. Nevertheless, the predictions of the current gap conductance models is in agreement with the measurements to such an extent that the temperature discrepancies is small. A series of three tests to evaluate gap conductance in Light Water Reactor (LWR) fuel elements [Reference 9] was performed in the Power Burst Facility (PBF) at the Idaho National Engineering Laboratory (INEL). Studies were also performed in the Halden boiling water reactor (HBWR) at Halden, Norway [References 13, 14].

The quantity, quality and comprehensiveness of fuel temperature data have increased dramatically. These have lowered the uncertainty bounds on measured temperatures to the point where the conservatism of the calculated values could be recognized. Experimental results show that fuel pellets crack, relocate, and are eccentrically positioned within the sheath. As a result, the heat transfer across the fuel-sheath gap is significantly greater than that which is calculated with fuel pellet modelling as solid concentric cylinder.

2.1. Modified Ross and Stoute Model

The international nuclear community has used the work of Ross and Stoute [References 10, 11] as a standard, classical reference for fuel-to-sheath heat transfer; essentially all of the present fuel-to-sheath heat transfer models are based to some extent on their correlations. The modified Ross and Stoute model is incorporated in ELESTRES.

Thermal conductance of the fuel-sheath gap is a strong function of hot gap size and of the composition and pressure of the gases in the fuel element. The thermal conductance of the fill gas/fission gas mixture at the fuel-to-sheath interface is given by

$$h_f = \frac{k_g}{1.5\,(R_1 + R_2) + t_g + g} \qquad (1)$$

Where, h_f = conductance through the gas in the gap ($W/cm^2 \cdot K$)

k_g = thermal conductivity of gas ($W/cm \cdot K$)

R_1, R_2 = surface roughnesses of the fuel and the sheath (cm)

t_g = circumferentially averaged fuel-sheath gap width (cm)

For the thermal conduction of a gas between two surfaces, a temperature drop at each surface due to gas molecule/surface collisions must be considered and can be accounted for by increasing the measured gap size by a "temperature jump distance (g)" for each surface. Since the value of g is proportional to gas mean free path which itself is a function of gas temperature, pressure, and composition, the following formula is used to calculate g

$$\frac{1}{g} = \sum_i \left[\frac{y_i}{(g_o)_i}\right]\left(\frac{T_g}{273}\right)^{s+1/2}\left(\frac{0.101}{P_g}\right) \qquad (2)$$

Where, g = temperature jump distance (cm)

y_i = mole fraction of i-th component of gas

$(g_o)_i$ = temperature jump distance of i-th component of gas at STP (cm)

T_g = gas temperature in the fuel-sheath gap (K)

P_g = gas pressure in the fuel-sheath gap (MPa)

s = exponen dependent on gas type

For fuel operating conditions, appropriate values of g_o are 5.2 μm for helium, 0.57 μm for argon, and 0.26 μm for fission gas.

2.2. Offset Gap Conductance Model

The offset gap conductance model correctly predicts the significant circumferential variation in fuel temperature that was measured during the test series. The model is consistent with test results indicating that fuel pellets are offset from the sheath center-line instead of centrally located within the sheath. This model has been incorporated into state-of-the-art calculation methods for fuel element thermal response (FRAP-T6, RELAP5, and GAPCON-THERMAL-2) [References 6, 7, 8].

Since the longitudinal axis of the fuel pellets is usually offset from the longitudinal axis of the sheath, the width of the fuel-sheath gap varies with circumferential position. This variation causes the conductance through the gas in the gap to vary with circumferential position. The circumferential variation of the conductance is taken into account by dividing the gap into several equal segments. The conductance for each segment is calculated and then an average conductance, h_f, is computed by the equation

$$h_f = \frac{k_g}{N}\sum_{n=1}^{N}\frac{1}{3.2\ (R_1 + R_2) + t_n + g'} \qquad (3)$$

By dividing the fuel-sheath gap into 8 equal segments (N=8), with the first segment including the point of the fuel pellet surface offset towards the sheath and the 8-th segment including the diametrically opposite point, the fuel-sheath gap width is given by the equation

$$t_n = [(2n-1)/N]\ t_g \qquad (t_g \le t_o) \quad (4)$$

$$t_n = t_g + 0.5\ t_o\ [-1 + (2n-1)/N] \qquad (t_g > t_o) \quad (5)$$

Where, t_n = width of fuel-sheath gap at the midpoint of the n-th circumferential segment (cm), $0 < t_n < 2\,t_g$

t_o = as-fabricated fuel-sheath gap width (cm)

The temperature jump distance terms account for the temperature discontinuity caused by incomplete thermal accommodation of gas molecules to the surface temperature. The terms also account for the inability of gas molecules leaving the fuel and sheath surfaces to completely exchange their energy with neighboring gas molecules, which produces a nonlinear temperature gradient near the fuel and sheath surfaces. The terms are calculated by

$$g' = 0.024688\left[\frac{k_g T_g^{-1/2}}{P_g \sum_i y_i a_i M_i^{-1/2}}\right] \qquad (6)$$

Where, a_i = accommodation coefficient of the i-th component of gas

M_i = molecular weight of the i-th component of gas

The accommodation coefficients for gases are obtained by using curve fits to the data of Ullman [Reference 15].

2.3. Relocated Gap Conductance Model

The correlation developed in the PBF gap conductance tests [Reference 9] provides a calculation method for an average relocated gap width, t_r. This provides predictive estimates of fuel element relocated gap conductance when used with the modified Ross and Stoute gap conductance correlation. The partition of total thermal resistance between fuel and gap has been reassessed. The result is that further gap size is reduced more than necessary to achieve a match to the experimental data of fuel center-line temperature. This overestimation is compensated by degrading the fuel conductivity again to achieve agreement to fuel center-line temperature data. The relocated gap conductance for uniform thermal expansion model is given by

$$h_f = \frac{k_g}{1.5\ (R_1 + R_2) + t_r + g} \qquad (7)$$

Where, t_r = gap width based on the relocated gap model (cm),

$= t_r(czp) - C\ (t_o - t_g)$

$t_r(czp)$ = relocated gap width at cold zero power (cm),

$= 1.665\times10^{-3} + 8.680\times10^{-1}\ t_o - 1.344\times10^{2}\ t_o^2 + 7.168\times10^{3}\ t_o^3$

C = empirical constant

As a fuel element is operated at power, thermal stresses cause the fuel pellets to crack and pieces of the fuel to relocate in such a manner that some of the initial gap area is redistributed toward the center of the pellet. Consequently, pellet cracking and relocation alter the pellet-to-sheath gap width.

3. Application of Gap Conductance Model

3.1. Experiment Simulation

On simulating normal operating conditions, the gap conductance model is coupled with the fuel element heat transfer model to calculate the temperature distributions within UO_2. Comparison with experimental data was conducted to ensure that the gap conductance model performed correctly in ELESTRES code and then to evaluate the offset and relocated gap conductance models.

Results of the experiment performed in Reference 11 were used to assess the applicability of the modified Ross and Stoute model implemented in ELESTRES code to in-reactor conditions. Campbell et al. performed a series of instrumented in-reactor measurements in which the fill gas composition and pressure were controlled. Variations in fuel temperature and sheath strain were determined as the internal gas pressure of helium or argon was varied. During these pressure cycles, the pressure was varied in steps with the size of each step more or less proportional to pressure. These experiments showed that where there was a fuel-to-sheath gap, the width of which could be calculated from the change in sheath strain and fuel expansion, the classical approach of Ross and Stoute based on laboratory measurements agreed closely with experiment.

In this study, h_t, total heat transfer through the fuel-sheath gap are inferred by matching a measured fuel surface temperature (at a given power and coolant temperature) with assumed thermal conductivity of the sheath used in the ELESTRES code:

$$h_t = \frac{q}{\pi\ d_g\ (T_{fs} - T_{si})} \tag{8}$$

Where, h_t = total heat transfer through the gap ($W/cm^2 \cdot K$)
q = linear heat rating (W/cm)
d_g = average gap diameter (cm)
ΔT_{fs} = fuel surface temperature (K)
ΔT_{si} = sheath inner surface temperature (K)

The temperature at the sheath inner surface, T_{si}, was calculated according to the standard equation

$$T_{si} = T_c + \Delta T_f + \Delta T_s \tag{9}$$

Where, T_c = coolant temperature (K)
ΔT_f = temperature drop across the coolant film (K)
ΔT_s = temperature drop across the sheath (K)

Where ΔT_f is found from the sheath-to-coolant film heat transfer coefficient defined by thermohydraulic simulation and with the assumption that the sheath thickness is small (so that the sheath can be treated as a plane rather than annulus in CANDU reactors) ΔT_s is calculated by

$$\Delta T_s = \frac{q\ t_s}{\pi\ d_s\ k_s} \tag{10}$$

Where, t_s = sheath thickness (cm)
d_s = average sheath diameter (cm)
k_s = thermal conductivity of sheath ($W/cm \cdot K$)

Note that the method does not use gap size or the nature of the fill gas in computing h_t. The calculation uses the coolant temperature, the heat flux, and a pellet surface temperature. The gap conductance, h_f, can be calculated based on the h_t value to match the three variables. The basic heat transfer relationship that was used in these calculations was that implemented in ELESTRES.

3.2. CANDU6 Fuel Element Simulation

ELESTRES models fuel element thermal and mechanical behavior during irradiation under normal operating conditions. In CANDU safety analysis, ELESTRES is used to provide fuel conditions (such as UO_2 temperature distribution, sheath temperature, sheath strain, internal gas pressure) at the time of a postulated accident, to be used as initial conditions for estimating the timing of fuel element (sheath) failure following the accident.

In this study, ELESTRES runs were performed with typical input data for CANDU6 fuel and a power history of an "overpower envelope" as used in safety analyses. Typical input data for CANDU6 fuel are given in Table 1 for fuel behavior assessments during irradiation at operating conditions. The steady-state coolant conditions, coolant temperature, coolant pressure, and sheath-to-coolant heat transfer coefficient, for an outer element of a high-power bundle in the channel O6 are obtained from the thermohydraulic simulations using CATHENA code [Reference 16]. The reference overpower envelope used for an outer element is a curve of element power versus element burnup which encompasses most of the bundle powers predicted in a fuel management simulation of reactor operation. As shown in Figure 1, the envelope is discretized into a series of power steps at constant burnup followed by a hold period at constant power for an interval of 10 MW · h/kg(U). The maximum power is equal to the operational limit, 59.3 kW/m for an outer element.

The ELESTRES runs produce the calculated values of fill gas composition, radial gap width, internal gas pressure and fuel-sheath interfacial pressure at

Table 1. Input Data for Calculation of the Gap Conductance Within Outer Element by ELESTRES Code

Variables	Values
Pellet Diameter (mm)	12.2
Density (mg/m^3)	10.6
Sheath Thickness (mm)	0.38
Sheath Outer Diameter (mm)	13.04
Film Coeff. between sheath-to-coolant (kW/m^{2}K)	56.926
Coolant Pressure (MPa)	10.757
Coolant Temperature (K)	571

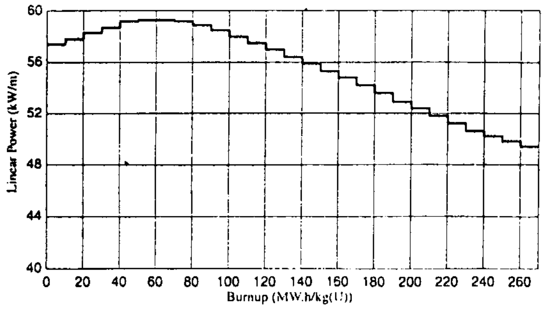

Fig. 1. Limiting Power Envelope of an Outer Element Used in ELESTRES Simulations

burnups ranging from 10 MW · h/kg(U) up to 270 MW · h/kg(U), in intervals of 10 MW · h/kg(U). These values are used to evaluate the different gap conductance models to predict the fuel surface temperatures under the normal operating conditions.

4. Results and Discussion

4.1. Experiment Simulation

Comparison with experimental data of heat transfer through the fuel-sheath gap was conducted to ensure that the gap conductance model performed correctly in ELESTRES code. As shown in Figures 2, 3, the good agreement between the inferred and calculated values demonstrates that the modified Ross and Stoute model has been implemented correctly in ELESTRES. In steady-state thermal calculations, lower values of gap conductance give higher fuel surface temperatures (initial stored energy).

The offset and relocated gap conductance models provide higher calculated values for gap conductance than those based on the modified Ross and Stoute model. As a result, the heat transfer across the fuel-sheath gap is estimated to be greater, especially in a wide-gap region~20 μm for helium pressure cycle and ~6 μm for argon pressure cycle), than what is calculated with the fuel pellet modelling as solid concentric cylinder. The greatest discrepancy in the gap conductance is in calculating the gap width;

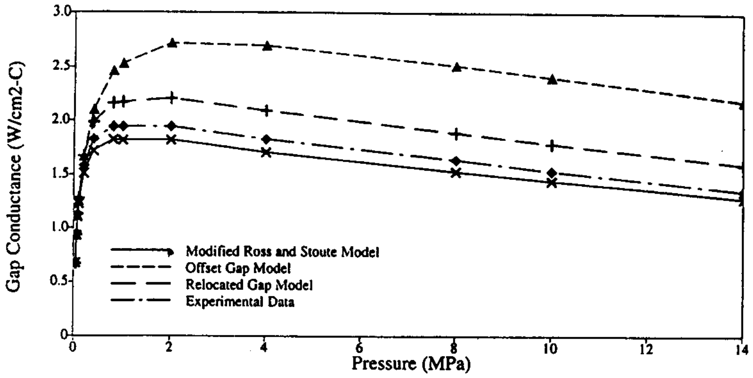

Fig. 2. Gap Condutances with Various Gap Models for Helium Pressure Cycle Experiments

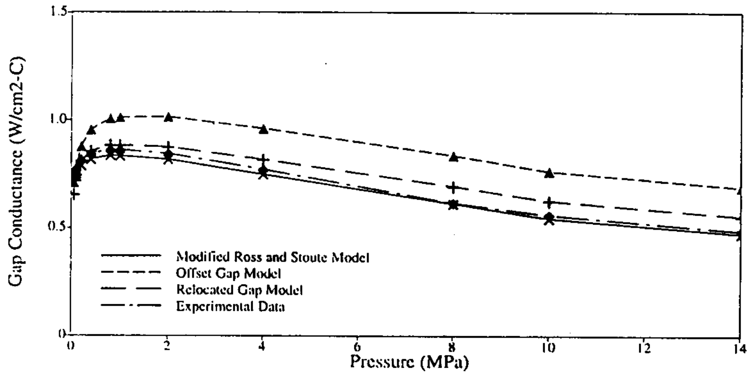

Fig. 3. Gap Condutances with Various Gap Models for Argon Pressure Cycle Experiments

Table 2. Effect of Gap Width Difference on Fuel Surface Temperature Using the Modified Ross and Stoute and Relocated Gap Conductance Models (He Pressure Cycle)

Internal He Pressure	Gap Width Difference (μm)	Temperature Difference (°C)	Temperature Difference per Unit Gap Width Difference (°C/μm)
0.06	0.1728	0.61	3.63
0.08	0.6029	2.17	3.60
0.10	0.9065	3.29	3.63
0.20	1.6425	5.96	3.63
0.40	1.9829	7.30	3.68
0.80	2.1899	8.09	3.69
1.00	2.2819	8.42	3.69
2.00	2.4429	9.02	3.69
4.00	2.7419	10.1	3.68
8.00	3.2019	11.8	3.69
10.0	3.4549	12.7	3.68
14.0	3.9839	14.5	3.64

Table 3. Effect of Gap Width Difference on Fuel Surface Temperature Using the Modified Ross and Stoute and Relocated Gap Conductance Models (Ar Pressure Cycle)

Internal Ar Pressure	Gap Width Difference (μm)	Temperature Difference (°C)	Temperature Difference per Unit Gap Width Difference (°C/μm)
0.20	0.1176	3.02	25.7
0.40	0.1797	4.62	25.7
0.80	0.2073	5.33	25.7
1.00	0.2211	5.68	25.7
2.00	0.2625	6.71	25.6
4.00	0.3683	9.29	25.2
8.00	0.6558	15.8	24.1
10.0	0.8122	19.6	24.1
14.0	1.0675	25.0	23.4

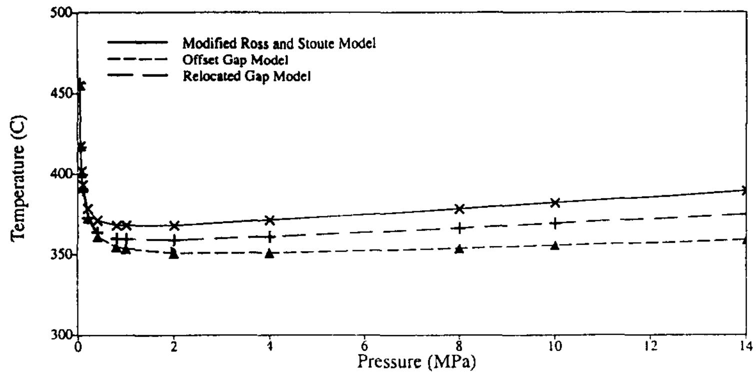

Fig. 4. Fuel Surface Temperatures with Various Gap Models for Helium Pressure Cylcle Experiments

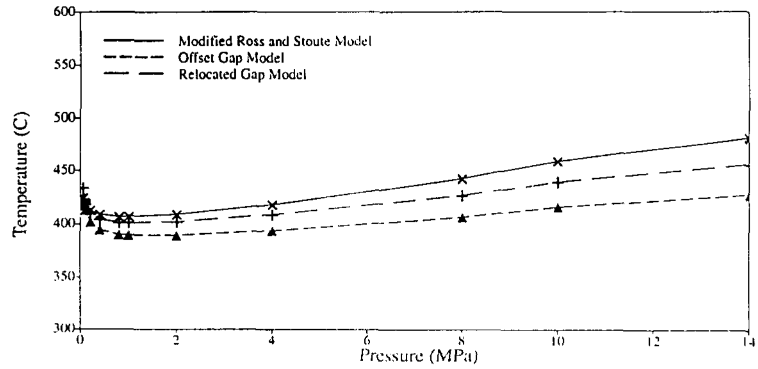

Fig. 5. Fuel Surface Temperatures with Various Gap Models for Argon Pressure Cylcle Experiments

a 1-μm reduction based on the relocated gap model can introduce reduction of ~4°C for helium pressure cycle and ~26°C for argon pressure cycle in calculating the fuel surface temperature as given in Tables 2, 3 and as shown in Figures 4, 5. The greatest discrepancy in the fuel surface temperature is ~50°C calculated on the basis of the offset gap conductance model at wide-gap region in high-pressure argon. Therefore, the relocated and offset gap models have a little effect on the fuel temperature compared to the present model in ELESTRES, especially for helium pressure cycle (similar gas composition to that at BOL). Furthermore, the discrepancies of fuel surface temperatures become more pronounced with increasing gap size for the recently-proposed models due to pellet cracking, relocation and pellet eccentricity.

4.2. CANDU6 Fuel Element Simulation

ELESTRES calculations were made using CANDU6 fuel data for each power history point to evaluate the modified Ross and Stoute model, the offset gap model, and the relocated gap model, respectively. Figures 6, 7 show the main estimated variables of internal gas pressure, interfacial pressure, and fill gas composition. In the case of CANDU fuel, the gap width is small, and the sheath is collapsed into contact with the pellet. A gap can exist under the internal pressure above coolant pressure, so the effects of fuel cracking and relocation should be considered to estimate the gap width correctly after a burnup of 140 MW · h/kg(U). By this point, about 95% of the fuel-sheath gap is filled with fission gas, xenon because the fission gas release is conservatively modelled in the code.

The analysis based on the above parameters demonstrates that the calculated gap conductance based on the modified Ross and Stoute model is lower than those predicted by other models as shown in Figures 8, 9. The gap conductance is lower even when the fuel-to-sheath gap is open. Fuel pellet cracking, fragment relocation, and pellet eccentricity are thought to be the probable causes of the discrepancy, and it is shown that the gap size is influenced by the pellet cracking and eccentricity as shown in Figures 10 to 12. Furthermore, the discrepancy of the gap width and gap conductance become more pronounced with increasing burnup for the offset gap conductance model due to enhanced eccentricity gap. For the relocated gap model, since the element power decreases as time goes, the difference for gap width is relatively constant with burnup. The only significant discrepancies of fuel surface temperatures

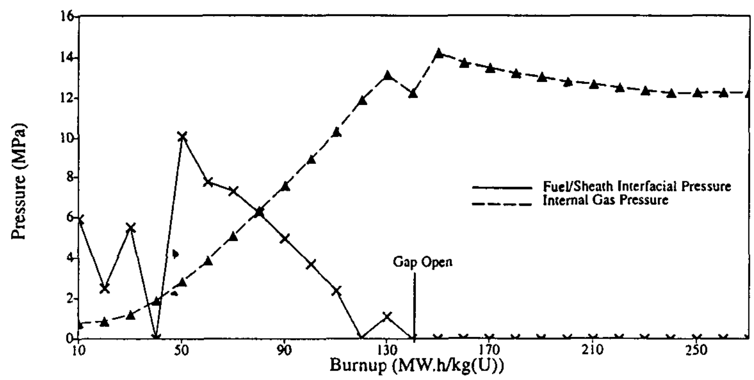

Fig. 6. Internal Gas and Interfacial Pressure Transients for an Outer Element of 59.3 kW/m

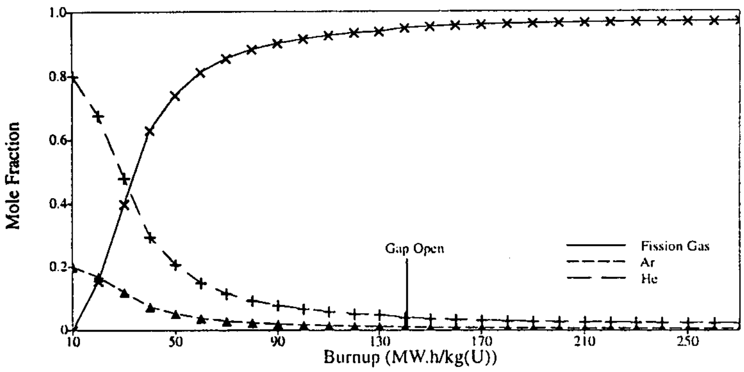

Fig. 7. Composition Distributions of Gases in the Gap for an Outer Element of 59.3 kW/m

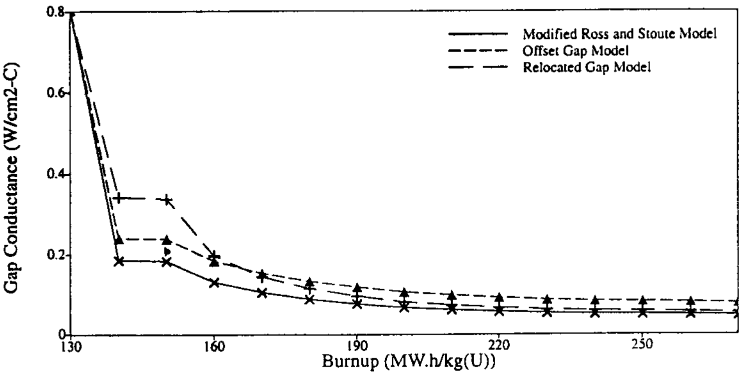

Fig. 8. Gap Condutances with Various Gap Models for an Outer Element of 59.3 kW/m

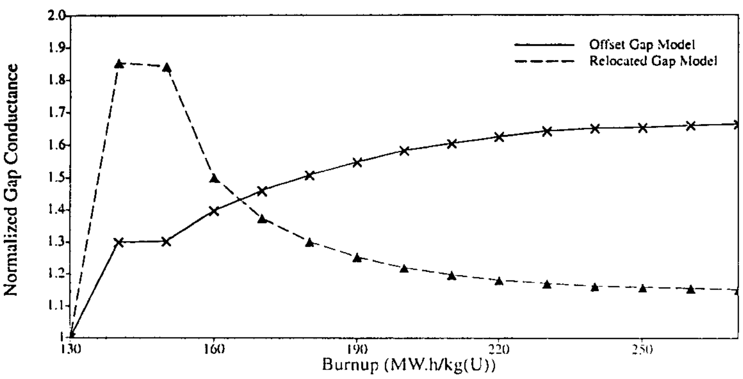

Fig. 9. Normalized Gap Conductance with Various Gap Models for an Outer Element of 59.3 kW/m (Relative to that Based on the Modified Ross and Stoute Model)

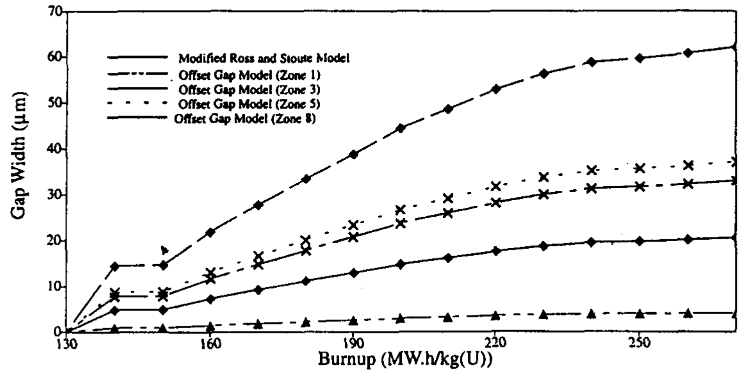

Fig. 10. Gap Width Based on the Modified Ross and Stoute, Offset Gap Models for an Outer Element of 59.3 kW/m

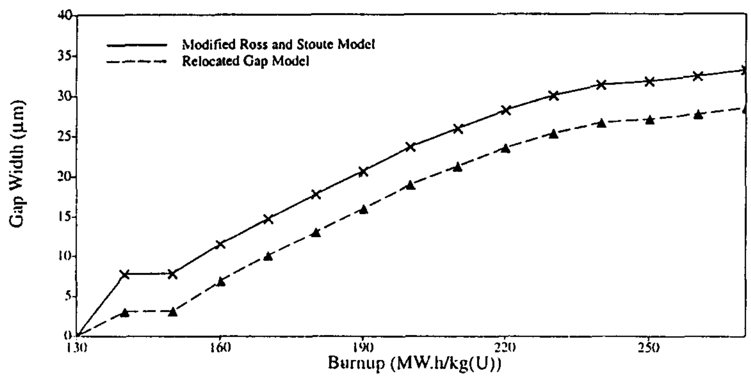

Fig. 11. Gap Width Based on the Modified Ross and Stoute, Relocated Gap Models for an Outer Element of 59.3 kW/m

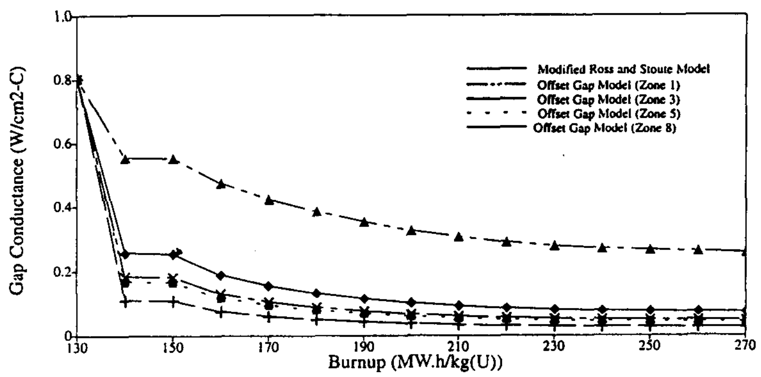

Fig. 12. Gap Width Based on the Modified Ross and Stoute, Offset Gap Models for an Outer Element of 59.3 kW/m

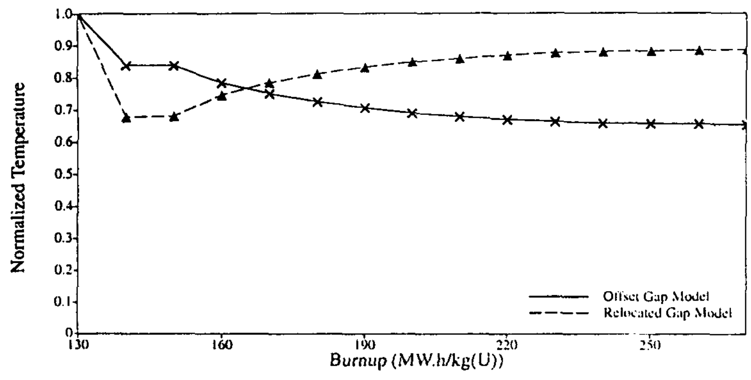

Fig. 13. Normalized Fuel Surface Temperatures with Various Gap Models for an Outer Element of 59.3 kW/m (Relative to that Based on the Modified Ross and Stoute Model)

occur at very small gaps. But for these high-conductance situations, a relatively large absolute discrepancy of the conductance translates into relatively small value in fuel temperature.

Figure 13 shows the corresponding predicted fuel surface temperature normalized to that based on the modified Ross and Stoute model. The calculated fuel surface temperature from the present model in ELESTRES is larger than those predicted by the other models. It is seen that the overall behavior closely reflects what is expected from the corresponding gap conductances. There is a spread of about 170°C between the highest and lowest predicted values of fuel surface temperatures.

Overall, there are relatively significant differences between the results from the modified Ross and Stoute model and the offset and relocated gap models using the conditions from ELESTRES runs for the same CANDU fuel.

The calculation of hot gap size should take into account the essential phenomena such as UO_2 fuel swelling, densification, creep, thermal expansion and fragment relocation, and sheath creep. Relocation quickly becomes complete in a fuel element. The fragment moves outward to lightly contact the sheath, creating an effective gap width. The choice of the effective gap width was relatively arbitrary to be adjusted for different conditions. Other adjustments have been tried, including accounting for possible pellet eccentricity and contact with the sheath. The offset gap conductance model correctly predicts the significant circumferential variation of fuel temperature that was measured during the test. As a result, the effective gap width and the calculated values for fuel temperatures and stored energy are reduced. The predicted values of the thermal consequences of fuel pellet densification should also be reduced if the pellet fragment relocation and eccentricity are real because the absolute increase in gap size resulting from the densification will be reduced.

Fission gas released from the pellet contaminates the original helium fill gas. Because fission gas is primarily xenon, with a conductivity 1/20 that of helium, fission gas reduces its conductivity, and raises the fuel temperature at constant element power. These effects produce more fission gas release, and the process continues until the fuel element stabilizes at the point that its fill gas is thoroughly saturated with fission gas ("thermal feedback"). If the pellet fragment relocation and eccentricity reduce the temperature effect of varying gap size and fill gas composition at BOL, then the phenomena could be expected to reduce the impact of "thermal feedback". The predicted temperature resulting from the thermal feedback with and without relocation and eccentricity is extreme; there is a spread of about 170°C between the highest and lowest predicted values of fuel surface temperatures as shown in Figure 13.

However, the predictions of the modified Ross and Stoute model provide conservative values for fuel-to-sheath gap heat transfer and fuel surface temperatures. End-of-life (EOL) burnups for LWR fuel are significantly higher than that for CANDU fuel, so the "tuning" that improves LWR predictions based on the offset and relocated gap models at EOL could be, more or less, inappropriate under some conditions for the low burnups applicable to CANDU fuel at EOL.

5. Conclusion

Existing gap conductance correlations in ELESTRES, have been compared to the offset gap model and relocated gap model. The following conclusions can be drawn:

1. the good agreement between the experimentally-inferred and calculated values demonstrates that the modified Ross and Stoute model has been implemented correctly in ELESTRES,
2. the pellet fragment relocation and eccentricity reduce the calculated values for fuel temperatures and stored energy because of the reduction of effective gap width and the impact of "thermal feedback", and
3. the predictions of the modified Ross and Stoute model provide conservative values for gap heat transfer and fuel surface temperatures compared to the physically-based models, the offset gap model and relocated gap model.

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