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CANFLEX Mk-IV Qualification Program and Readiness for Implementation

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CANFLEX MK-IV QUALIFICATION PROGRAM AND READINESS FOR IMPLEMENTATION

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ABSTRACT

A formal design verification process was followed to qualify the CANFLEX® Mk-IV fuel bundle for use in CANDU® 6 reactors. Extensive out-reactor testing, combined with analysis, was used to show that CANFLEX meets the CANDU 6 fuel design requirements. The design requirements, assessments and performance tests results were documented in the Point Lepreau Generation Station (PLGS) Fuel Design Manual, which was subjected to an industry-wide formal Design Review. The final step before the implementation of CANFLEX fuel was to conduct a demonstration irradiation of these bundles in a power reactor to show compatibility with the fuel channel and fuel handling systems.

The Demonstration Irradiation (DI) has been successfully completed with 24 CANFLEX bundles at PLGS. Sixteen bundles were irradiated in a high-power channel (S08) to burnups ranging from 163 to 242 MWh/kgU, and to maximum outer-element linear powers of 25 to 39 kW/m. A further eight bundles were irradiated in a low-power channel. All bundles were visually inspected in the PLGS spent fuel bay, and two were subjected to full Post Irradiation Examination at the Chalk River Laboratories hot cells. The bundles were in good condition with no defects. All observations have been formally dispositioned.

All activities identified in the Design Verification Plan have been fully completed, all questions from the Design Review Panel have been resolved, and all observations from the DI bundle inspections have been formally dispositioned. The CANFLEX Fuel Design Manual has been revised to include results from the new analysis, testing and inspections that have been concluded through the final stages of the review process. AECL's Office of the Chief Engineer has concluded that the CANFLEX Mk-IV fuel bundle design is qualified for implementation in a CANDU 6 reactor. Discussions are underway with utilities in Canada and Korea, to quantify the benefits from implementing this new fuel design.

This paper will provide an overview of the verification process, with a focus on the most recent activities that are intended to resolve questions arising from the Design Review. This paper will describe the activities undertaken to address all observations from the inspections performed on the DI bundles. Finally, this paper will show the readiness of this new product for implementation, and the potential benefits that current stations can derive from its application.

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

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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 would provide enhanced performance with natural uranium (NU) fuel, through higher operating margins in existing CANDU reactors [1,2,3].

From 1998 September to 2000 August, New Brunswick Power (NBP), at the Point Lepreau Generating Station (PLGS), conducted a two-year demonstration irradiation (DI) of CANFLEX® fuel bundles, as the final verification of the CANFLEX design, and as a prerequisite to full-core conversion. Recently, the Korean Electric Power Corporation (KEPCO) announced a program in Korea to prepare for a DI in Wolsong Unit 1, followed by a potential full-core CANFLEX implementation.

This paper provides a summary of the CANFLEX qualification and performance assessment program. This paper also provides a summary of the disposition of all findings from the DI, and discusses the readiness of CANFLEX Mk-IV for full-core implementation.

CANFLEX BUNDLE DESIGN

The CANFLEX design is a 43-element fuel-bundle assembly that offers improved operating and safety margins, compared to the standard 37-element fuel bundle, for operating CANDU reactors. The CANFLEX bundle design includes critical heat flux (CHF) enhancement devices that lead to higher critical channel power (CCP) in a full-length fuel channel, compared to 37-element fuel bundles. The lower heat rating of the CANFLEX fuel elements at current bundle powers leads to lower fuel temperatures. As a result, less free fission-gas inventory is produced under normal operating conditions, compared with the free fission-gas inventory produced in standard 37-element fuel elements at a similar bundle power.

The CANFLEX bundle consists of two fuel element sizes: small diameter elements in the outer and intermediate rings, and larger diameter elements in the inner and centre rings. Special buttons are attached to the elements at two planes, to provide improved heat- transfer, and hence, critical heat flux enhancement. To maintain the 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 the 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 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, i.e., to be "transparent" to all reactor systems. To verify this transparency, tests were performed for pressure drop and bundle strength under a number of situations such as radial cross flow; a test of the long-term fretting performance was also performed.

CANFLEX VERIFICATION PROGRAM

The CANFLEX bundle has undergone an extensive verification program [4]. 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, and drew on the capabilities of AECL's facilities in Canada and KAERI's facilities in Korea [5]. 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 [6]. The DVP called for the preparation of a Test Specification outlining the test procedure, acceptance criteria and required documentation.

Thermalhydraulic Testing of CANFLEX to Establish Licensing Data

To characterize the thermalhydraulic performance of CANFLEX, pressure drop, CHF and post dryout (PDO) experiments were performed in Freon-134a in the MR-3 facility at CRL. The pressure-drop characteristics of the CANFLEX bundle were determined in both Freon tests, and hot and cold water.

Full-scale CANFLEX bundle tests were performed to obtain licensing data in the high-pressure steam-water loop at Stern Laboratories [7,8]. 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, with an outlet pressure range of 6 to 11 MPa, mass flowrate range of 7 to 25 kg/s, and inlet fluid temperature range of 200°C to 290°C. CANFLEX was found to provide CHF enhancement over 37-element bundles for all conditions with increasing enhancement as the channel creep increases. The water CHF data have been used to derive a CHF correlation for the NUCIRC computer code, which is used to calculate critical channel powers [9]. NUCIRC Version 2.01 has been verified with the CANFLEX thermalhydraulic relationships.

Out-Reactor Flow Testing

AECL and KAERI have subjected the CANFLEX fuel bundle to a set of out-reactor flow tests, in order to simulate reactor conditions, and to verify that the design is compatible with existing CANDU 6 reactor hardware. In addition to the heat transfer and pressure drop tests, the following mechanical flow tests have been successfully completed:

- **Strength Test:** Strength tests showed that the fuel can withstand the hydraulic loads imposed during refuelling. Post-test bundle geometry measurements showed no significant distortion.
- **Impact Test:** Impact tests showed that the CANFLEX bundle can withstand bundle impact loads during refuelling.
- **Cross Flow:** Cross flow tests demonstrated that, during refuelling, when the bundle is in the cross-flow region, the bundle withstands the flow-induced vibration for a minimum of 4 h.
- **Fuelling Machine Compatibility:** Fuelling machine compatibility showed that the bundle is dimensionally compatible with the fuel handling system.
- **Flow Endurance:** Flow endurance tests demonstrated that the CANFLEX bundle maintains structural integrity during operation. Fretting wear on the bearing pads, inter-element spacers and pressure tube remained within design limits over the 3000-h test time.

In-Reactor Testing

CANFLEX bundles AJK, AJM, AJN and AKT were irradiated in the NRU research reactor at Chalk River Laboratories (CRL) Canada, to demonstrate performance under expected in-reactor conditions. Typical power changes during refuelling and peak bundle powers during operation were calculated, in order to establish the irradiation conditions for the NRU tests. Actual peak powers experienced were over 25% greater than in a CANDU 6. Once the bundles were removed, detailed post-irradiation examination (PIE) was performed. All design requirements were met.

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 NU bundles, in order 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, in order 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. Acceptance criteria, established from years of operating experience with 37-element fuel and previous 37-element testing, were met by the CANFLEX design.

Formal Design Review

The Verification Program results were summarized in the Fuel Design Manual. This document captures all the design requirements, points to the individual analysis or test, and shows that the requirements have been met. In 2000 February, 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 Quebec, 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, which were dispositioned. The reviewers' comments were incorporated into the CANFLEX fuel design manual. The design review has been closed, and the CANFLEX Mk-IV fuel bundle design has been declared qualified for full-core implementation in CANDU 6 reactors.

CANFLEX DEMONSTRATION IRRADIATION

As a final verification of the CANFLEX design, in preparation for full-core implementation, a DI was performed at the Point Lepreau Generation Station (PLGS) [10,11,12]. The aim of the DI program is two-fold: (i) to confirm the performance of the CANFLEX bundle design in a power reactor operating environment, and (ii) to qualify the production-type CANFLEX bundles. The DI bundles were manufactured as close as practical to the mass-production route, according

to the Canadian Quality Assurance Program Standard of CAN3-Z299.2. PLGS fuel engineers selected two channels (S08 and Q20) for the DI. Channel S08 has a higher channel power and coolant flow rate than channel Q20 (6473 kW versus 4688 kW, and 23.7 kg/s versus 17.1 kg/s). All configurations of CANFLEX bundles mixed with 37-element bundles in a single channel during transition and full-core refuelling were tested. Upon discharge and transportation to the PLGS spent fuel bays, the CANFLEX bundles were visually examined. Two bundles were selected, and were shipped to CRL for post irradiation examinations. The DI was fully documented, including station data and PIE reports.

Details on the Demonstration Irradiation

In 1998 September, New Brunswick Power (NBP), at PLGS, began a two-year 24-bundle DI program. In 2000 August, the last of the DI bundles were discharged, completing the irradiation of 24 CANFLEX bundles at PLGS. From an operational perspective, the CANFLEX fuel behaved exactly as 37-element fuel would have, and there were no significant differences in any monitored aspect of station behaviour that could be attributed to CANFLEX fuel. During the summer shutdown, channel S08 underwent Spacer Location And Repositioning (SLAR) and Channel Inspection and Gauging Apparatus for Reactors (CIGAR) inspection. The fuel handling associated with these procedures was uneventful, and the results of the CIGAR inspection did not indicate any unusual wear in the channel that was related to the use of CANFLEX fuel. The high-power channel, S08, had a relatively high burnup of over 250 MWh/kgU, compared to the more standard burn-up of 175 MWh/kgU.

Irradiated Fuel In-bay Inspection

All 24 CANFLEX bundles that were irradiated have been visually inspected in the fuel bays at PLGS. 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 were sent to the design team for review and disposition. Full inspection reports have been prepared. [13].

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. This bundle reached a calculated bundle burnup of 144 MWh/kgU, and a peak outer-element linear power (OELP) of 29 kW/m. Bundle FLX007Z, irradiated in channel S08 position 8, was shipped to CRL on 2000 March 30 from PLGS. This bundle reached a calculated bundle burnup of 223 MWh/kgU, and a peak OELP of 37 kW/m.

The visual, non-destructive and destructive examinations have been completed for both bundles. No unusual features or anomalies were found visually. The following is a brief summary of the PIE results:

- 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 was 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.
- Element gamma scans are normal, and no Cs migration to the pellet interface was evident, 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 or FLX007Z (e.g., typical fuel microstructure).

Formal Disposition of DI Observations

All observations from the in-bay inspections and PIE have been formally dispositioned by the design team through root cause assessment. Some further tests and the comparison of the observations against 37-element experience were performed. Five observations were dispositoned as follows:

(*a*) Marks on the sides of the CHF buttons: These marks appeared on the sides of about 1% of the buttons on the outer elements of bundles inspected in the bay. The apparent material loss on the CHF buttons was not expected. Inspection of the two archive DI bundles revealed that these buttons also had the same features as those seen in the PLGS bay; i.e., an area with a raised periphery at the side of some buttons. Based on a comparison of the marks from the irradiated fuel and the unirradiated fuel, it was concluded that this feature is a manufacturing artifact due to beryllium that was side-coated on the CHF buttons and subsequently brazed at high temperature. ZPI agreed that the artefact observed was related to a small batch production, and would not occur in a mature manufacturing line. No design action is required.

(*b*) Scuff marks on end caps: These marks were not caused during manufacturing or handling. It was determined that the scuff marks were caused by the separator feeler (also called the Sensor and/or Retractor) rather than the sidestops. Chipping of the chrome plating on the feeler tip has been observed on several of the separator assemblies at the CANDU 6 stations. This results in sharp edges that would be likely to cause scratching. Similar marks have been observed on 37-element bundles in the past, because of worn components. It is concluded that the scuff marks are not related to CANFLEX design. No design action is required.

(*c*) Marks on one location on all end plates: These marks were present on all CANFLEX end plates at the element 19 location. Similar marks were also found on the archived bundles. These were typical machining and deburring marks caused by the Electric Discharge Machining method used to manufacture the small prototype lot. Stamping with a die would normally be used to make end plates. Thus, no design action is required.

(*d*) Near-full-surface bearing pad wear: With the exception of one mid-plane bearing pad, all end bearing pads of the DI bundles had normal wear. In general, the wear on the mid bearing pads was light, and was less than those of the 37-element bundles. Because of the surface contour of the bearing pad, the sliding wear made when a pad transverses through the channel is normally reflected in a pattern of non-full-surface wear. The near-full-surface wear was observed on one mid bearing pad of CANFLEX bundle FLX008Z, and 37-element bundle

C00131Z, both from channel S08. The near-full-surface wear does not indicate a performance problem, and is not CANFLEX-specific.

CIGAR inspections of channel S08, during the summer shutdown, detected no additional flaws and no significant degradation of pre-existing flaws that could be attributed to the irradiation of CANFLEX bundles. Based on this observation, it is concluded that the flow-induced vibration and fretting behaviour of the CANFLEX bundles in S08 is similar to the 37-element fuel bundles. The bearing pad wear was within the current irradiated fuel experience, and no design action is required.

(*e*) Large gap between outer elements: The CANFLEX bundles were found to have element settling in high power and high crept positions. Gaps of about 3 mm were observed between outer elements, predominantly along the sides of bundles at either the 9 or 3 o'clock positions. Sideways and outward bowing was observed on some outer elements. These large gaps between adjacent elements along the sides of the bundles led the inspection team to suspect spacer interlocking.

Bundle FLX007Z, irradiated in S08 position 8, and was shipped to CRL for PIE. This bundle achieved a discharged burnup of 223 MWh/kgU, and a peak rating of 37 kW/m. PIE found no evidence of spacer interlocking. Spacer pad wear on the top surface of the spacers was normal, and the proper mating of spacers was indicated.

Analyses on the DI bundles using as-fabricated dimensions indicated that relatively large gaps existed between spacers on the intermediate elements. From the analysis, it is concluded that (1) interelement spacers are undersized, particularly on intermediate elements; and (2) centre bearing pads are undersized (1.1 mm in height), relative to end bearing pads (1.4 mm). The large gaps between spacers, combined with centre pads that were lower than the end pads, likely contributed to the amount of fuel element deformation observed on the DI bundles. Design has proposed to (1) tighten the manufacturing specification on minimum heights for all spacer groups, in order to reduce the current gaps, but to leave sufficient gap to maintain bundle assembly and to allow passage through the bent tube gauge; and (2) set minimum bearing pad heights as 1.4 mm uniformly along the bundle, in order to reduce the amount of element deformation in-reactor. As a normal quality assurance principle, to provide feedback from the irradiation experience to design, the identified changes have been formally incorporated into Revision 5 of the CANFLEX Design Drawing.

READINESS OF CANFLEX MK-IV FOR FULL-CORE IMPLEMENTATION

Potential Benefits to Existing Stations from the Implementation of CANFLEX Fuel

Implementing CANFLEX fuel in existing CANDU 6 reactors will increase the critical channel powers (CCP). The actual CCP gain depends on individual channel conditions, such as channel creep shape, power shape and local flow conditions. CCP is calculated using the computer code NUCIRC. The increase in the 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 three 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 fission-product gap inventory and lower power will also lead to a lower activity burden in the heat transport circuit, in the event of fuel failures during normal operation. The lower fission-product 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.

Implementation Plan

AECL, in discussion with utilities in Canada, have prepared an Implementation Plan for full-core conversion of an operating plant from 37-element fuel bundles to CANFLEX. The plan consists of the following main components:

- **Design approval:** AECL and KAERI have completed the fuel qualification program and independent design reviews. AECL's Implementation Plan calls for the design information to be presented to the CNSC, to seek acceptance that CANFLEX is an approved fuel type for normal operating conditions. All the design information is compiled into a Fuel Design Manual (FDM). The FDM contains all the design requirements for the fuel, a summary of the test results or analysis results that show CANFLEX meets these requirements, and provides references to detailed reports. All CANFLEX reports are contained in a report series, and will be provided to utilities under license.

- **Regulatory interaction, safety and licensing:** The regulatory approval process is planned to occur in two stages: (1) approval for CANFLEX loading into the reactor, and (2) approval to raise trip set-points. The division of the safety submissions in support of conversion into two separate approval steps allows the program schedule to be optimized, by first demonstrating that CANFLEX can be implemented while maintaining the safe operation of the reactor, and second, that the reactor operating set-points can be safely raised. Thus, the safety analysis objectives are to (*i*) demonstrate that the use of CANFLEX fuel will not result in unacceptable consequences to the design basis accidents considered in the Safety Report, and (*ii*) quantify the improved trip set-points that CANFLEX allows, and gain regulatory approval for their implementation once the core conversion has progressed sufficiently far to credit them.

- **Operational planning and implementation:** Since one of the design requirements of CANFLEX fuel is that it interfaces as 37-element fuel does to other reactor systems, only minimal changes should be required to operational documentation and procedures. This group of activities includes the completion of all tasks at site to change over from 37-element fuel to CANFLEX. Examples of theses activities include the following: (1) review operational documents and procedures, and make the required revisions for the use of CANFLEX fuel; (2) revise core-tracking methodology, including the possibility of using

RFSP fuel management computer code with WIMS for fuelling simulations; and (3) manage fuel procurement and the fuel inventory.

Readiness of Design and Licensing Tools and Methods for CANFLEX

A formal review of the design and licensing tools has been completed. The review identified, for all computer codes used in licensing and support work, whether or not the current methodologies covered the CANFLEX design, and whether or not the current Code Validation Program (CVP) covered the CANFLEX application. With the exception of ELESTRES- IST, it was determined that all codes are capable of performing the licensing calculations for CANFLEX, and the CVP covers CANFLEX. ELESTRES is being modified and validated to address the smaller diameter elements in the CANFLEX bundle. This work will be finished by March 2002. As well, a CANFLEX CHF Look-Up Table and a CANFLEX PDO correlation are being developed for the next release of CATHENA, in order to update the current methodology.

CONCLUSIONS

The CANFLEX fuel design has been verified through extensive testing and analyses 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. AECL has developed a detailed implementation plan to convert existing CANDU 6 reactors from 37-element fuel bundles to CANFLEX bundles. 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, in order to provide greater operating margins.

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