AN UPDATE ON THE DESIGN VERIFICATION OF THE CANFLEX® FUEL BUNDLE

by

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ABSTRACT

This paper discusses a number of the design analyses and assessments that were performed. The design assessments are grouped into the following 3 categories:

1. thermal considerations,
2. structural integrity considerations, and
3. compatibility with other components.

The assessments such as bundle strength, sheath collapse, end flux peaking, circumferential ridging, bundle droop etc., show that the performance of the CANFLEX bundle will be similar to or better than the performance of the 37-element bundle.

INTRODUCTION

CANDU® fuel is designed to meet a set of design requirements that are specified in the Fuel Design Manual, and these requirements define the conditions that the fuel must meet in service. They include dimensions, properties, and operation requirements. The important ones for the continued satisfactory operation of the reactor are the requirements imposed on the fuel by the reactor systems. These expose the fuel to a variety of operating conditions that stress the fuel. It is possible to reproduce most of these conditions in out-reactor tests or in design analyses, and from these procedures to determine the fuel's acceptability for the intended duty.

Over the past few years, the CANFLEX program has focused on implementing CANFLEX fuel in CANDU 6 reactors. The use of CANFLEX fuel will enhance the thermalhydraulic operating margin of CANDU 6 reactors, compared with the use of the 37-element bundle. The increased sub-division of elements in the CANFLEX bundle reduces the peak linear element rating by about 20%, and the critical-heat-flux (CHF)-enhancing buttons provide substantial increase in critical channel power (CCP).

To ensure that the CANFLEX design will meet the in-reactor service requirements, a design verification plan (DVP) was established to document the prescribed methods of qualifying the CANFLEX design [1]. The CANFLEX qualification program consisted of ZED-2 reactor physics tests, a series of mechanical and thermalhydraulic out-reactor tests [2], and irradiation in the NRU reactor. A formal design review was conducted by the AECL's Office of the Chief Engineer, and the Atomic Energy Control Board (AECB) approval of DI at the Point Lepreau Generating Station (PLGS) was granted. In this conference, the manufacturing of the CANFLEX bundles, an update on the DI at PLGS, and full-scale water CHF tests are presented in References 3 to 6.

The verification of the CANFLEX design has relied primarily on out-reactor and in-reactor tests, which has been the practice in previous fuel design activities. Over the years, computer code capabilities have been improved so that design code analysis is becoming an alternative means for some design verification activities. Design code analysis is also useful in the sensitivity assessment of design parameters, and helps to establish the margin to failure in some cases. Since the last design review meeting for the 24 CANFLEX bundles demonstration irradiation (DI), additional analyses have been performed and they further confirmed that the CANFLEX bundle will perform similarly or better than the 37-element bundle. The results of these analyses are presented in this paper.

1. THERMAL CONSIDERATIONS

a. End Temperature Peaking

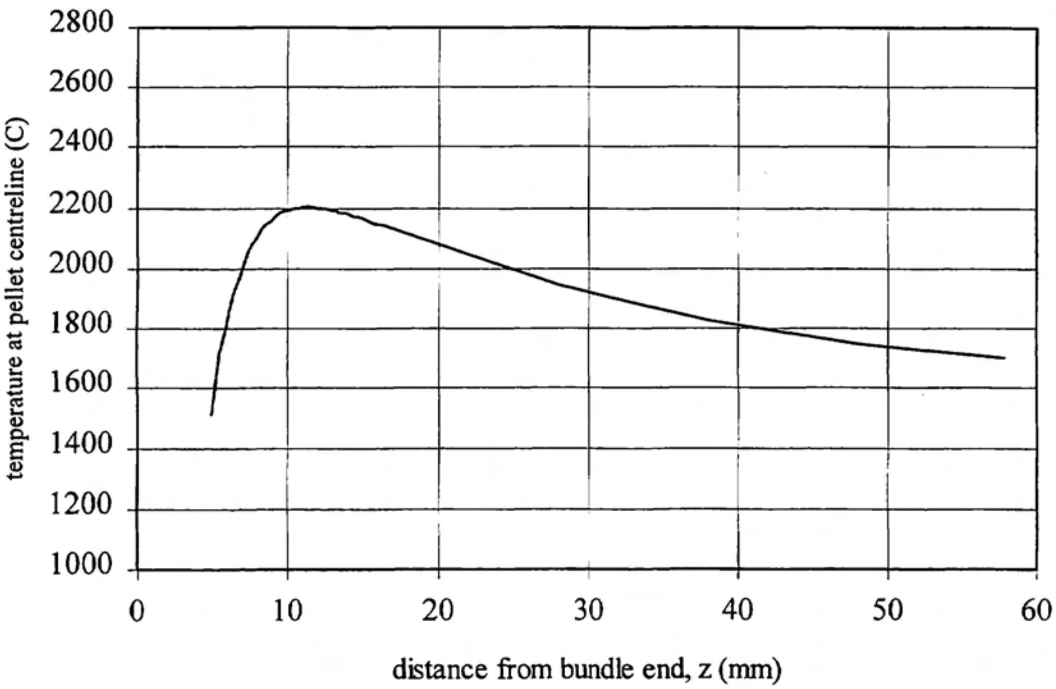
Because UO_2 material has a higher absorption rate of thermal neutrons than Zircaloy material and D_2O coolant, thermal neutron flux is higher near the bundle's ends than at the bundle's mid-plane which in turn can lead to end temperature peaking. This phenomenon is known as "thermal neutron flux peaking". The thermal effect of the additional neutron flux is balanced by additional heat transfer through end caps. This flux peaking occurs during normal operation (because of bundle-to-bundle contact) and during refuelling (because of bundle-to-coolant contact).

The absorption rate of thermal neutrons for D_2O coolant is lower than Zircaloy, therefore peaking factor is greater during refuelling than during normal operation. Peaking factors for these two situations are listed in Table 1. The peaking factor is a ratio of thermal neutron flux at end of the bundle to the thermal neutron flux at the mid-plane of the fuel bundle. The highest degree of end flux peaking occurs at the end of a fuel string during loading of new fuel when the new fuel bundle is pushed through the central regions of the core by the coolant drag. This repositioning of the bundle causes a relatively high thermal neutron flux at the bundle end of the outer elements. For this set of conditions during refuelling, the net effect on pellet temperature for an outer CANFLEX element was determined by using the FEAT (finite-element analysis for temperature) code.

The ELESTRES code was used to calculate the pellet-to-sheath heat-transfer coefficient. Sheath-to-coolant heat-transfer coefficient and coolant temperature were based on NUCIRC

Fuel Element Ring	Peaking Factor (Bundle-to-Bundle Contact)	Peaking Factor (Bundle-to-Coolant Contact)
Centre Ring	1.316	1.862
Inner Ring	1.245	1.787
Intermediate Ring	1.180	1.619
Outer Ring	1.132	1.462

Table 1: Flux Peaking during Normal Operation (Bundle-to-Bundle Contact) and during Refuelling (Bundle-to-Coolant Contact).



The following parameters were used for the FEAT code:

- Coolant temperature: 311°C. This is the highest coolant temperature (at downstream of the fuel bundle string) in channel O6 that has the highest power in the core. This value is obtained from the NUCIRC evaluation of channel flows during refuelling.
- Heat-transfer coefficient between sheath and coolant: 46.1kW/m^2 × °K (= 4.61 W/cm^2 × °K).
- Heat-transfer coefficient between pellet and sheath: 65.0 kW/m^2 × °K (= 6.5 W/cm^2 × °K). This value is obtained by running the ELESTRES code for the CANFLEX–NU outer element.
- Linear power of the outer element: 48 kW/m.

Figure 1: FEAT-Code-Predicted Temperatures at Centreline of CANFLEX–NU Outer Element

evaluation of channel flows during refuelling in a high-power channel in the PLGS. To determine the net thermal effect of end flux peaking, nominal heat rating of the fuel element, degree of end flux peaking and degree of two-dimensional heat flow near the pellet end have to be considered.

Figure 1 shows the predicted centreline temperature profile near the end of an outer fuel element. The centreline temperature increases from 1507°C at the end of the pellet stack, to a peak temperature of 2202°C at an axial distance of 11 mm from the bundle end. In comparison, the minimum melting point in CANFLEX natural-uranium (NU) pellet at 360 MW•h/kg U is 2757°C (this number accounts for the effects of measurement uncertainties and irradiation on the melting point). Thus a difference of 555°C. For this reason, the peak local temperature during end flux peaking in a CANFLEX outer element is acceptable.

b. Voids in Braze Joints of the Bearing Pads

Voids in the braze alloy between the bearing pad and the sheath increase the temperature in the sheath. Because it is difficult to transfer heat through the voids, the width of a braze void is therefore expected to affect the temperature in the sheath. This section summarizes the results obtained from 28- and 37-element bundles containing voids, modelled by using the FEAT code.

In past analysis different circumferential widths of void were used: 0% void, 25% void, 50% void and 75% void (the percentage is calculated from the ratio of the width of the void to the width of the bearing pad). The input parameters that were used for the analysis included dimensions of the sheath, dimensions of the bearing pad, dimensions of the void, heat flux at sheath inner surface, thermal conductivity of Zircaloy, coolant temperature, heat transfer coefficient at 3 convective boundaries, and heat transfer coefficient in the void.

The analysis concluded that the maximum temperature in the sheath occurs at the intersection of the axis of symmetry and the sheath's inner surface and that braze voids affect the temperatures in the sheath. The FEAT code predicted that circumferentially wider brazed voids cause the maximum sheath temperature to rise more than narrow voids do. A 75% wide void can cause about 57°C increase in the maximum sheath temperature; the maximum sheath temperature will increase rapidly when braze void size exceeds 25%. To minimize the effect of braze void on the maximum sheath temperature, the accumulated size of braze voids should be controlled below 25% of the width of the bearing pad.

For CANFLEX fuel elements, the heat flux is lower than the 28-element and the 37-element bundles, and therefore braze voids are expected to have similar effect on the temperatures in the sheath. The accumulated size of braze voids is controlled by AECL Technical Specification.

2. DIMENSIONAL STABILITY CONSIDERATIONS

a. Sheath Collapse Under Coolant Pressure

Fuel that has the sheath collapsed onto the pellets gives an increased heat-transfer coefficient between the pellet and the sheath, which leads to lower pellet temperatures. Calculations were performed to check whether the sheath will collapse onto the pellets under reactor operating conditions. The key parameters that affect the critical collapse pressure of fuel sheathing are sheath size and properties, sheath ovality, coolant pressure, internal gas pressure, and operating temperature.

The collapse pressure (P_c) of standard size fuel sheathing has traditionally been calculated using Bryan's equation [7]. However, it is valid for a long circular cylinder subjected to uniform external pressure in the radial direction only. The effects of axial load and ovality have not been considered. To account for axial loads, the critical collapse pressure (P_{cr}) of a thin-walled sheath with circular cross-section under both lateral and axial loads is given by Flugge [8]. The critical collapse pressure of a sheath with some ovality is expected to be lower than that for a sheath with a perfectly circular cross-section. To account for ovality, the critical collapse pressure can be determined from Timoshenko [9].

Incorporating the effect of axial pressure and ovality, the effective collapse pressure ($P_{C_{eff}}$) is given by

$$P_{C_{eff}} = P_{cr}\, k_\varepsilon$$

where,

k_ε	=	represents the effect of ovality and is obtained by the ratio of q_{cr}/q_{cro}
q_{cro}	=	critical collapse pressure for a sheath with zero ovality i.e., $\varepsilon = 0$
q_{cr}	=	critical collapse pressure for a sheath, as given by Timoshenko for an oval-shaped sheath, i.e., $\varepsilon > 0$.

A default ovality of 7.5 μm was used here based on measurements by Tayal.

The analysis concluded that

1. The traditional method of Bryan's equation calculates a smaller degree of collapse for the fuel sheath because it ignores the effects of axial load and ovality. The latter effects were considered here by using Flugge's and Timoshenko's equations.
2. The sheath will collapse onto the fuel stack, the same way as does the 37-element bundle.

b. Circumferential Ridge Strains

During on-power operation, UO_2 pellets in the fuel element generally become hourglass-shaped. Under the external coolant pressure, the fuel sheath collapses onto the fuel pellets, and its profile closely resembles that of the fuel-pellet stack. Stress relaxation, resulting from sheath creep and plasticity, leads to the formation of permanent circumferential ridges on the sheath at the pellet-to-pellet interfaces. Circumferential ridges have been observed and measured during post-irradiation examination of irradiated fuel elements.

In this assessment, a comparison of the calculated circumferential ridge strain between fuel elements used in the 37-element and CANFLEX bundles was conducted. The ELESTRES code version M13B.8, was used to calculate the on-power and end-of-life (EOL) ridge strain.

The power histories (high-power and nominal-power envelopes) for 37-element and CANFLEX were obtained from the 37-element and CANFLEX fuel design manuals for CANDU 6 reactors. Three power ramp excursions, lasting approximately 10% of the final burnup (300 MW•h/kg U), from the nominal-power envelope to high-power envelope at low, mid- and final-element burnups were studied.

The calculated EOL circumferential ridge height of the CANFLEX fuel elements is approximately 1.4 to 7 times lower than that of the fuel elements used in the 37-element bundle. The EOL plastic ridge strain of the CANFLEX fuel elements ranged from -0.62% to 0.14%. This value is less than the calculated plastic strains for the fuel element used in the 37-element bundle, which ranged from 0.44% to 1.03%. The change in total strain, caused by the power ramp, ranged from 0.13% to 0.23% for the CANFLEX fuel elements. This change is less than the change in total strain calculated for the fuel elements used in the 37-element bundle, which ranged from 0.22% to 0.3%.

c. Bundle Strength

In normal operation the fuel bundles are subjected to compressive axial loads that may cause axial compression and bowing of the fuel elements, and bending of the end plates. During refuelling, the last bundle in a fuel channel is supported by a set of 2 side stops, and the total axial loads on a fuel string are carried only by 8 fuel elements that are in contact with the 2 side stops. During this operation, the supported fuel elements are stressed the most among the fuel elements. Also, eccentric support and unsupported fuel elements, end-plate rings, and ribs cause additional bending of the end plates.

Version 5.3 of the ANSYS commercial computer program has been used to assess and compare the strength of a 43-element fuel bundle with a 37-element fuel bundle during a refuelling operation. Two end conditions were considered: shield-plug support and double side-stops support.

The maximum stress value in the 43-element fuel bundle is 45% and 93% of the maximum in the 37-element fuel bundle during shield-plug support and double side-stops support, respectively. ANSYS results, in general, show that the strength of the 43-element fuel bundle is as good as that of the 37-element fuel bundle.

At this conference, 2 papers describe the strength assessment of CANFLEX bundles [10,11].

d. Buckling Strength

The definition of column buckling refers to the condition when the axial load on a column is so great that the column loses its flexural rigidity. The column is then in a state of neutral equilibrium, and a small lateral load can cause large lateral deflections. Fuel bundles are tight assemblies. A fuel element cannot fully buckle because it is constrained. However, if the element diameter is small enough, then fuel elements can bend excessively under the in-reactor loads. If this happens, the bundle can jam against the pressure tube, and this jamming can cause difficulties in subsequent removal of the bundle. The key parameters that affect the fuel bundle's buckling strength are the size of sheath, the yield strength of the sheath, the size of end plate, and the amount of clearance between neighbouring fuel elements. Previous assessments for CANDU 6 fuel showed that the limiting case for buckling occurs during refuelling, when the fuel string rests on side stops. In the "base" configuration, 8 elements of the CANFLEX bundle are supported by the CANDU 6 side stops.

The buckling strength of the CANFLEX fuel bundle was assessed using the BOW code. Figure 2 shows the loads and restraints used in the calculation. It is expected that outer elements are supported by side stops bent inwards and that the element at the position diametrically opposite to the side stops is bent outwards.

The calculation using the BOW code showed that a CANFLEX outer element has a buckling strength of 2.81 kN at 312°C. This value includes the effects of the supports provided by the other fuel elements and by the end plates. Thus 8 elements supported on the double side stops provide a nominal buckling strength of 22.48 kN at 312°C for the CANFLEX bundle. This is a factor of 3 higher than the expected in-reactor load of 7.3 kN. Hence elements will not buckle, and the excessive bending of fuel elements that can lead to bundle sticking is not expected to occur during normal operation of CANFLEX fuel.

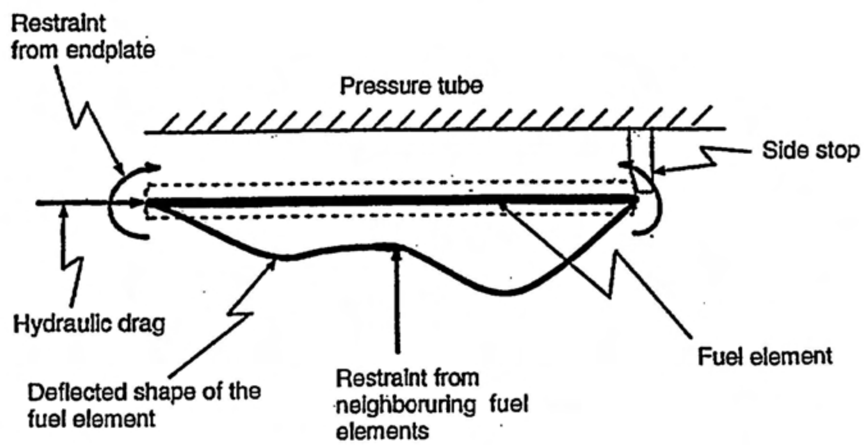


Figure 2: Loads, Restraints, and Boundary Conditions of a Fuel Element (This schematic is not drawn to scale. The amount of element deflection is exaggerated.)

3. COMPATIBILITY WITH OTHER COMPONENTS

a. Analysis of Fretting Wear

The inter-element spacer and pressure-tube fretting behaviour of CANFLEX fuel bundles are compared with the data from 37-element endurance tests having similar test conditions to those of the CANFLEX endurance test [2]. This comparison is used as an indicative measure of the potential fretting behaviour of CANFLEX fuel bundles throughout the length of a fuel channel.

This analysis shows that:

- Although the inter-element spacer wear of CANFLEX bundles is greater than that of the 37-element bundles, the maximum wear seen on any of the CANFLEX bundles is less than 25% of the acceptance criterion after 3000 h, leaving a significant margin for CANFLEX bundles.
- The CANFLEX bundles caused fewer pressure-tube fretting marks than the 37-element bundles. Although one of the fret marks with CANFLEX has a measurable depth, this wear is substantially less than 25% of the acceptance criterion.

b. Bundle Droop

The combined weight of all the elements not in contact with the pressure tube is transferred to the bottom elements, primarily through the end plates. This downward load, applied to the ends of the bottom elements extending past the end-bearing pads, is cantilevered over the bearing pads. The net result is that the bottom elements bow inward, away from the pressure tube at their mid-plane and towards the pressure tube at their ends. This response is known as bundle droop, and tends to dominate over element sag for elements near the bottom of the fuel channel [12].

CANFLEX bundle droop was measured as part of the CANFLEX fuel bundle and CANDU 6 fuelling machine compatibility tests [1,2]. In these tests, 4 CANFLEX fuel bundles were cycled between a test channel and a CANDU 6 fuelling machine at representative temperature, pressure, and flow conditions. The clearance below the ends of the bottom elements was measured both before and after the compatibility tests. The bundles were rotated and measured at each end of each bundle for 21 bundle rotations. The minimum measured clearance was 1.17 mm before and 1.11 mm after the compatibility tests, whereas the average of all measurements was 1.26 mm before and 1.22 mm after the tests. Although the clearance was reduced somewhat during the compatibility tests, bundle droop did not compromise the required minimum clearance of 1.00 mm. The compatibility tests were satisfactorily performed and showed no visible adverse effects to the fuelling machine or to the fuel bundles, particularly in the areas that interface with the fuelling machine separator-sidestops assembly.

CONCLUSIONS

The CANFLEX–NU fuel bundle design has been qualified for normal operation in a CANDU 6 reactor. This qualification has been achieved through a combination of the following: out-reactor and in-reactor prototype tests, analytical assessments, engineering judgment, operational experience gained from using similar fuel, and demonstration irradiation. Design assessments presented here provide further confidence that:

- The CANFLEX fuel bundle temperatures will stay within acceptable levels. Pellet temperatures are below melting - away from the end caps as well as near the end caps after allowing for end flux peaking during refuelling. Temperature increase in the sheath, due to braze voids, is acceptably low.

- The CANFLEX fuel bundle will maintain a stable geometry under normal operating conditions. When the sheath does collapse under coolant pressure, the strains in longitudinal ridges are acceptably low. The bundle has sufficient strength to withstand the expected in-reactor mechanical and hydraulic loads. The buckling strength exceeds the load expected during normal operation.
- The CANFLEX fuel bundle geometry will remain compatible with all interfacing components. Fretting wear is acceptably low. The on-power droop does not interfere with fuel removal.

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