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ABSTRACT

The CANFLEX® fuel bundle is the latest design in the evolution of CANDU® fuel. Its 43-element fuel-bundle assembly and its patented critical-heat-flux (CHF) enhancement appendages offer higher operating and safety margins than those of current fuel, while maintaining full compatibility with operating CANDU reactors. The greater element subdivision and the use of two element sizes lower the peak linear-element rating. Therefore, the bundle is well suited for use in advanced fuel cycles, particularly those that can attain high fuel burnup. The higher operating and safety margins offer the potential of reactor power uprating, which would further increase the economic competitiveness of the CANDU reactor.

Since 1991, Atomic Energy of Canada Limited has partnered with the Korea Atomic Energy Research Institute to complete the development, qualification testing, and analysis of the CANFLEX fuel bundle. In 1994, New Brunswick Power became interested in CANFLEX as part of an overall program on plant life management. Because of the increase in critical channel power with CANFLEX, the utility recognized that it could use CANFLEX to recover some of the heat transport system operation margins, which had decreased because of reactor aging. International cooperation between AECL & KAERI, driven by specific utility requirements, has been a key factor in CANFLEX coming to fruition.

The CANFLEX bundle has undergone extensive design analysis, performance and qualification testing, as well as an independent review within the Canadian nuclear industry and independently in Korea. Final confirmation of CANFLEX compatibility involved a 24-bundle demonstration irradiation at the Point Lepreau Generating Station (PLGS) in New Brunswick, Canada. The demonstration irradiation objectives were to confirm the compatibility and the irradiation performance of the CANFLEX bundles, and to confirm the fuel fabrication processes for this new bundle design.

In 1998 September, the demonstration irradiation at PLGS was started when 8 CANFLEX bundles were loaded into channel Q20 and 8 bundles were loaded into channel S08, using standard on-power refueling. Since then, an additional 8 bundles were loaded into the reactor and all 24 fuel bundles have been discharged into the fuel bays. Twenty of the twenty-four bundles were examined in the fuel-bays to verify bundle integrity and condition. Two of those bundles have been destructively examined in post-irradiation examinations in the hot cells at the Chalk River Laboratories.

While CANFLEX was being demonstrated at PLGS, the thermalhydraulic licensing data were being established by water CHF testing. Experimental data of dryout power and pressure drop were obtained with a simulated string of 12 aligned, full-scale, CANFLEX fuel bundles in 3 different flow channels with axial variation of the inside diameter. Pressure drops over the fuel string were obtained. A wide range of steam-water flow conditions was covered in the current tests: an outlet-pressure range from 6 to 11 MPa, a mass-flow-rate range from 7 to 25 kg/s and an inlet-fluid-temperature range from 200 to 290°C. The enhancement in critical channel power was confirmed to be from 5 to 8%, depending on specific conditions.

This paper describes the results of the demonstration irradiation at PLGS, as well as the results of the thermalhydraulics test program. It summarizes the benefits involved in implementing this new technology in existing operating stations.

INTRODUCTION

Since the early 1990's, Atomic Energy of Canada Limited (AECL) and the Korea Atomic Energy Research Institute (KAERI) have pursued a collaborative program to develop, verify, and prove a new fuel design that would introduce advanced fuel cycles such as slightly enriched uranium (SEU), recycled uranium (RU) and others into CANDU reactors and provide enhanced performance with natural uranium (NU) fuel through higher operating margins in existing CANDU reactors.

In 1998 September, New Brunswick Power (NBP), at the Point Lepreau Generating Station (PLGS), began a two-year demonstration irradiation of CANFLEX fuel bundles, as final verification of the CANFLEX design as a prerequisite to full-core conversion. Recently, the Korean Electric Power Corporation (KEPCO) announced a program in Korea to prepare for a demonstration irradiation in Wolsong Unit 1 and then potentially implement CANFLEX full-core. This document provides a summary of the CANFLEX qualification and performance assessment program and discusses the benefits existing plants can derive from using this fuel design.

CANFLEX BUNDLE DESIGN

The CANFLEX design is a 43-element fuel-bundle assembly offering improved operating and safety margins, compared with those of the standard 37-element fuel bundle, for operating CANDU reactors [1-4]. The CANFLEX bundle design includes critical heat flux (CHF) enhancement devices leading to 5 to 8% higher critical channel power (CCP) in a full-length fuel channel, compared with that of 37-element fuel bundles. The lower heat rating of the CANFLEX fuel elements at current bundle powers leads to lower fuel temperatures. Hence less fission-product gap-inventory is produced under normal operating conditions compared with the fission-product gap-inventory produced in standard 37-element fuel elements at a similar bundle power. The CANFLEX bundle consists of 2 fuel element sizes: small-diameter elements in the outer and intermediate rings, and larger-diameter elements in the inner and centre rings (Figure 1). Special buttons are attached to the elements at 2 planes, to provide improved heat-transfer and hence CHF enhancement. To maintain compatibility of the new bundle design with the design of existing CANDU 6 reactor and fuel handling systems, the basic overall dimensions of the CANFLEX fuel bundle were designed to be the same as those of the 37-element fuel bundle. The small-diameter elements of the outer ring result in a slightly larger end-plate diameter compared with end-plate diameter of the standard 37-element bundle. Consequently, the bearing pad heights of the bundle are designed to be larger than those of the 37-element bundle. This feature makes the CANFLEX bundle fully compatible with the sidestop/separator assembly of the CANDU 6 fuelling machine. The sidestop/separator assembly is an important component in the fuelling machine. The fuel bundle dimensions must be compatible with this assembly.

CANFLEX fuel is designed to have hydraulic and neutronic characteristics that are similar to those of the existing fuel. This feature allows operators to introduce CANFLEX bundles during normal on power refuelling. The fuel bundle, in all other respects, is designed to be equivalent to the 37-element bundle - that is it should be "transparent" to all reactor systems. To verify this, tests were performed for pressure drop, bundle strength under a number of situations such as radial cross-flow, and a test of the long-term fretting performance.

CANFLEX QUALIFICATION AND PERFORMANCE ASSESSMENT

The CANFLEX bundle has undergone an extensive verification program [5,6]. The verification program has been conducted following the strategy laid out in the Design Verification Plan (DVP). The verification work consisted of analysis and testing, drawing on the capabilities of AECL's facilities in Canada and KAERI's facilities in Korea. The DVP identifies the performance requirements, specifies the test or analysis required to verify that the requirement is met, and identifies responsibility and procedures. All testing and analysis conformed to the quality standard CAN/CSA-N286.2 or equivalent [7]. The DVP called for preparation of a Test Specification, Test Procedure, and Acceptance Criteria and identified the required documentation.

Thermalhydraulic Testing of CANFLEX to Establish Thermalhydraulic Performance Data

Full-scale CANFLEX bundle tests [8,9] were performed to obtain licensing data in a high-pressure steam-water loop. The test string consisted of a 6-m-long, 43-element, bundle simulator. A wide range of steam-water flow conditions was covered in the CHF experiment: an outlet-pressure range from 6 to 11 MPa, mass-flow-rate range from 7 to 25 kg/s, and inlet-fluid-temperature range from 200 to 290°C. Single- and two-phase pressure-drop measurements along the string were performed at lower pressures and fluid temperatures, as well as at higher mass-flow rates (Figure 2). The data corresponded closely to those previously obtained with a simulated string of 37-element bundles at the same test facility. The dryout power enhancement of CANFLEX over 37-element fuel ranges from 8 to 18% for the range of conditions of interest at the same inlet-fluid temperature (Figure 3). The water CHF data have been used to derive a CHF correlation for the NUCIRC computer code [10], which is used to calculate critical channel powers in CANDU reactors.

NUCIRC applies the correlations to the range of channel geometries, power shapes and operating conditions specific to a given reactor. Pre-release versions of NUCIRC with the CANFLEX correlations show that a typical CANDU 6 reactor will operate with 5 to 8% higher critical channel powers when fuelled with CANFLEX compared to the standard 37-element bundles. NUCIRC Version 2.01, which will contain the CANFLEX calculation options, is currently being verified and should be formally released late in fiscal year 2000/01.

Out-reactor Flow Testing

AECL and KAERI have subjected the CANFLEX fuel bundle to a set of out-reactor flow tests to simulate reactor conditions and verify that the design is compatible with existing reactor hardware. These tests include Strength Test, Impact Test, Cross flow tests, Fuelling Machine Compatibility and a 3000 h Flow Endurance Test.

In-reactor Testing

CANFLEX bundles, AJK, AJM and AJN, were irradiated in the U-1 and U-2 loops in the NRU research reactor to demonstrate performance under expected in-reactor conditions. Typical power changes during refuelling and peak outer element midplane powers exceeding 70 kW/m were used for the irradiation conditions in the NRU tests. For the high burn-up NRU irradiations, burn-ups of greater than 480 MWh/kgU were achieved. Once the bundles were removed, detailed post-irradiation examinations

(PIE) were performed. The irradiation in NRU reactor confirmed the performance of the CANFLEX bundles under in-reactor operating conditions.

Reactor Physics Testing and Analysis

The ZED-2 facility at CRL was used to measure the fine-structure, reaction rates, and reactivity coefficients for CANFLEX natural-uranium bundles, to validate the reactor physics lattice code WIMS-AECL. The data showed excellent agreement with code predictions. A fuel management computer code was used to simulate reactor operation over 600 full-power days, to determine peak bundle powers, power changes during refuelling, burnups, and residence times. Various fuel schemes were studied. Fuel performance requirements were established for NRU irradiation tests. The analysis showed that the CANFLEX bundle meets or exceeds all power requirements.

Structural Analysis

The CANFLEX design was analyzed for sheath strains, fission-gas pressure, end-plate loading, thermal behaviour, mechanical fretting, element bow, end-flux peaking, and a range of other mechanical characteristics. The CANFLEX design met the acceptance criteria.

Formal Design Review and Licensing

In Canada, AECL's Chief Engineer conducted a formal design review to assess the CANFLEX verification and qualification program, and the bundle's readiness for full-core implementation. Industry experts from New Brunswick Power, Hydro Québec, Ontario Power Generation, the two domestic fuel fabricators, and subject-area experts reviewed the CANFLEX Fuel Design Manual and other CANFLEX documentation. Reviewers provided written comments that the Design Team addressed. Closure was achieved for most issues. Actions are underway to complete outstanding items, such as PIE of the DI bundles and completion of the thermalhydraulic licensing report.

In Korea, KAERI prepared a Fuel Design Report on CANFLEX-NU, and submitted it to the Korea Institute of Nuclear Safety (KINS) in July 1996 to obtain approval of the fuel design and fabrication method, as part of the Korean licensing process. In August 6, 1999, the Korean Government Approval of the CANFLEX-NU fuel design and fabrication method was released to KAERI. However, as outlined in the previous paragraph, several actions were also assigned for the completion of outstanding work- these included submissions of the PIE reports of the fuel irradiations in the NRU reactor and a CANDU power reactor and the water CHF test report of the fuel bundle string

Demonstration Irradiation Plan

The principle objective of a demonstration irradiation is to show compatibility with all reactor systems [11,12]. The PLGS applied its standard process for special fuel irradiations for the CANFLEX demonstration irradiation [13]. This process involves preparation of an Information Report that is the basis on which both management and regulatory approvals are built. The demonstration irradiation plan called for Zircatec Precision Industries to manufacture 26 CANFLEX bundles to the Quality Assurance levels normally applied to 37-element fuel supplied to PLGS- 24 bundles for fuelling in PLGS and 2 for archiving. All configurations of CANFLEX bundles mixed with 37-element bundles in a single channel during transition and full-core refuelling were to be tested. On discharge and transportation to the PLGS spent fuel bays, the CANFLEX bundles were to be visually examined. Two bundles would be selected and shipped to the CRL for PIE. The demonstration irradiation will be fully documented, including station data and PIE reports.

CANFLEX Demonstration Irradiation Status

Once Canadian Nuclear Safety Commission (formerly the AECB) approval for the DI was secured in the late summer of 1998, PLGS fuel engineers selected channel S08 for the high-power channel (Figure 4) and channel Q20 for the low-power channel. As part of the routine on-power fuelling in 1998 September, 8 CANFLEX bundles were fuelled into each of the 2 channels. In 1999 March, the low-power channel Q20 was refuelled and the first 4 DI CANFLEX bundles were discharged into the fuel bays. The PLGS had planned a fuel-channel inspection in channel S08 during a summer maintenance shutdown, and it was decided to leave the CANFLEX fuel in the channel during the shutdown to demonstrate its compatibility with all maintenance handling systems and operations. Thus the high-power channel S08 was refuelled after reactor start-up in 1999 August, discharging 4 CANFLEX fuel bundles and establishing a full channel of 12 CANFLEX fuel bundles. In 2000 January, the final fuelling in channel Q20 was successfully completed, discharging 4 CANFLEX bundles and restoring the channel to full 37-element configuration. In 2000 February, channel S08 was refuelled, discharging 8 CANFLEX bundles and leaving 4 CANFLEX bundles to complete their irradiation. In 2000 August the last of the DI bundles was discharged thereby completing the irradiation of 24 CANFLEX bundles at PLGS.

The power history of bundles irradiated in the high power channel S08 (Figure 5) show a relatively high burnup of over 220 MWh/kgU, compared with a more standard burn-up of 175 MWh/kgU. From an operational perspective, the CANFLEX fuel behaved exactly as 37-element fuel would have: there were no differences in any monitored aspect of station behaviour that could be attributed to CANFLEX fuel.

Irradiated Fuel In-bay Inspection

Of the 24 CANFLEX bundles irradiated, 20 bundles have been visually inspected in the fuel bays at PLGS (the remaining 4 bundles discharged in August require 2 months of cooling before a full inspection can be made). The inspection team included fuelling experts from the station, a member of the CANFLEX design team and a member of the AECL fuel inspection group - who will conduct the PIE in the cells. The examination was done using an underwater periscope; photography was achieved using a television camera attached to the periscope and digital imaging. The inspection team concluded that the bundles were in very good condition. All observations, photographs and irradiation data have been sent to the design team for review and disposition.

Full inspection reports have been prepared and the design team's disposition of the findings documented for inclusion in the Demonstration Irradiation Report. In conclusion, the 20 bundles irradiated to date have shown good performance, confirming the acceptability and compatibility of this new design.

Post-irradiation Examination

Two CANFLEX DI fuel bundles were shipped to CRL for post-irradiation examination (PIE). Bundle FLX019Z, irradiated in channel Q20 position 8, was shipped to CRL on 1999 December. Bundle FLX019Z reached a calculated bundle burnup of 144 MWh/kgU and reached a peak outer-element linear power (OELP) of 38 kW/m. Bundle FLX007Z, irradiated in channel S08 position 8, was shipped to CRL on 2000 March 30 from PLGS. Bundle FLX007Z reached a calculated bundle burnup of 221 MWh/kgU and reached a peak OELP of 45 kW/m.

The visual and non-destructive examinations have been completed for both bundles and the destructive examinations are in progress. The following is a brief summary of the PIE results to date:

- No unusual features or anomalies were found visually.
- Outer element straightness was found to be consistent with that of irradiated 37-element bundles.
- Bearing and spacer pad wear, and end plate distortion was minor and also consistent with irradiated 37-element fuel.
- Typical pellet-interface ridging was found for FLX007Z but it was not distinctive for the lower power bundle FLX019Z (Figure 6).
- Element gamma scans are normal, and no Cs migration to the pellet-interface was evident (Figure 7), consistent with lower internal fission gas release.
- Fission gas volumes (1.4 to 1.7 mL at STP) and release (less than 0.1%) were small.
- No unusual features or anomalies have been found in the metallographic and ceramographic examination of bundle FLX019Z (e.g., typical fuel microstructure Figure 8).

The plant data, fuel-bay examinations, PIE, and assessment work will be documented in a full report in 2001. This action will conclude the demonstration irradiation program for the CANFLEX bundle.

CANFLEX DEMONSTRATION IRRADIATION IN KOREA

With the successful completion of the demonstration irradiation of CANFLEX fuel in PLGS, KEPCO has initiated a program to use CANFLEX fuel in Wolsong Unit 1, which has been operating since 1983. Korea Electric Power Research Institute (KEPRI) of KEPCO and KAERI starting in September 2000 is conducting an industrialization program for the use of CANFLEX fuel in the Wolsong reactor jointly. This 3-year program will be under Korea's Nuclear Energy R & D Mid- and Long-Projects that have been financially supported and operated by the Korea Ministry of Science and Technology since 1992. The program mainly involves a small-scale irradiation of 24 CANFLEX-NU bundles in the Wolsong reactor and production of a safety assessment report for full-core implementation of CANFLEX-NU fuel. The CANFLEX fuel is expected to be loaded in Wolsong Unit 1 in the later part of 2001. Successfully demonstrating the irradiation of CANFLEX fuel in the Wolsong power reactor will lead the way towards the full-core implementation of CANFLEX fuel in Korean CANDU reactors.

INCREASING CANDU OPERATING MARGINS WITH CANFLEX FUEL

Implementing CANFLEX fuel in existing CANDU 6 reactors will increase the critical channel powers (CCP) by 5 to 8%. The actual CCP gain depends on individual channel conditions such as channel creep shape, power shape and local flow conditions. Critical Channel Power is calculated using the computer code NUCIRC. The increase in CCP margin can be used by station operations to offset the margin reductions resulting from reactor aging, such as the effect of heat transport system fouling and of diametral creep of the pressure tubes. Alternatively, the increase in margin could be utilized to increase the core power output, particularly in a new reactor.

The ~20% reduction in the linear element rating of the CANFLEX bundle (compared with the 37-element bundle) results in a substantial reduction of the fission product inventory in the fuel-to-sheath gap (i.e., gap-inventory). For example, at the same maximum bundle power, the iodine gap-inventory in the maximum-rated element in a CANFLEX bundle is estimated to be 3 times lower than for the maximum-rated element in a 37-element bundle. This reduction provides several benefits. For accidents in which a number of fuel elements are predicted to fail and their fission-product gap-inventory released, the radiological consequences will be reduced with the use of the CANFLEX bundles. This further enhances the safety performance of the reactor. The lower gap-inventory and lower power will also lead to lower activity burden in the heat transport circuit in the event of fuel failures during normal operation. While the performance of CANDU fuel has been excellent, and the fuel failure rate has been very low, on-power fuelling and failed fuel detection and location systems are designed to provide the means for an operator to locate and remove failed fuel. The lower gap-inventory will also reduce the radiological contamination in the heat transport circuit arising from activity release from failed fuel. Consequently, the man-rem exposure during reactor maintenance is expected to be less, resulting in occupational health and cost benefits.

CONCLUSIONS

The CANFLEX fuel design has been verified through extensive testing by AECL and KAERI and has been critically reviewed under a Formal Design Review. Results from the 24 CANFLEX bundles irradiated to date in PLGS confirm the compatibility of this fuel type with existing reactor systems. After the successful demonstration irradiation of CANFLEX fuel in PLGS, KEPRI and KAERI will jointly conduct a 3-year industrialization program on the use of CANFLEX-NU fuel in Wolsong reactors starting with plans for a demonstration irradiation in the later part of 2001. Successfully demonstrating the irradiation of CANFLEX fuel in the Wolsong power reactor will lead the way towards the full-core implementation of CANFLEX-NU fuel in Korea. The economic analysis based on the CHF-enhancement data indicates a significant payback to utilities operating CANDU reactors. The utilities now have an alternative fuel that can be deployed with confidence to provide greater operating margins.

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