BRINGING THE CANFLEX FUEL BUNDLE TO MARKET

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ABSTRACT

CANFLEX* is a 43-element CANDU** fuel bundle, under joint development by AECL and KAERI, to facilitate the use of various advanced fuel cycles in CANDU reactors through the provision of enhanced operating margins. The bundle uses two element diameters (13.5 and 11.5 mm) to reduce element ratings by 20%, and includes the use of critical-heat-flux (CHF) enhancing appendages to increase the minimum CHF ratio or dryout margin of the bundle. Test programs are underway to demonstrate: the irradiation behaviour, hydraulic characteristics and reactor physics properties of the bundle, along with a test program to demonstrate the ability of the bundle to be handled by CANDU-6 fuelling machines. A fuel design manual and safety analysis reports have been drafted, and both analyses, plus discussions with utilities are underway for a demonstration irradiation in a CANDU-6 reactor.

1. INTRODUCTION

A program to identify, optimize and develop a high-burnup CANDU bundle for use with advanced fuel cycles was first pursued by AECL in 1987, and the CANFLEX 43-element bundle was identified as the most appropriate candidate for that role.[1,2] Following the completion of a joint AECL/KAERI study in 1990, KAERI joined the CANFLEX program in 1991, and the program has operated as a joint AECL/KAERI effort since that time.

A number of papers have been presented during the past five years in Canada, Korea and elsewhere, identifying the technical advances made in this program, the most recent of which are cited in references (3,4). Papers on CANFLEX have also been presented at previous Canadian Nuclear Society Fuel Conferences.[5,6] The intent of this paper is thus to review the progress made on the CANFLEX development program since the last CNS Fuel Conference in 1992 October, and cover the following aspects of the program: design/analysis, fabrication development, hydraulic behaviour, CHF and CHF-enhancement testing, irradiation testing, reactor physics testing, and a range of mechanical tests to ensure satisfactory behaviour and compatibility with CANDU-6 fuelling machines. Also reviewed are recent studies to identify the benefits that the extra operating margins in the CANFLEX bundle can bring to counteract aging effects in operating CANDU reactors.

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* CANDU FLEXIBLE FUELLING, registered trademark.
** CANada Deutrium Uranium, registered trademark.

2. DESIGN

The major feature of the CANFLEX bundle is an increase in the number of fuel elements, from 37, 13.1 mm diameter elements in the standard CANDU-6 bundle, to 43 elements of two different diameters. The 11.5 mm diameter elements in the outer two rings of the CANFLEX bundle allow the peak element ratings in the bundle to be reduced by 20% in comparison to the standard 37-element bundle, as shown in Figure 1. The 13.5 mm diameter elements in the inner rings of the bundle compensate for the fuel volume lost due to the smaller-diameter outer elements. Another important feature is the use of CHF-enhancing features on all elements in the CANFLEX bundle. These will provide larger operating margins in existing CANDU reactors, thus permitting more flexibility in the use of fuel cycles with the CANDU-reactor on-power fuelling system.

The detailed design features of the bundle have continued to evolve as a result of ongoing design analysis, thermalhydraulics testing, and feedback from fabrication development work, which was undertaken at KAERI, AECL, and a Canadian commercial fuel fabricator. The result is the Mk.4 bundle design, which incorporates an optimized CHF-enhancing feature that is based both on extensive thermalhydraulics testing and fabrication development testing. The detailed CANFLEX Mk.4 design has now been consolidated onto a joint AECL/KAERI reference drawing.

The first draft of the CANFLEX fuel design manual and bundle technical specification has also been produced, as have a large number of supporting design analysis reports.

3. REACTOR PHYSICS

The uranium content in a CANFLEX bundle is similar to that in the standard 37-element bundle, and reactor physics effects in a reactor loaded with natural-uranium CANFLEX fuel will not differ significantly from those experienced in existing CANDU reactors. This has been confirmed by comparing WIMS-AECL[7] calculations of various reactivity coefficients for both bundle geometries as a function of burnup. However, because the CANFLEX bundle geometry is outside the range of the existing experimental database that is used to validate the physics codes, a program to validate AECL lattice codes for CANFLEX fuel is underway.

An important aspect of the validation program is a series of measurements in the ZED-2 critical facility. The test program to make the measurements started in August, and is expected to be completed in early November of this year. The test uses 35 natural-uranium CANFLEX bundles, plus one specially segmented CANFLEX bundle, fabricated to allow the efficient insertion and removal of activation foils from between the pellets of elements within each of its rings. The measurements made will include the buckling of the CANFLEX fuel lattice both with and without heavy-water coolant, as well as the effect on reactivity of heating the fuel and coolant to 300°C. In addition, many reaction rate ratios will be measured.

It is also possible to validate one calculational method against another that is believed to be more accurate. Monte Carlo methods can provide the most accurate estimates of some of the neutronic aspects of reactor design. The Monte Carlo code MCNP[8] has therefore been used to alculate the coolant void reactivity effect for infinite lattices of both CANFLEX and 37-element CANDU fuel, and the results have been compared with those predicted by WIMS-AECL.

Due to a limited number of temperature compilations of the data in the MCNP cross-section libraries, the calculations have been restricted to a uniform temperature of 300 K, and the data should be seen as a WIMS-AECL validation exercise rather than a direct calculation of the void effect in an operating CANDU. For further simplification, and to ensure an exact correspondence between the WIMS-AECL and MCNP calculations, only the infinite lattice with fresh fuel is considered.

For the 37-element fuel, both codes predict the same coolant void reactivity effect within the statistical accuracy of the MCNP calculation (±0.14 milli-k), although the value of k_{inf} predicted by MCNP is about 3.4 milli-k larger for both the cooled and voided lattices. For the CANFLEX fuel, the MCNP values of k_{inf} are again larger by similar amounts, but the predicted coolant void reactivity is also larger by 0.29±0.13 milli-k. Within the statistical accuracy of the MCNP calculation, the WIMS-AECL predicted 7% increase in the void reactivity of the CANFLEX, compared to the 37-element bundle, is confirmed.

4. CHF ENHANCEMENT

CHF-enhancement features have been incorporated into the CANFLEX bundle to provide greater operating flexibility. For example, the use of fuel cycles involving high concentrations of fissile material, can result in extensively distorted axial power profiles in some channels, and steep radial flux gradients in the bundles. These perturbations to the normal power profiles in bundles could result in a lowering of bundle (and channel) powers, if CHF-enhancement features were not available. These CHF-enhancement features become even more important when fuel cycles are introduced to older reactors, because some of the originally available operating margins may have been lost due to the effects of steam-generator fouling and pressure-tube creep.

The CHF-enhancement features incorporated into the CANFLEX bundle have been derived from a series of small-scale CHF tests using a variety of sizes, shapes and locations for CHF-enhancing devices. These were applied to the CANFLEX Mk.3 design bundle, and were further optimized in several bundle CHF tests using Freon-22 as the modelling fluid. This has resulted in the arrangement used in the CANFLEX Mk.4 design. It is estimated that the CHF-enhancing features in the Mk.4 CANFLEX bundle will result in an increase in critical channel power (CCP) of approximately 7%. A key component of the current CANFLEX program is to undertake prototype CHF tests on Mk.4 bundles intended to confirm this increase; this is discussed further in section 9.

5. IRRADIATION TESTING

Although the first irradiation testing of CANFLEX bundles started in late 1990, it was terminated by a loss-of-flow incident in the loop in which the test was being done. Further irradiation testing of CANFLEX bundles was not able to start until 1994 February, because of modifications to the NRU reactor and the U-1 and U-2 fuel-bundle test loops. The various CANFLEX bundles irradiated since the re-commencement of irradiation testing are listed in Table 1, along with their operating parameters and current status. The lead bundle (AJK) has achieved a burnup of 192 MWh/kgU.

A CANFLEX MK3 bundle (bundle AJJ) was in the first fuel string to be irradiated in NRU following the re-licensing of the NRU loops. This irradiation started in the U-1 loop, but due to a problem with the loop, the bundle had to be removed with a burnup of less than 200 MWh/kgU. It was subsequently added to a string in the U-2 loop, when that loop started operation in 1994 October. However, because of a defect in a non-CANFLEX bundle in that fuel string, bundle AJJ had to be removed once again, and did not get back into the loop until 1995 January, where it operated satisfactorily until 1995 March, when it was removed because of a defect signal. The bundle, which achieved a burnup of 290 MWh/kgU, is currently undergoing PIE to determine the cause of its defect.

All of the remaining CANFLEX bundles (with the exception of AHT and AHV) contain UO_2 fuel enriched to 2.25 wt% U-235, in order to be able to maintain high-power operation up to the target burnup of 500 MWh/kgU. However, this enrichment has resulted in higher bundle powers than anticipated, and has resulted in a limitation in the positions in which these bundles can be irradiated. The CANFLEX Mk.3 design contains representative (although not optimized) CHF-enhancement devices. This allows most aspects of this technology to be irradiation tested. The bundle was fabricated by a commercial fuel manufacturer (Zircatec Precision Industries), to allow the demonstration of standard manufacturing technology in the CANFLEX bundles.

Two CANFLEX Mk.4 bundles with an enrichment of 2.25 wt% have been fabricated recently at the KAERI fuel manufacturing facility, in preparation for irradiation testing in NRU. The bundles contain all of the design features currently planned for the CANFLEX bundle, and will serve to qualify the KAERI fabrication of CANFLEX bundles. One of these bundles will be incorporated into the irradiation test at the earliest opportunity.

6. FUEL HANDLING

The CANFLEX Mk.3 and 4 bundles have been designed to be interchangeable with the standard 37-element bundles currently used in CANDU-6 reactors. Also, to be acceptable in a specific operating CANDU reactor, the CANFLEX bundle must be shown to be compatible with the type of fuel-handling equipment used in that reactor. Hence it is a requirement that the CANFLEX Mk.4 bundle be capable of being handled by the existing CANDU-6 fuel-handling system without any modification or special procedures during normal on-power fuelling.

Fuelling in a CANDU-6 reactor means charging two new fuel bundles into the upstream end of a channel, and discharging two irradiated bundles out the other, downstream end of the channel, by means of a fuelling machine connected at each end of the channel. Because this operation is done at full reactor power, the bundles must conform perfectly with the mechanisms in the fuelling machines. Bundles within a fuelling machine are contained in a rotating magazine, each chamber of which can hold two fuel bundles. The entry of bundles into the magazine is controlled by two separator/sidestops, which engage with the ends of a few elements in the outer ring of the bundle. These separator/sidestops can transmit very high loads to the elements with which they engage, and so a very precise fit is required to avoid distortion and possible damage.

Tests have been done with both the CANFLEX and the existing 37-element CANDU-6 bundles, to study how the bundles interact with the sidestops under axial loads up to and beyond normal design load. An important part of the tests with CANFLEX bundles has been to measure the clearances between the bundle's endplate and the sidestops, to make sure that there are adequate clearances for normal handling. At the same time, the "engagement" of the sidestops with the end caps of the fuel elements has to be adequate to prevent damage to the fuel itself. These features are shown in Figure 2. To make these measurements and to refine the design of the bundle, we fabricated a special "sidestop fixture" in which a bundle could be positioned against sidestops, Figure 3. The relevant clearances and penetrations were then measured. This work showed the bundles to be compatible with the fuelling-machine mechanisms.

The final "acceptance" tests for fuelling-machine compatibility involve the use of an actual CANDU-6 fuelling machine in the test rig at AECL's Sheridan Park Laboratories. These tests have been scheduled to begin in 1995 mid-October, and coincide with the availability of a new CANDU-6 fuelling machine that will just have completed its acceptance tests at Sheridan Park. Four CANFLEX Mk.4 bundles have been fabricated at the KAERI fuel production facility for use in these tests.

7. FABRICATION

To date, fifteen CANFLEX fuel bundles have been fabricated in Canada. The first nine of these were early prototype bundles that utilized additional planes of bearing pads and spacer pads to increase CHF. As the bundle design evolved, a decision was made to use strategically placed appendages to enhance CHF. AECL staff worked with commercial fuel fabricators to develop the welding technology, plus the design and acceptance criteria for CHF-enhancement appendages. Six additional Mk.3 bundles have been fabricated with welded CHF-enhancement appendages, and one more is due to be completed shortly. These bundles contain 2.25% enriched UO_2 for irradiation testing in NRU.

KAERI has also fabricated a significant number of natural-uranium CANFLEX bundles in their large-scale fabrication facility for use in various in- and out-reactor tests. Over 40 CANFLEX bundles have been made in Korea to date, and of these, over 26 bundles have been fabricated to the latest Mk.4 or reference design. These bundles contain additional CHF-enhancement appendages in subchannels, where CHF is most likely to occur. There was initial concern that the additional CHF appendages may complicate the bundle assembly process, but this has been avoided with a specially designed assembly jig. Thirty-six CANFLEX bundles have recently been delivered to the ZED-2 reactor at Chalk River Laboratories (CRL) for reactor physics tests, and four Mk.4 bundles, with the most recent bearing pad height, have been fabricated for use in tests, to demonstrate the compatibility of CANFLEX bundles with the CANDU-6 fuelling machine. Two enriched CANFLEX Mk.4 bundles have also been fabricated by KAERI for irradiation testing in the NRU reactor.

8. FLOW TESTING

Four types of flow testing have been involved in the CANFLEX bundle development program: flow excitation tests, pressure drop (ΔP) tests, flow-based strength tests, and endurance (vibration and fretting) tests. Excitation tests were undertaken by AECL early in the CANFLEX program, to investigate the vibration excitation characteristics of the small-diameter outer elements in the CANFLEX bundle. This work showed that the small-diameter CANFLEX element had only a slightly lower natural frequency, and a slightly higher vibration amplitude, than a corresponding element for a 37-element bundle,(3) as had been anticipated. The other three components of the flow-testing program are being undertaken by KAERI.

Two major campaigns of pressure-drop measurements have been completed by KAERI, the most recent of which was on a string of twelve CANFLEX Mk.4 bundles, which showed an average pressure drop that was essentially identical to that of a string of standard 37-element bundles, as shown in Figure 4. It is important to note that these CANFLEX Mk.4 bundles do not have a higher pressure drop than standard 37-element bundles, even though they are equipped with CHF-enhancing devices. Two flow-based strength tests are required for all bundle designs for CANDU reactors: a strength test to show that the bundle can support the hydraulic drag of a full string of bundles on the fuelling-machine sidestops without bundle damage, and a single sidestop test to demonstrate that the hydraulic force of a full channel of bundles can be carried by one sidestop. Both of these tests have been completed at KAERI. The results indicate that the bundle can withstand the hydraulic forces, but detailed evaluation is still underway. A refuelling impact test, simulating the impact of a new fuel bundle coming to rest against the stationary bundles in the channel, is also required.

The final test required is a flow endurance test, to demonstrate acceptable vibration and fretting behaviour of the CANFLEX bundles in a fuel channel operating at a specified set of flow conditions. Preparation of the loop at KAERI, where this test will be done, is nearing completion; the test is due to start in early 1996.

Preparation is also underway at CRL to undertake pressure-drop tests on CANFLEX Mk.4 bundles using a new retractable probe technique, and using Freon-134a as a modelling fluid, rather than cold water. This offers the prospect to get more precise measurements of bundle junction pressure drop at Reynolds numbers closer to actual reactor operating conditions.

9. CHF TESTING

As discussed earlier, a CHF-enhancement technology has been developed, optimized, and integrated into the design and manufacturing procedures for the CANFLEX Mk.4 bundle. However, it is also necessary to undertake separate, precise measurements of the resultant CHF capabilities of the bundle over a wide range of flow conditions, to provide the kind of quality-assured data necessary to support the introduction of CANFLEX bundles into an operating CANDU-6 reactor. A test program to do this has been set up in the MR-3 Freon loop at CRL. The electrically heated, fuel-bundle-string simulator required for this test is now nearing completion, and testing is expected to commence in 1995 October. These tests will measure the CHF characteristics of the CANFLEX bundle over a set range of flow conditions, both with and without CHF enhancement. This will enable the contribution of the enhancement devices to the overall bundle CHF to be qualified. It is anticipated that the CHF results from an enhanced CANFLEX bundle will be available in 1996 April. The results will also be compared with the results made on an electrically heated, fuel-bundle-string simulator for standard 37-element bundles, measured over the same range of flow conditions, to provide a direct comparison with the CHF behaviour of current 37-element bundles. Bundle CHF tests are also planned in channels simulating various degrees of pressure-tube creep. The results of these tests will be used in conjunction with the subchannel code ASSERT,[9] to predict CANFLEX-bundle CHF behaviour for reactors with any degree of pressure-tube creep.[10]

10. CONCLUSIONS

Most of the critical testing and analysis required to support the introduction of a small number of CANFLEX bundles into a CANDU-6 reactor have either been completed or are well advanced in the preparation stage, and should be completed by the end of 1997.

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TABLE 1
CANFLEX BUNDLES IRRADIATED TO DATE

BUNDLE	ENRICHMENT (wt% U-235)	BUNDLE POWER (kW)	LINEAR RATING (kW/m)		BURNUP TO 95 AUG. (MWh/kgU)	STATUS
			PEAK	AVERAGE		
AJJ (Mk3)	2.25	1106	69	57	290	Undergoing PIE to determine the cause of the defect.
AHT (Mk1)	Natural U	272	-	30	27	Discontinued.
AHV (Mk1)	Natural U	369	-	18	25	Replaced with Mk3 design.
AJK (Mk3)	2.25	821	50	42	192	Continuing irradiation.
AJL (Mk3)	2.25	1143	73	64	75	Defect detected 1995 June.
AJN (Mk3)	2.25	839	57	50	118	Continuing irradiation.
AJM (Mk3)	2.25	806	30	28	71	Continuing irradiation.

FIGURES

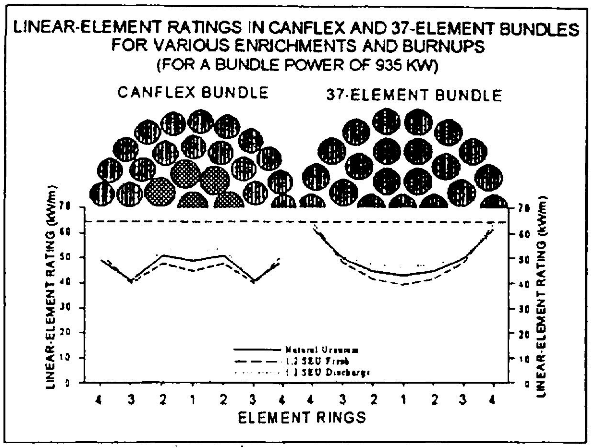

FIGURE 1: COMPARISON OF CANFLEX AND 37-ELEMENT BUNDLE FUEL RATINGS.

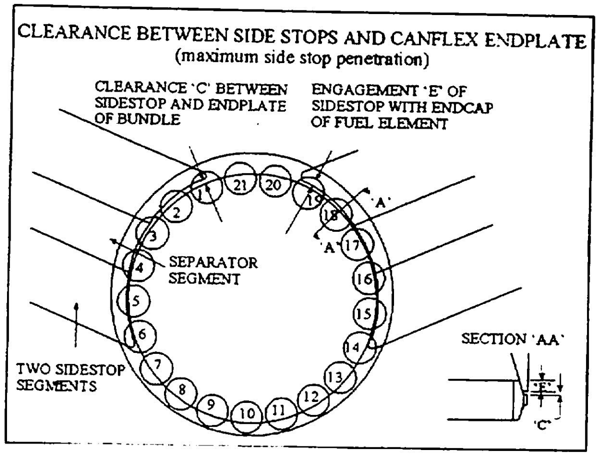

FIGURE 2: INTERACTIONS BETWEEN CANFLEX BUNDLE AND CANDU-6 FUELLING MACHINE.

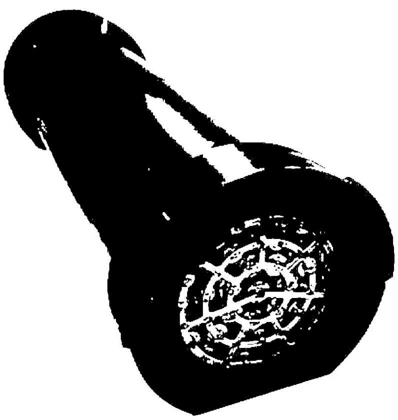

FIGURE 3: CANFLEX BUNDLE IN SIDE STOP SIMULATOR (PLEASE NOTE THE ABILITY TO ADJUST THE TWO SIDE STOPS, AND THE GAP IN EACH SIDE STOP TO ACCOMMODATE BUNDLE SEPARATORS).

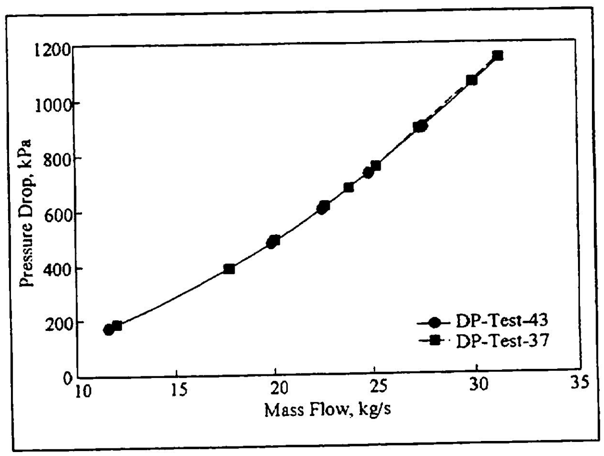

FIGURE 4: COMPARISON OF 37 AND CANFLEX BUNDLE PRESSURE DROPS.