Derivation of a Correlation Between Fuel Temperature and Power for CANFLEX Fuel Bundles

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Abstract

Using the ELESTRES fuel-modelling code and the WIMS-AECL lattice-physics code, a correlation between bundle-average fuel temperature and bundle power has been derived for CANFLEX natural-uranium fuel. WIMS-AECL calculations provided the relationship between bundle power and the power of the various pins in the bundle, and the ELESTRES code provided the pin volume-average fuel temperature versus pin linear power at various values of burnup. A uniform bundle-average temperature, which reproduced the lattice-cell reactivity for the CANFLEX bundle, was then determined at various values of bundle power and fuel burnup. This bundle-average fuel temperature was then correlated to bundle power, and the correlation was programmed into RFSP (Reactor Fuelling Simulation Program) for use in full-core, local-parameter calculations. Some comparisons were made of the core power distribution obtained with CANFLEX fuel with that obtained with 37-element fuel. In the time-average model, the maximum channel and bundle powers were very close (difference about 0.1%) to those calculated with 37-element fuel in core, and the maximum difference in any bundle and channel power was less than 0.2%. An 8-bundle-shift refuelling of channel N14 in a 37-element-fuel time-average core was simulated; the maximum bundle power was found to be only very slightly (about 0.1%) higher for the refuelling with CANFLEX fuel than when 37-element fuel was used.

I. Introduction

The CANFLEX® fuel bundle represents the next generation of fuel design for CANDU® reactors. CANFLEX fuel provides a reduction in peak linear element ratings, and a significant enhancement in thermalhydraulic performance.

In preparation for the demonstration irradiation of 24 CANFLEX fuel bundles in the Point Lepreau reactor, we have derived a correlation between the bundle-average fuel temperature and the bundle power for natural-uranium CANFLEX fuel. This correlation is designed to preserve reactivity. In this paper, the methodology for the derivation of the correlation is given. This correlation has been coded into the Reactor Fuelling Simulation Program (RFSP)[1], which is used to perform fuel-management calculations for CANDU reactors.

RFSP simulations with the local-parameter methodology require a correlation between fuel temperature and bundle power. This methodology is more realistic and gives lower peak powers[2,3] than the uniform-parameter method; the latter method makes the approximation that certain lattice parameters, such as the fuel temperature, are spatially constant over the core. A correlation between fuel temperature and bundle power is coded in existing versions of RFSP, but is appropriate to 37-element fuel. An analogous correlation for CANFLEX fuel is the subject of the present paper.

The basic data of pin-average fuel temperature versus element linear power was obtained with the ELESTRES[4] code, as described below. Based on these data, a correlation between bundle-average fuel temperature and bundle power was established in the form of a second-order polynomial, for various values of fuel burnup. The analysis was performed by means of the computer code WIMS-AECL[5], version wims-aecl.2-4x, and the ENDF/B-V-based library (HP 9000 1994 November 5).

Section II describes the ELESTRES calculations. Section III describes the derivation of the correlation. The effect on flux-power distributions is discussed in Section IV. The conclusions and recommendations are summarized in Section V.

II. ELESTRES Calculations

The computer code used for determining the initial fuel conditions is the ELESTRES code[4]. ELESTRES was developed by combining two programs: ELESIM (a one-dimensional fuel performance code) and SAFE (a two-dimensional axisymmetric stress-analysis finite-element code). ELESTRES is a fuel-performance code that calculates the behaviour of a CANDU fuel element for a given power history under normal operating conditions. It contains one-dimensional models of heat generation, temperature distribution, fission-gas release, and pellet-to-sheath heat transfer.

The ELESTRES input parameters for the CANFLEX bundles such as geometry, fuel density, filling gas volume, material properties, the presence of CANLUB coating, and so on, are the CANFLEX design values. To ensure consistency with previous calculations for 37-element fuel, the same code version of ELESTRES, as well as the same input parameters (where applicable) and correlations were used. For example, the thermal conductivity correlation used for both 37-element and CANFLEX fuel was the CRL-SIMFUEL correlation[6].

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Element linear powers were varied in a range from 5 kW/m to 70 kW/m, and the element burnup was varied from 0 MW.h/kg(U) to 300 MW.h/kg(U) for each value of linear power. The element linear power range and the element burnup range more than cover the possible spectrum of expected operating conditions for natural-uranium CANFLEX fuel.

The CANFLEX fuel bundle design has elements of 2 different diameters. The outer 2 rings of elements are of a smaller diameter than the inner 2 rings of elements. Therefore, it was necessary to calculate the volume-average temperatures of both types of elements as a function of element linear power and burnup. The results of these calculations are presented in Tables 1(a) and (b).

III. Derivation of the Correlation

A. Methodology

A CANFLEX fuel bundle contains 43 fuel elements, arrayed in 4 rings. The linear power $\boldsymbol{P}_i$ for an element in ring i can be calculated from

$$\boldsymbol{P}_i = (P_b/M) * M_i * r_i / L_i \qquad i = 1, 2, 3 \text{ or } 4$$

where

P_b is the total power of the bundle,
M is the total mass of fuel in the bundle,
M_i is the mass of fuel in element of ring i,
r_i is the relative power per unit mass in element i obtained from the WIMS-AECL lattice calculation (average over bundle =1), and
L_i is the fuel stack length in element i.

The burnup $\boldsymbol{B}_i$ of fuel in each ring i (i = 1, 2, 3, 4) is obtained from the WIMS-AECL lattice calculation.

If we select a bundle power P_b , then, based on $\boldsymbol{P}_i$ and $\boldsymbol{B}_i$, the fuel temperature for each ring can be interpolated from the ELESTRES results in Table 1.

B. WIMS-AECL Calculation Procedure

We define the bundle-average fuel temperature as the single fuel temperature, used for all rings in the WIMS-AECL simulation, which reproduces the k_∞ as calculated with a different temperature in each ring.

1. For a given bundle power, an initial WIMS-AECL calculation is performed with a single value of fuel temperature for all elements, to find the relative values of power per unit mass (r_i) and element burnup ($\boldsymbol{B}_i$) for the 4 rings of the fuel bundle (i = 1, 2, 3, 4).
2. Using the element power $\boldsymbol{P}_i$ and the equation above, and $\boldsymbol{B}_i$ from WIMS-AECL, the fuel-element temperature in each ring of the bundle is determined from Table 1.
3. A detailed WIMS-AECL calculation is performed with each element at its corresponding temperature, and the value of the infinite-multiplication constant k_∞ is noted.
4. Another WIMS-AECL calculation is performed with a guess for the effective common fuel temperature for all elements, and k_∞ is recalculated. If this k_∞ value is different from that found in step 3, the calculation is

repeated using a different guess for the effective fuel temperature, and this process is repeated until the k_∞ obtained in step 3 is reproduced.

5. If the 4 values of the relative power per unit mass (r_i) obtained at step 4 are not the same as those from step 1, then steps 2 to 4 are repeated until the values of the r_i and k_∞ converge.

The temperature T found in step 5, which reproduces the k_∞ value of the calculation with 4 fuel-element temperatures, is then taken as the effective bundle-average fuel temperature.

C. Polynomial Correlation

There is much less burnup dependence of the correlation of fuel temperature to bundle power for CANFLEX fuel than for 37-element fuel below bundle powers of 900 kW. Therefore, using the calculational procedure described above and averaging over the burnup range, we determined a burnup independent bundle-average fuel temperature as a function of bundle power. This relationship was fitted to a second-order polynomial:

$$T = a+b*P+c*P^2$$

where T is the fuel temperature (in units of ^oC), and P is the bundle power (in units of kW). The values of the coefficients were found to be

a = 0.308276 E+03
b = 0.241530 E+00
c = 0.343775 E-03

The polynomial correlation above for CANFLEX fuel is compared with the polynomial for 37-element fuel in Figure 1. This comparison shows that the bundle-average fuel temperature for CANFLEX fuel is significantly lower than that for 37-element fuel, the difference increasing from zero at low power to ~150 ^oC at 900 kW.

IV. Effect on Power Distribution

The above correlation has been implemented in RFSP version 2-16. The effect on the channel- and bundle-power distributions of introducing CANFLEX fuel in core, with this correlation for the fuel temperature, has been investigated. Some examples are given below.

A. Time-Average Calculation

A time-average calculation was performed for a core entirely fuelled with CANFLEX fuel. Table 2 shows the results and the comparison with results obtained with 37-element fuel. Table 2 shows that the maximum channel and bundle powers in the two calculations are very close (difference about 0.1%). Moreover, all the bundle and channel powers in the core are in close agreement, the maximum difference being less than 0.2%.

B. Refuelling Calculation

An 8-bundle-shift refuelling of channel N14 was simulated, using the history-based local-parameter methodology and accounting for the fact that fresh fuel is fission-product free. The *refuelling simulation* assumed that the 8 new bundles inserted into channel N14 were CANFLEX bundles, and the remainder of the core was modelled as a time-average core containing 37-element fuel. Table 3 shows the results of the bundle-

power distribution in channel N14, compared with those obtained if the new fuel were 37-element bundles. The maximum bundle power in channel N14 is very slightly (about 0.1%) higher for the refuelling with CANFLEX fuel than it is with 37-element fuel.

V. Conclusions and Recommendations

From Figure 1, it is clear that the correlation for CANFLEX fuel yields a significantly lower fuel temperature than that for 37-element fuel. The differences range from zero at low power to ~150 ^{o}C at 900 kW.

Tables 2 and 3 indicate that, for the cases studied, the CANFLEX correlation makes no significant difference to the channel- and bundle-power distributions. The maximum channel power and maximum bundle power are very slightly higher with the CANFLEX correlation than with the 37-element-fuel correlation.

The new correlation is ready for use with all natural-uranium CANFLEX fuel introduced into a CANDU core.

References

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Table 1. Element Volume-Average Fuel Temperature for CANFLEX Fuel Bundles Under Constant Power Conditions, from ELESTRES Calculations

(a) Element in Inner 2 Rings of CANFLEX Bundle

Element Linear Power (kW/m)	Element Volume-Average Fuel Temperature (^{o}C) at Burnup Shown in First Row (MW.h/kg(U))						
	0	50	100	150	200	250	300
5.0	339	337	336	335	335	334	334
10.0	388	385	383	382	380	379	378
20.0	489	483	479	476	474	472	470
30.0	603	592	585	580	576	573	570
40.0	731	714	703	696	690	686	683
50.0	876	858	876	892	909	907	921
60.0	1036	1036	1097	1159	1225	1231	1235
70.0	1205	1247	1405	1433	1441	1445	1447

(b) Element in Outer 2 Rings of CANFLEX Bundle

Element Linear Power (kW/m)	Element Volume-Average Fuel Temperature (^{o}C) at Burnup Shown in First Row (MW.h/kg(U))						
	0	50	100	150	200	250	300
5.0	340	338	337	336	336	335	335
10.0	390	387	385	383	382	381	381
20.0	494	487	483	480	477	475	474
30.0	610	597	591	586	582	578	576
40.0	742	724	712	704	699	694	691
50.0	890	872	894	914	933	981	1031
60.0	1055	1060	1129	1264	1278	1285	1289
70.0	1228	1278	1469	1492	1502	1506	1509

Table 2. Results of Time-Average Calculations

	37-Element Fuel	CANFLEX Fuel
k_{eff}	1.003158	1.003022
Mass of uranium per bundle (kg)	19.08	18.68
Average Burnup (MW.h/kg(U))	180.43	179.49
Maximum Channel Power (MW)	6.610 (N06)	6.618 (N06)
Maximum Bundle Power (kW)	789.4 (O06/6)	790.4 (O06/6)
Reactivity Decay Rate (mk/FPD)+	-0.389	-0.401
Feed Rate (Bundles/FPD)	15.03	15.43
Average Dwell Time (FPD)	202.22	196.98
Maximum Channel Power Ratio	-	1.0011 (N05)
Maximum Bundle Power Ratio	-	1.0018

+ FPD = Full–Power Day

Table 3. Comparison of Bundle Powers in Channel N14 Following an 8-Bundle-Shift Xe-Free Refuelling

	Bundle Power (kW)											
	1	2	3	4	5	6	7	8	9	10	11	12
(A)	192	454	644	740	739	806	807	744	754	629	423	172
(B)	190	450	639	741	741	808	808	745	755	631	424	173

(A) : An 8–bundle shift 37–Element fuel refuelling in channel N14

(B) : An 8–bundle shift CANFLEX–fuel refuelling in channel N14

Note: The refuelling direction is from bundle 1 to 12; that is, after an 8-bundle shift, the bundles 1 to 8 will have fresh fuel, and the original bundles 1 to 4 will have been shifted to positions 9 to 12. The original bundles 5 to 12 are discharged.

Figure 1. Polynomial Fit of Fuel Temperature vs. Bundle Power for CANFLEX and 37-Element Fuel