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《Original》

Review of Calculational Models for the Performance of CANDU-Type Nuclear Fuel Element and Parametric Study on the Fuel Performance

Man Sung Yim and Un Chul Lee, Ho Chun Suk*

Seoul National University, *Korea Advanced Energy Research Institute
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CANDU형 핵연료거동에 관한 계산모형의 검토 및 거동특성에 관한 변수적 연구

임 만 성 · 이 은 철 · 석 호 천*

서울대학교 · *한국에너지연구소
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Abstract

The LWR fuel performance analysis computer code, FRAPCON-1, are evaluated to investigate the performance of CANDU fuel elements loaded in Wolsung-1 reactor. The FRAPCON-1 models of neutron flux depression in fuel and of fuel-to-cladding heat transfer are modified, and the validity of fission gas release model for CANDU fuel is evaluated. And the heavy water properties are provided in calculating the heat transfer coefficient between cladding and coolant. By using the modified code, FRAPCON-1-CSK, the sensitivity studies are carried out for Wolsung-1 fuel element design parameters. The performance analysis is also performed for Wolsung-1 fuel elements. The calculated results are discussed in terms of LWR fuel design criteria because of unavailability of CANDU fuel design criteria.

요 약

경수형원자로 핵연료봉의 거동분석을 위한 전산코드인 FRAPCON-1 코드가 월성 1호기에 장전되는 CANDU형 핵연료봉의 거동분석을 위해 적절한지를 평가하였다. 연료내의 중성자속의 감소와 연료피복재간 열전달을 계산하는 FRAPCON-1 코드의 모형들을 수정하였으며 핵분열 기체방출모형의 CANDU 핵연료에 대한 타당성여부를 검토하였고 피복재와 냉각수간의 열전달 계수 계산을 위해 중수특성을 사용하였다. 수정된 코드 FRAPCON-1-CSK를 사용하여 월성 1호기 핵연료의 각 설계변수들에 대한 민감도 분석을 수행하였다. 아울러 월성 1호기 핵연료봉의 거동특성분석도 수행하였는데 계산된 결과들은 CANDU 핵연료봉에 대한 설계기준이 알려져 있지 않는 관계로 경수로 핵연료봉 설계기준의 입장에서 검토되었다.

1. Introduction

The Wolsung unit 1 is the first CANDU-PHWR nuclear power plant in Korea. The Wolsung CANDU reactor uses deuterium oxide as moderator and natural uranium dioxide as fuel. Hence, the Wolsung CANDU reactor fuel elements have several peculiar characteristics[1),2),3)] in comparison with PWR fuel elements. The Wolsung CANDU reactor fuel, consists of Zircaloy-sheathed UO_2 pellets, assembled into elements, which are then welded to end plates to form a fuel bundle. There are many design features or fabrication processes that could influence fuel performance: e.g. short bundle length, collapsible sheathing, high density pellet, natural UO_2 fuel, welded end caps, brazed appendages to maintain bundle geometry, and CANLUB coating between the fuel pellets and cladding, horizontal orientation of fuel bundle. Although the cladding thickness to diameter ratio varies in fuel for different reactors, in all CANDU systems the cladding collapses on to the pellets under normal operating conditions. Accordingly, pellet/clad interaction may occur, circumferential ridges are formed, and the internal gas pressure increases very high as burnup proceeds. Therefore it becomes very important to design, fabricate, and analyze the fuel elements with high degree of reliability and conservatism to assure the mechanical integrity of fuel element during lifetime under the normal and transient operating conditions.

In this study, the steady state LWR fuel rod performance code, FRAPCON-1[4)] is applied for the CANDU fuel element performance analysis. The FRAPCON-1 code had been developed to predict the behaviour of fuel rods during long-term irradiation and to calculate initial conditions for transient analysis by combining features from FRAP-S[5)] and GAPCON-THERMAL[6)]. The program calculates the interrelated effects of fuel and cladding temperature, rod internal pressure, fuel and cladding deformation, release of fission product gases, fuel swelling, cladding thermal growth, cladding corrosion, and crud deposition as a function of time and specific power.

In order to apply the FRAPCON-1 code for CANDU fuel analysis it is required to review the calculational models in detail. If the models are inadequate for CANDU fuel, the model provided in FRAPCON-1 should be replaced. Accordingly the FRAPCON-1 models of neutron inverse diffusion length and of fuel-to-cladding heat transfer are modified, and the validity of fission gas release model for CANDU fuel is evaluated. And the heavy water properties are provided in calculating the heat transfer coefficient between the cladding and coolant. By using the modified code, FRAPCON-1-CSK, we carried out the sensitivity studies about Wolsung-1 fuel element design parameters. We also performed the performance analysis for Wolsung-1 fuel elements. The calculated results are discussed in terms of LWR fuel design criteria[7),8)] because of unavailability of CANDU fuel design criteria.

2. Verification of Calculational Models for CANDU Fuel Performance Analysis

2.1. Heat Transfer between Cladding and Coolant

It is required to calculate the coolant temperature distribution and heat transfer coefficient between cladding and coolant using the heavy water properties instead of light water properties. To provide the heavy water propertiees, new subprogram named DOD81 is introduced. The DOD81 calculates the thermodynamic and transport properties of heavy water and is des-

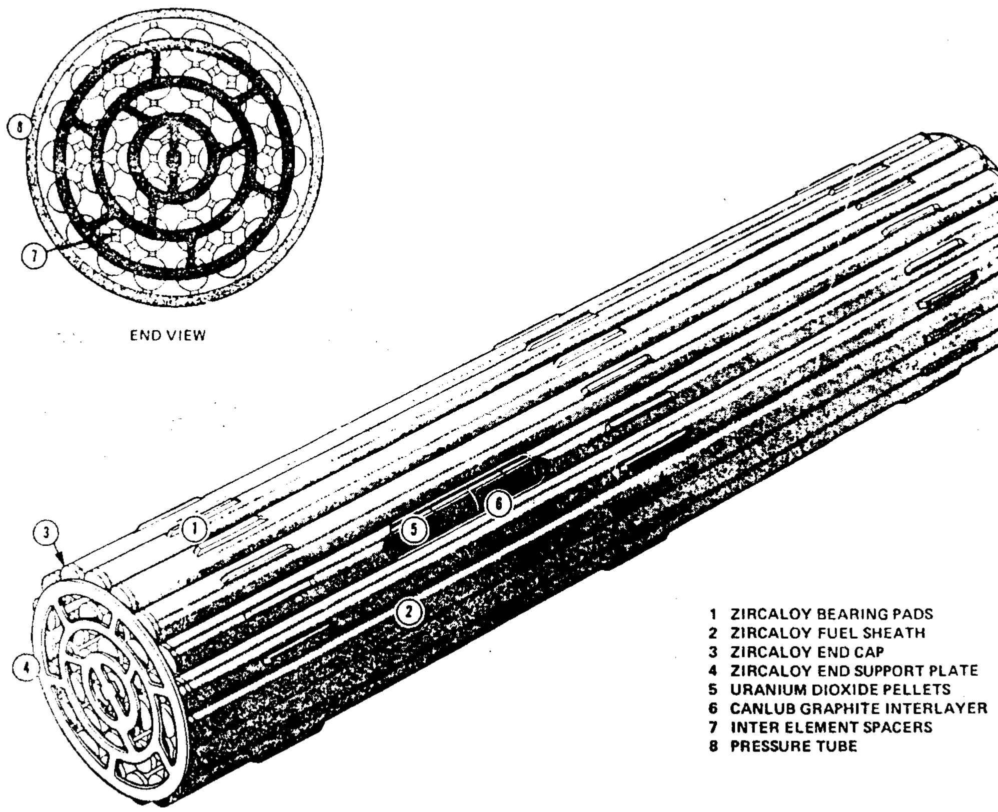

Fig. 1. CANDU 37-Element Fuel Bundle

cribed in reference 9. The heat transfer coefficient between cladding and coolant is calculated using the Dittus-Boelter correlation[7),9)].

The calculated results of heat transfer coefficient, h_f, in Wolsung-1 condition for light water and for heavy water are as follows,

$$h_f = \begin{cases} 11120 \ (\text{Btu/hr-ft}^2\text{-}^\circ\text{F}) \ \text{for } H_2O \\ 9760 \ (\text{Btu/hr-ft}^2\text{-}^\circ\text{F}) \ \text{for } D_2O \end{cases}$$

The calculated condition is; the channel power is 6.5 MW, coolant mass flow rate is 5.16×10^6 lbm/ft^2-hr, coolant pressure is 1545 psia, and coolant inlet temperature is 511.4°F. And calculated results show maximum 5°F difference in cladding surface temperature and maximum 10°F difference in fuel center temperature between the calculations using light water properties and heavy water properties, respectively.

2.2. Heat Transfer between Fuel and Cladding

The fuel-to-cladding heat transfer coefficient is composed of conduction through solid/solid contact spots and conduction through the fluid medium trapped in the voids between these spots, and radiation through this medium[10)], namely, $h_T = h_s + h_f + h_r$. (T: total, s: solid conduction, g: fluid medium conduction, r: radiation) In CANDU fuel, the cladding is collapsed onto the fuel pellet and remains in firm contact, hence the solid/solid conduction is importnt and should be calculated accurately. There are several different models describing the solid/solid conduction as follows,

—[5)]Ross-Stoute model

$$h_s = \frac{K_m \cdot P}{a_0 \ R^{1/2} H}$$

—[11)]Campbel et al. model

$$h_s = \frac{K_m \cdot P^{1/2}}{a_1 R^{1/2} H}$$

—[5]Cracked pellet model

$h_s = a_2 \cdot P^n$

where, $n=1$ for $0 \leq P \leq 1000$ (psi)

$n=0.5$ for $P > 1000$ (psi)

—[6]Beyer-Hann model

$$h_s = \frac{a_3 \cdot K_m}{(R^2_f + R^2_c)^{1/2}} \left(\frac{P}{H}\right)^n \left(\frac{R_f}{\lambda_f}\right)$$

where, $n=1$ for $(P/H) > 0.01$

$n=0.5$ for $(P/H) < 0.001$, and

$(P/H)^n = 0.01$ for $0.001 \leq (P/H) \leq 0.01$

$(R_f/\lambda_f) = \exp(0.5825 \ln R_f - 5.738)$

= a dimensionless ratio of fuel surface roughness and wavelength

$$K_m = \frac{2K_f \cdot K_c}{K_f + R_c}$$

$$R = \left[\frac{R^2_f + R_c^2}{2}\right]^{1/2}$$

P = interfacial pressure

H = Meyer hardness

K_f, K_c = thermal conductivity of fuel and cladding

R_f, R_c = arithmetic mean roughness of fuel and cladding

a_0, a_1, a_2, a_3 = constant

The cracked pellet model can not describe the effects of solid thermal conductivity and surface roughness adequately, thus it is abandoned here. And by using the Ross-Stoute model, Campbell model, and Beyer-Hann model, fuel temperature is calculated for WR1-HWR condition and compared with the experimental results of WR1-HWR[12]. WR1-HWR conditions are described in reference 12. Figure 2 and Table 1 show the results predicted by the FRAPCON-1 using several heat transfer models. The COMETHE-III-J and LIFE-THERMAL 1 code predictions are also included. From the comparison of the calculated results with experimental value, the Beyer-Hann model predictions are most close to the experimental results,

Table 1. Fuel Center Temperature Predicted by FRAPCON-1

	Ross-Stoute	Beyer-Hann	Campbell	Experiment (°F)
1	3,871	3,893	3,828	4,180
2	3,853	3,893	3,800	4,340
3	4,226	4,275	4,234	
4	4,105	4,160	4,051	4,340
5	4,293	4,350	4,235	
6	4,097	4,170	4,037	
7	4,256	4,353	4,222	
8	2,111	1,957	1,954	
9	3,658	3,709	3,587	
10	4,123	4,185	4,045	4,380
11	4,365	4,448	4,373	
12	4,173	4,252	4,144	

hence, the Beyer-Hann model may be selected as a best describing model for CANDU condition.

2.3. Neutron Flux Depression in Fuel

The neutron inverse diffusion length required to calculate the volumetric heat generation is calculated using the following formula.

$$Q(r) = N(Z + YY\, r^2 + W\, r^4)$$

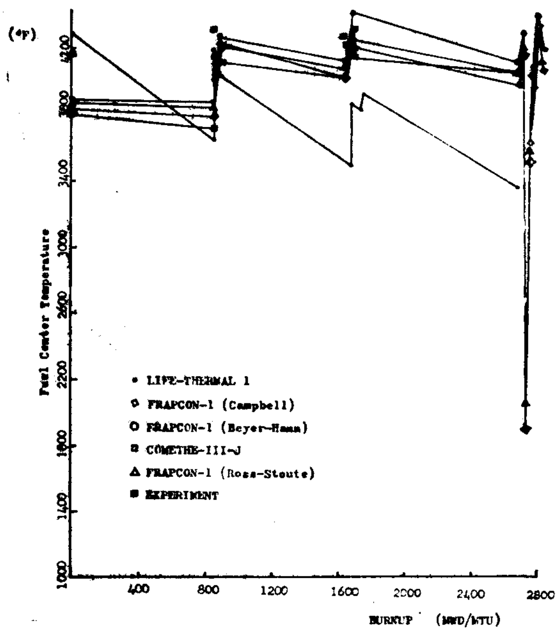

Fig 2. WRI-HWR Experiment Fuel Center Temperature

where, $Q(r)$ = volumetric heat generation

N = a normalization constant

Z = 1

$YY = \left(\frac{\kappa}{4}\right) \cdot 10^4$

$W = (YY)^2/4$

κ = neutron inverse diffusion length (cm^{-1})

$$= \left\{ 3\Sigma_a \Sigma_t \left[1 - \frac{4}{5} \frac{\Sigma_a}{\Sigma_t} \right] \right\}^{1/2} \left[1 + 0.6 \frac{(T-70)}{394} \right]$$

$\Sigma_a = N_{238}\ \sigma_a^{238} + N_{235}\ \sigma_a^{235} + N_0 \sigma_a^0$

$\Sigma_t = N_{238} \sigma_t^{238} + N_{235} \sigma_t^{235} + N_0 \sigma_t^0$

N_{238}, N_{235}, N_0 = number density of U_{238}, U_{235} and oxygen

σ_a, σ_t = microscopic cross section at reference temperature 40°C(absorption & total)

T = coolant inlet temperature(°F)

Table 2. Example of Neutron Inverse Diffusion Length Value Used in FRAPCON-1-CSK

MWD/MTU	FRAPCON-1 0.71 W/O	Hammer Results Used for Modification 0.71 W/O	2.0 W/O	3.0 W/O
	(cm^{-1})			
0	0.7698	0.84282	1.2394	1.4588
1000		0.924	1.2204	1.424
2000		0.972	1.2060	1.406
3000		1.008	1.1958	1.391
4000		1.037	1.1860	1.370
5000		1.062	1.1621	1.344
6000		1.085	1.1480	1.325
7000		1.106	1.1353	1.305
8000		1.135	1.1099	1.279
9000		1.163	1.0910	1.248
10000		1.189	1.0794	1.227
11000		1.214	1.0676	1.204
12000		1.236	1.0505	1.175
13000		1.256	1.0411	1.149
14000		1.275	1.0365	1.126
15000		1.292	1.0322	1.103
16000		1.306	1.0253	1.073
17000		1.320	1.0274	1.052
18000		1.330	1.0362	1.034
19000		1.340	1.0418	1.011
20000		1.347	1.0488	0.987

In present FARPCON-1, once the value of neutron inverse diffusion length is calculated as a function of coolant inlet temperature, it is set as a constant throughout the whole power steps. Calculations showed for low-enrichment CANDU fuel, that plutonium buildup at the fuel surface led to a significant drop in fuel center temperature as burnup proceeds[1]. Therefore, it is required for CANDU fuel to calculate the neutron inverse diffusion length according to the fuel burnup[1]. The calculated results of neutron inverse diffusion length from the neutron physics code, HAMMER[17], are used as a data Table. An interpolation routine then selects the appropriate set of data at each burnup interval for the particular element and initial enrichment under consideration. Here the Lagrange interpolation is adopted[31]. The examples of data Table for some enrichment are listed in Table 2. The predicted results of fuel center temperature for Wolsung-1 reactor with the

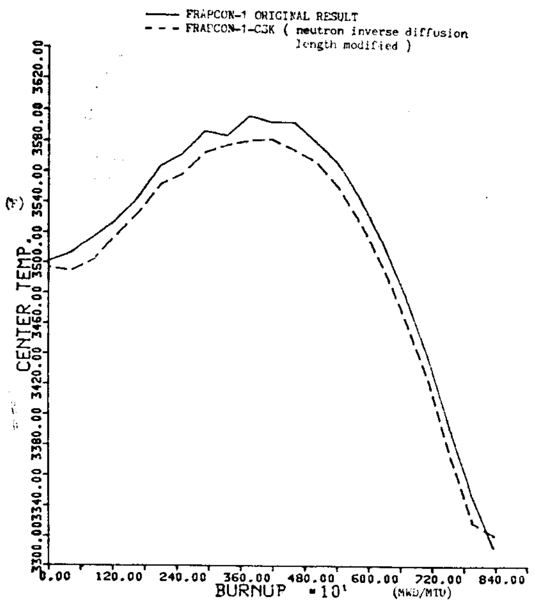

Fig. 3. Frapcon-1 Fuel Center Temperature Results

neutron inverse diffusion length correction are lower than the results from the original FRAPCON-1 model about 20°F as shown in Figure 3.

2.4. Fission Gas Release

The FRAPCON-1 code contains two fission gas release model, the Macdonald-Weisman model[18], and the Booth-Diffusion model[19]. It is necessary to verify the validity of these models for CANDU fuel.

1) The Macdonald-Weisman Model

The Macdonald-Weisman model takes into account the amount of fission gas release to be determined by escape of gas from the fuel matrix and release of trapped gas from grain boundaries and dislocations. At constant power the total fractional release is,

$$F=1-(1-K^1)\frac{1-e^{-K^1Kt}}{K^1Kt}$$

where, K^1 = the proportion of fission gas that escapes without being trapped

K = the probability of trapped particle release per unit time

(K and K^1 are calculated from empirical correlation as functions of fuel temperature and density.)

At variable power histories reactor operation is described by a series of constant power steps. The number of moles released, Δni, during the ith interval is then,

$$\Delta n_i=n_i-n_{i-1}=P_i\left\{\Delta t_i-\frac{1-K_i^1}{K_iK_i^1}[1-\exp(-K_iK_i^1\Delta t_i)]\right\}+C_{i-1}[1-e^{-K_iK_i^1\Delta t_i}]$$

The fraction of total gas released is

$$F=\frac{\sum_{i=1}^{m}\Delta n_i}{\sum_{i=1}^{m}p_i\ \Delta t_i}$$

where, P_i = gas production rate during i_{th} interval

Δt_i = time duration during i_{th} interval

2) The Booth-Diffusion Model

The fractional release for a constant power and temperature may be calculated by the Booth model[19]. The fractional release at the end of constant power and temperature operation is,

$$F=4\sqrt{\frac{\tau}{\pi}}-\frac{3}{2}\tau \qquad \text{for } \pi^2\tau\leq 1$$

$$F=1-\frac{0.43}{\pi_2\tau}-\frac{6}{\pi^2\tau}\{e^{-1}-e^{-\pi^2\tau}\} \quad \text{for } \pi^2\tau>1$$

where,

$$\tau=D\cdot t$$

$$D=\begin{cases} 0.95\times10^{-9}\ \exp\left\{\left(\frac{3\times10^4}{1.986}\right)\left[\frac{1}{1673}-\frac{1}{973}\right]\right\} \text{ for } T<1292°F \\ 0.95\times10^{-9}\ \exp\left\{\left(\frac{3\times10^4}{1.986}\right)\left[\frac{1}{1673}-\frac{1.8}{T+459.4}\right]\right\} \text{ for } T>1292°F \end{cases}$$

T = fuel temperature (°F)

t = time (sec)

By using these models, calculations are performed for fission gas release. At present, adequate fission gas release experimental results are unavailable, but calculational model predictions[12] for CANDU reactor condition using several LWR fuel performance codes are available as listed in Table 4, and experimental results from PWR and the predicted results using these codes for PWR conditions[12] are also available as listed in Table 3. Thus the FRAPCON-1 model is compared firstly with experimental result for fission gas release and the code predictions for PWR condition and

Table 3. Comparison with PWR Experiment and other Computer Code Predictions for Fission Gas Release[12]

Experiment[12]	13.4 (%)
FRAPCON-1 (Macdonald-Weisman)	8.5 (%)
FRAPCON-1 (Booth)	0.5 (%)
BEHAVE-4	14.4 (%)
COMETHE-III-J	22.4 (%)
LIFE-THERMAL 1	5.9 (%)
GAPCON-THERMAL 2	49.5 (%)

Table 4. Comarison with other Computer Code Predictions for WRI-HWR Fission Gas Release[12]

FRAPCON-1 (Macdonald-Weisman)	24.9(%)
BEHAVE-4	30.1(%)
COMETHE-III-J	21.9(%)
LIFE-THERMAL 1	16.0(%)
GAPCON-THERMAL 2	40.8(%)

secondly with the computer code predictions for CANDU reactor condition.

As represented in Table 3, the Macdonald-Weisman result does not accurately correspond to the experimental value, but appears better than the LIFE-THERMAL 1 and the COMETHE-III-J result. And it can be said that the predicted value by Macdonald-Weisman model is among the interval of BEHAVE-4, COMETHE-III-J, and LIFE-THERMAL predictions. The Booth model is considered to be inadequate.

From the results in Table 4 we can see that the predicted value by the Macdonald-Weisman model is among the interval of BEHAVE-4, COMETHE-III-J, and LIFE-THERMAL 1 predictions. Especially, the Macdonald-weisman model piedictions for PWR case and WR1-HWR case are always set between the predicted results of BEHAVE-4 and LIFE-THERMAL 1. Correspondingly the PWR experimental result is located between the LIFE-THERMAL 1 prediction and the BEHAVE-4 prediction. Thus we may presume that the WR1-HWR fission gas release experimental result would be located between the BEHAVE-4 prediction and the LIFE-THERMAL 1 prediction. Therefore we may say that the Macdonald-Weisman model in FRAPCON-1 code may predict the fission gas release in CANDU fuel adequately.

3. Parametric Study on Fuel Design Parameters

Parametric study is carried out for nuclear fuel design parameters such as, fuel density, fuel diametral gap, clad thickness, pellet diameter, pellet dish, dish land width, fuel grain size, axial gap length, and pellet length. Each design parameter has its own specified design value range[9]. In Table 5 the fuel design parameter ranges are listed. Thus, calculations are performed for the parameter's maximum and minimum value except fuel density. When one parameter is considered, other parameters are taken to be the nominal design value[20,28].

1) Fuel Density

Fuel density of CANDU reactor is ranged from 10.55 to 10.75gm/cm³. Calculations are carried out by dividing the range into 10.55, 10.60, 10.65, 10.70. and 10.75. Calculated results for various fuel design parameters according to density change are illustrated in Figure 4, 5, and 6. Fuel center temperature decreases with the density increase because thermal conductivity is increased due to densification[25]. In high density fuel, fuel expansion is smaller at initial low burnup because of lower fuel temperature than the expansion of low density fuel, but is larger as burnup proceeds because swelling effect is gradually dominant in high density fuel. Fractional fission gas release dec-

Table 5. Fuel Design Parameters Range

PARAETERS	DESIGN VALUE RANGE
PELLET DIAMETER	0.4785±0.0004 (in)
CLAD INNER DIAMETER	0.4820±0.0015 (in)
CLAD DIAMETRAL THICKNESS	0.0165±0.0015 (in)
CLAD OUTER DIAMETER	0.5150±0.0015 (in)
DIAMETRAL CLEARANCE	0.0015 to 0.006 (in)
AXIAL GAP	0.095 ±0.055 (in)
L/D RATIO	1.32 ±0.04
DISH DEPTH	0.0100±0.003 (in)
DISH LAND WIDTH	0.01 +0.015 −0.000 (in)
FUEL DENSITY ( ): nominal design	10.55 to 10.75(10.6) (gm/cm³)
FUEL GRAIN SIZE	5 to 15 (μ)

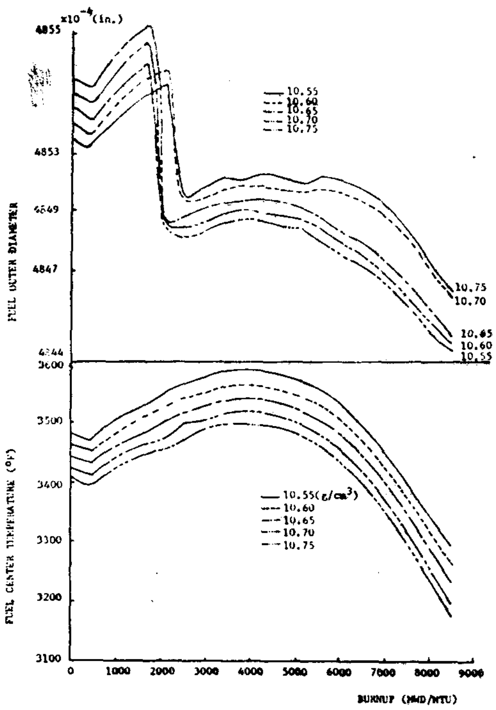

Fig. 4. Fuel Center Temperature & Fuel Outer Diameter Distribution according to Fuel Density Change

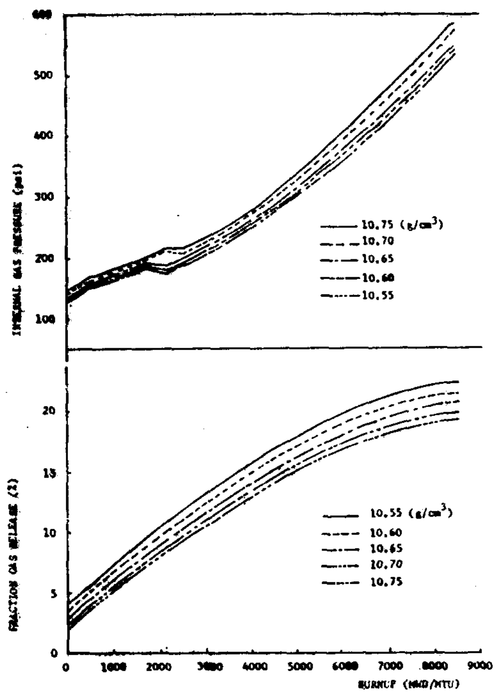

Fig. 5. Fractional Gas Release & Internal Gas Pressure Distribution according to Fuel Density Change

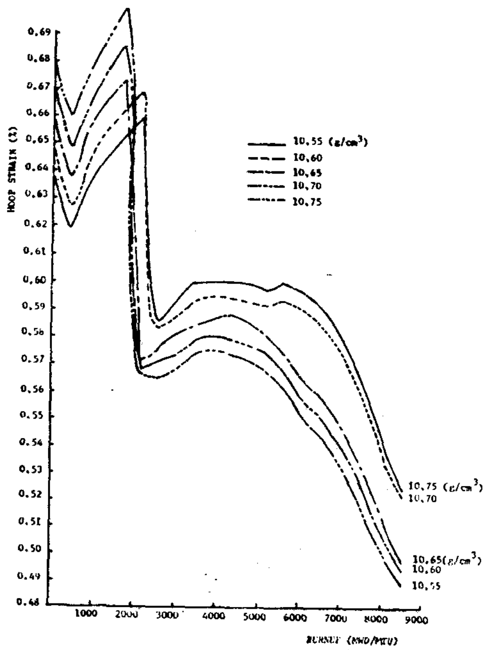

Fig. 6. Clad Hoop Strain Distribution according to Fuel Density Change

reases as density increases because the fuel temperature is lowered as density increases.[30] In high density fuel, although the fractional gas release is lower, the internal gas pressure is higher because the internal void volume is small and cladding stress and strain are smaller at initial low burnup than in low density fuel. But as burnup preceeds the cladding stress and strain (both hoop and axial) increase more rapidly and larger than those of low density fuel. The fuel performance is worse in high density fuel at high burnup as burnup reaches end of life, but the performance of low density fuel element is worse at initial low burnup. The current design-nominal value of fuel density 10.6gm/cm^3, is turned out to be adequate.

2) Fuel Diametral Gap

By using the maximum, nominal, and minimum diametral gap, performance calculation is carried out. The fuel center temperature and

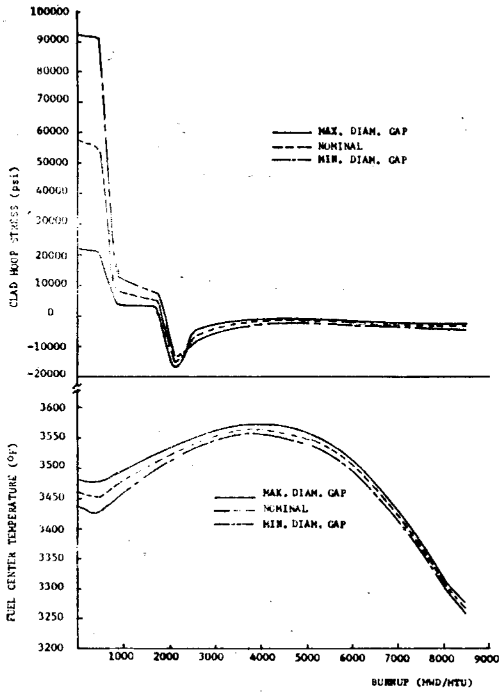

Fig. 7. Fuel Center Temperature & Clad Hoop Stress Distribution according to Diametral Gap Change

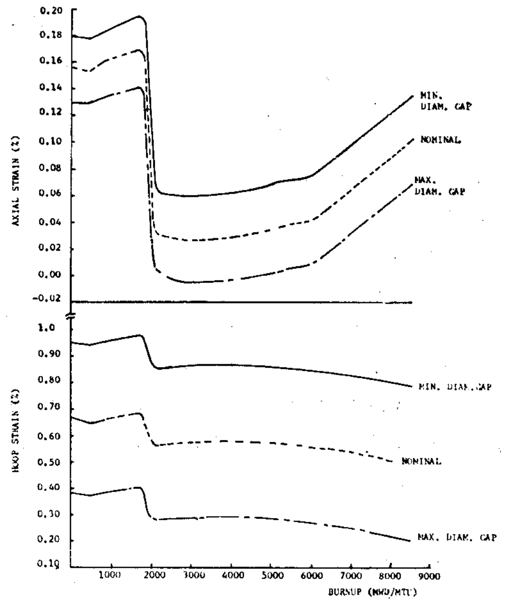

Fig. 8. Clad Hoop Strain & Axial Strain Distribution according to Diametral Gap Change

clad hoop stress distribution are shown in Figure 7. The clad hoop and axial strain distribution are illustrated in Figure 8. In fuel with maximum diametral gap the fuel center temperature becomes higher due to smaller fuel-to-clad heat transfer coefficient. And due to higher fuel temperature the fractional gas release, internal gas pressure, and fuel expansion becomes larger than those of minimum diametral gap. But the more important problem in fuel peformance, clad stress and strain (both hoop and axial axial), are much higher in fuel with minimum diametral gap due to severe pellet-clad interaction, and hoop strain approaches the design limit of 1%. But the clad stress and strain of the element with minimum diametral gap are much lower than those of maximum diametral gap element. And calculation shows that the performance of the element with maximum diametral gap is best among all other parameter variations. Thus, it can be concluded that the fuel diametral gap is the most important parameteramong the fuel design parameter determining the CANDU fuel performance, and it is recommend to increase the cold diametral gap of the fuel element within the bound of design value to improve the fuel performance.

3) Clad Thickness

Results for minimum and maximum design clad thickness show only slight difference. Fuel center temperature, fractional fission gas release, internal gas pressure, fuel outer diameter, clad hoop and axial stress, clad hoop and axial total strain are slightly higher or larger in fuel with maximum clad thickness. Only axial and hoop plastic strain are higher in minimum clad thickness fuel.

4) Pellet Diameter

Fuel pellet diameter should be considered more seriously in neutronics and fuel cycle aspects[26]. But it is also concerned with L/D (length-to-diameter) ratio of fuel pellet and has effect on the fuel performance[22),23)]. Results show that smaller diameter has slightly worse performance. But it is supposed that the circumferential ridge formation which is related to L/D ratio can not be described by FRAPCON -1.

5) Pellet Dish Depth

From the results for minimum and maximum pellet dish depth, it is known that the internal gas pressure is higher and fuel center temperature, clad axial stress, clad axial strain, and clad hoop strains are slightly higher in fuel with minimum dish depth. But it is also supposed that the circumferential ridge effect related to dish depth can not be described by FRAPCON-1.

6) Pellet Land Width

The results show that the clad axial stress and strain are much higher in fuel with maximum land width, and internal gas pressure, clad hoop strain are also higher than in minimum land width fuel. But the circumferential ridge effect is not described either.

7) Fuel Grain Size

Calculations are carried out for fuels with minimum and maximum grain size, but the predicted results have no difference. It can be concluded that FRAPCON-1 code can not describe the effect of grain size change.

8) Axial Gap Length

The axial stress and strain are higher in minimum axial gap and the internal gas pressure is also higher than that of the maximum axial gap. The results show that general performance are slightly better in maximum axial gap. But the end flux peaking effect due to the presences of axial gap and end plugs can be increased in large axial gap. This peaking effect can not be described by FRAPCON-1.

9) Pellet Length

Pellet length considerations in fuel performance is principally related to circumferential ridge formation [13,22)] which can not be adequately described by FRAPCON-1. Calculational results from FRAPCON-1 show that the performance of fuel having shorter pellets is better than that of longer pellets. The clad strain is slightly higher in fuel with longer pellets.

From parametric sensitivity study it is manifested that the initial cold diametral gap size is the most important parameter among the design parameters considered. And it is recommended to increase the cold diametral gap within design value range. The most unfavourable combination of parameters is selected as the case for minimum fuel density, minimum diametral gap, mimimum pellet diameter, minimum pellet dish depth, maximum pellet dish land width, maximum clad thickness, maximum pellet length, and minimum axial gap length. Performance calculation is carried out for this case with using the steady state upper bound power history at S-13 channel of the outermost ring fuel element. Predicted results indicate that the design criteria of LWR fuel is exceeded for the clad strain.

4. Performance Analysis for Wolsung-1 Fuel Element

By using the FRAPCON-1-CSK code the performance analysis for Wolsung-1 fuel elements is carried out. All fuel design parameters are taken to be the nominal design values specified in Safety Report. The power-burnup history is taken from the actual upper bound power history of a Gentilly-2 (in Canada) fuel element because the Wolsung-1 reactor is not operated yet. The Gentilly-2 reactor is also a 600MWe CANDU reactor and its upper bound power history is used at AECL for 600MWe reactor fuel element performance analysis.[9,21)] The channel coolant properties required are

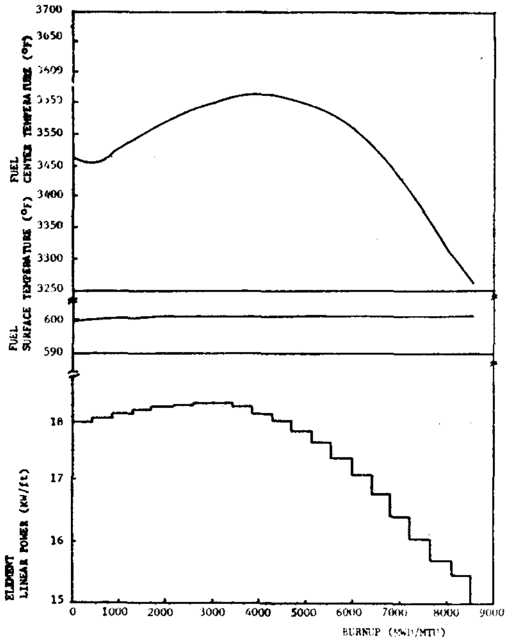

FIG.9 Linear Upper Bound Power History & Fuel Temperature Distribution for Wolsung-1 Nominal Design Fuel

Fig. 9. Linear Upper Bound Power History & Fuel Temperature Distribution for Wolsung-1 Nominal Design Fuel.

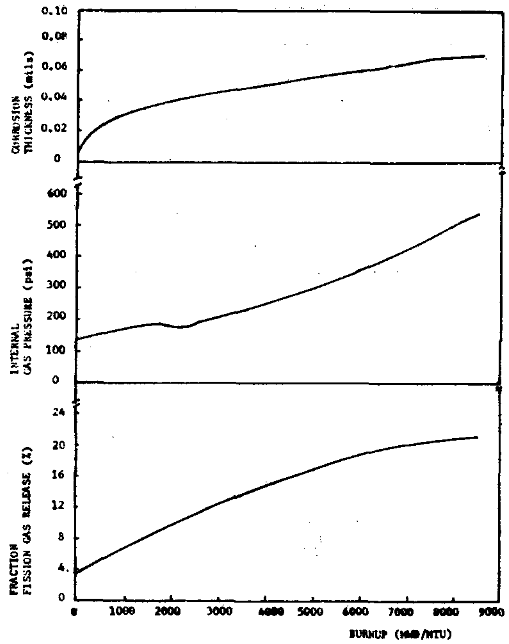

Fig. 10. Fractional Fission Gas Release, Rod Internal Gas Pressure & Corrosion Thickness for Wolsung-1 Nominal Design Fuel.

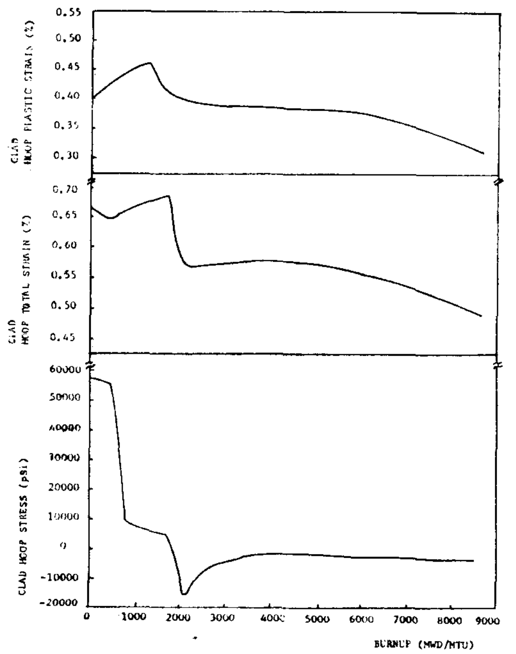

Fig. 11. Clad Hoop Stress, Clad Hoop Total Strain & Clad Hoop Plastic Strain for Wolsung-1 Nominal Design Fuel.

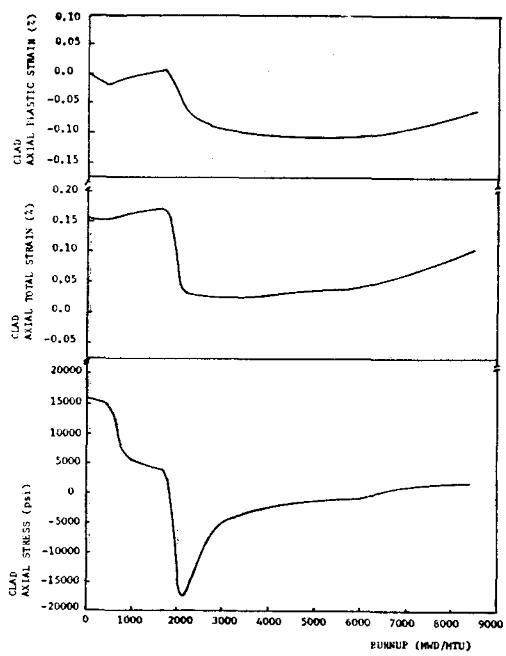

Fig. 12. Clad Axial Stress, Clad Axial Total Strain & Clad Axial Plastic Strain for Wolsung-1 Nominal Design Fuel.

taken from the subchannel properties of outermost ring element located in maximum power-generating bundle of S-13 channel. These subchannel properties are calculated from the COBRA-IV code (modified version for heavy water reactor)[9]. The calculation is performed dividing the element into 19 axial nodes, and peak power node outputs are reviewed. The predicted fuel surface temperature and fuel center temperature distribution of Wolsung-1 fuel are shown in Figure 9. The predicted fractional fission gas release, rod internal gas pressure, and corrosion thickness distribution are illustrated in Figure 10. The predicted clad hoop stress, clad hoop total strain, and clad plastic strain distribution are shown in Figure 11. The predicted clad axial stress, clad axial total strain, and clad axial plastic strain distribution are also drawn in Figure 12. The outputs are discussed in terms of LWR fuel design criteria.[7,8]

—The maximum fuel center temperature predicted by FRAPCON-1-CSK is 3564°F and is far below the melting point, 5080°F.

—The maximum clad surface temperature is 602°F and is far below the corrosion enhancing temperature, 770°F.

—The maximum clad hoop strain is 0.69% and is less than the design limit 1%.

—The maximum internal gas pressure is 545 psi and is less than external coolant pressure, 1435 psi.

—The maximum Zircaloy corrosion thickness is 0.07 mil and is far less than the design limit 10% thickness, 1.65 mil.

—The maximum hydrogen uptake in Zircaloy is 19ppm and is far less than the design limit 250ppm.

From the above results it can be said that the performance of Wolsung-1 fuel element designed by the Safety Report specification is very good in comparison with the LWR fuel design criteria. Besides, although the design criteria for CANDU fuel are not known at present, we may say that the actual design criteria of CANDU fuel have somewhat larger allowable limits than those of LWR fuel due to the fact that the CANDU fuel irradiation time is relatively short and fuel discharge burnup is low in comparison with those of PWR case.

5. Conclusions

From the analysis carried out in this study, several important viewpoints can be drawn.

1) The predicted results of fuel center temperature for Wolsung-1 reactor with the neutron flux depression correction are lower than the results from the original FRAPCON-1 model about 20°F.

2) The calculated outputs show 5°F difference in cladding surface temperature and maximum 10°F difference in fuel center temperature between the calculations using light water properties and heavy water properties.

3) The Beyer-Hann gap conductance model is the best-describing model for CANDU fuel performance among Ross-Stoute model, Campbell model, Cracked pellet model, and Beyer-Hann model.

4) The Macdonald-Weisman fission gas release model is valid for CANDU fuel performance.

5) The fuel diametral gap is the most important parameter among the fuel design parameters determining the CANDU fuel performance. It is recommended to increase the cold diametral gap of the fuel element within the bound of design value to improve the fuel performance.

6) The current design nominal value of fuel density is adequate for CANDU fuel performance.

7) The FRAPCON-1 code is not adequate for considering the effects of fuel grain size change

and circumferential ridge formation in CANDU fuel elements.

8) The fuel elements loaded in Wolsung-1 CANDU reactor satisfy all the design criteria for the steady state upper bound power history.

9) Further study about the design criteria of CANDU fuel is suggested to ensure the accurate judgement for the CANDU fuel performance.

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