PERFORMANCE OF THE CANFLEX™ FUEL BUNDLE UNDER MECHANICAL FLOW TESTING

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ABSTRACT

CANFLEX[1] is a 43-element fuel bundle consisting of two element sizes, to reduce element ratings, while maintaining the same bundle power, and an uranium content very close to the uranium content of a standard 37-element bundle. The overall dimensions of the bundle are designed to be the same as the overall dimensions of the standard 37-element fuel bundle. Several out-reactor tests were performed, under in-reactor operating conditions of flow, pressure and temperature, to demonstrate the hydraulic performance and mechanical integrity of the CANFLEX fuel-bundle design. The hydraulic performance and mechanical integrity of the CANFLEX fuel-bundle design were verified through various out-reactor tests conducted at the laboratories of KAERI and AECL to show that the CANFLEX bundle design meets the design requirements of the CANDU 6 reactor fuel [1] and that it is also compatible with the CANDU 6 fuelling machine.

INTRODUCTION

The CANFLEX fuel-bundle design is being developed jointly by KAERI and AECL to facilitate the use of various advanced fuel cycles in CANDU reactors by providing enhanced fuel behaviour and thermalhydraulic performance in bundle design. As a first stage of the CANFLEX joint program, the CANFLEX fuel bundle with natural uranium has been developed. The KAERI effort is focused on fabrication and mechanical flow testing of prototype CANFLEX bundles; the AECL effort has been concentrated on the thermalhydraulic optimization of the bundle design and the in-reactor demonstration of the bundles in a research reactor [1]. There is also a joint AECL-KAERI component focused on establishing those aspects of fuel design, fuel management and safety analysis that must be in place to support any CANFLEX bundle demonstration irradiation in a CANDU reactors.

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Several kinds of mechanical flow test were performed, under typical reactor operating conditions of flow, pressure and temperature, to demonstrate the hydraulic performance and mechanical integrity of the CANFLEX fuel bundle-design [2]. These tests were conducted in the KAERI Hot Test Loop facility and at AECL. The hydraulic performance of the bundle was verified in the fuel-string pressure drop test, and the mechanical integrity of the bundle was demonstrated in the bundle strength test, refuelling impact test, cross-flow test and endurance fretting test. The compatibility of the bundle with a CANDU 6 fuelling machine was tested in a Wolsong CANDU 6 fuelling machine while the machine was at AECL in Canada, under typical fuel-machine operating conditions. This out-reactor testing is part of the qualification program to verify the mechanical and hydraulic performance of the CANFLEX bundle design prior to the irradiation demonstration of 24 bundles in a CANDU 6 reactor.

TEST APPARATUS

Fuel Test Loop Facility

The KAERI Hot Test Loop is a high-temperature/high-pressure fuel test facility in which heat transport system conditions, including water chemistry of a CANDU reactor, can be simulated [3]. The loop has a test rig consisting of a prototype CANDU 6 fuel channel and inlet and outlet feeder pipes as shown in Figure 1. The geometry of the feeders next to the fuel channel is equivalent to the geometry of L5, which is one of the high-flow channels of the Wolsong 1 and other CANDU 6 reactors. The fuel-channel closure was achieved by installing blind flanges on both sides of the end fittings. The garter spring supports were arranged in a manner similar to the arrangement of a CANDU 6 reactor installation.

The test rig was instrumented to measure test conditions such as pressure, temperature, flow rate and pressure drop, which are common to each out-reactor test. The temperature and flow rate of the coolant through the test rig were measured with a resistance temperature detector and orifice flow meter, respectively. All transmitters were calibrated to offer an optimized measuring range and accuracy. An HP 3054A data acquisition system was used to collect and process signals from the transmitters and sensors for test condition measurements. An high-speed video motion analysing system, Fast Fourier Transform (FFT) and accelerometers were used for the fuel-bundle out-reactor testings.

CANFLEX Fuel Bundle

The major feature of the CANFLEX bundle is an increase in the number of fuel elements, from 37-elements in the standard CANDU 6 bundle to 43 elements of two different diameters. The small-diameter elements are located in the outer two rings of the CANFLEX bundle to reduce the peak element ratings, and large-diameter elements are located in the centre and inner ring to produce a flatter power density across the bundle cross-section. The overall diameter of the CANFLEX bundle was maintained at the same diameter as the standard 37-element bundle so that the CANFLEX bundle can be used in the existing CANDU 6 reactors. Two planes of oblong CHF (Critical Channel Flux) enhancement buttons are located along the elements of the bundle to produce more flow turbulence downstream of the buttons. The resulting improved heat transfer gives an increase in critical channel power (CCP), allowing greater operational flexibility to the reactor operators.

FUEL-BUNDLE MECHANICAL FLOW TESTING

Fuel-String Pressure Drop Tests

A series of fuel-string pressure drop tests was performed to verify that the CANFLEX bundle meets the acceptance criteria specified for the pressure drop test and to provide relevant test data to fuel design and safety analysis groups, to evaluate the new fuel design. The fuel-string pressure drop test was a single-phase, high-pressure, light-water test for a fuel channel loaded with 12 CANFLEX bundles. The pressure measurements were obtained for both CANFLEX bundles and reference 37-element bundles to compare the test results under the same test environment.

The fuel-channel pressure drop is a function of the junction misalignment angles between the 12 bundles in the fuel channel. A single-junction pressure drop test was performed in a short test rig to determine the dependence of pressure drop on angular alignment between bundles, and it was found that the most probable pressure drop and maximum pressure drop of the 12-CANFLEX-bundle string occurs at 28 and 41 degrees of bundle misalignment angle, respectively.

The conditions for the fuel-string pressure drop test were flow rates of 12 to 30 kg/s at a temperature of 266 °C, and fuel channel inlet pressure of 11.2 MPa. The test results for the CANFLEX and reference 37-element bundle strings are compared in Figure 2. From a hydraulic point of view, the major difference between the 2 bundle designs is a change in the flow area and wetted perimeter, and the presence of the CHF enhancement buttons on the CANFLEX fuel elements. The test results of the CANFLEX bundle string were determined to be about 15 kPa higher than the test results of the 37-element bundle string at 23.9 kg/s, 266 °C, and 11.2 MPa. The button and wetted perimeter effects on the bundle pressure drop were dominant compared to the flow area effect.

The acceptance criterion for the test is that the most probable pressure drop over 12 bundles should not exceed 718 kPa at the reference condition (mass flow of 23.9 kg/s and density of 781 kg/m^3) for the CANDU 6 reactor. The measured most probable pressure drop data were adjusted to the reference condition by a scaling equation, and a pressure drop of 644 kPa was obtained. Thus the CANFLEX bundle satisfied the pressure drop acceptance criterion set for the CANDU 6 fuel bundle.

Fuel-Bundle Strength Tests

The main objective of the fuel bundle strength test is to determine whether the bundle will withstand the normal and abnormal loads imposed during refuelling and whether the bundle can be discharged from the reactor without difficulty after being exposed to abnormal refuelling loads. The strength tests simulated normal fuel loading (the double side-stop test) and abnormal fuel loading (the single side-stop test). The amount of outer element bowing and general bundle shape distortion of the fuel bundle were determined for each test.

The strength test setup consists of a test rig, a 15 fuel-bundle string and fuelling machine side-stop simulators, as shown in Figure 3. The side-stop simulators were designed and fabricated to fit correctly into the outlet end-fitting of the rig. The fuel-bundle string of 3 test bundles and 12 filler bundles was placed in the fuel channel. The channel flow rate was adjusted to establish a specified fuel string pressure drop resulting in the desired hydraulic drag force against the side-stop. The specified pressure drop corresponded to the maximum (13.1 bundles) number of fuel bundles which reside in the axial flow region of the fuel channel during refuelling. For each of these tests, the coolant temperature and the inlet pressure were set to 120 °C and 11.2 MPa, respectively, and held for 15 minutes. After that the test bundles were unloaded and measured to obtain any dimensional changes due to the testing.

The double and single side-stop strength tests were performed successfully. The inspection and measurements of the test bundles showed that the CANFLEX bundle satisfied the acceptance test criteria as follows: the test bundles maintained their structural integrity and no significant distortions were observed. The test bundles passed through the kinked tube gage, which is used as an acceptance check for all bundles at final inspection.

Refulling Impact Test

The CANDU reactor reference refuelling scheme is an eight-bundle shift. During the normal refuelling sequence, a new bundle is accelerated a short distance by the coolant flow as it passes through the upstream liner hole region of the fuel channel. The bundle then hits the stationary bundles that are already in the channel. The objectives of the impact test are to demonstrate, with proper conservatism, that the fuel bundles can withstand this impact without significant damage. The severity of the impact increases with bundle velocity, which depends on the acceleration distance and coolant flow.

The impact test setup is shown in Figure 4. The ram shaft and sensing wire penetrate the inlet closure flange, the ram shaft is connected to a pneumatic cylinder to push the impacting bundle into the cross-flow region from an upstream rest position. One end of the sensing wire is connected to the impacting bundle, and the other end to the velocity transducer, which measures the velocity of the moving bundle. A ball indicator was also attached on the sensing wire to measure displacement of the moving bundle by taking pictures with a high-speed camera.

The impact test was performed at a temperature of 266 °C and a pressure of 10.2 MPa. The test flowrate was set to 31 kg/s to allow conservatism because of pressure-tube radial creep during the lifetime of the reactor. To provide the increased acceleration distance that is due to pressure-tube axial creep, the number of stationary bundles against the downstream shield plug were reduced from 12 to 10. Figure 5 shows the measured velocity of the moving bundle along the pressure tube. The impact velocity at the instant of collision was measured as 2.85 m/s. The velocity of the moving bundle had reached a nearly constant value after gradually being accelerated at the beginning. After the impact test, the CANFLEX fuel bundle survived the refuelling impact force, and the dimensional changes of the fuel elements and end plate profile were all within the specified requirements; visual examination showed no marks on the pressure tube as a result of the test.

Cross-Flow Test

As part of normal refuelling sequences, both new and irradiated bundles can be parked in the cross-flow region of the liner tube. The fuel bundle that is subjected to the crossflow should be capable of withstanding the consequences of the crossflow for normal periods, and should maintain its mechanical integrity.

The cross-flow test was conducted in the KAERI Hot Test Loop with a new CANFLEX test bundle and 10 filler bundles, as shown in Figure 6. The inlet cross-flow region was chosen as the test location because the fuel vibration is more severe there because of less restraint from adjacent bundles. The test was done at a flow rate of 31 kg/s, temperature of 266 °C and a pressure of 11 MPa. When the test condition was reached, a set of readings of the test parameters and rig pressure drop was recorded every 30 minutes for 4 hours.

Upon completion of the testing, the test bundle was inspected and measured. The 4-hour test showed no visible damage or unusual changes to the test bundle. The wear of the bearing pads was acceptably small and showed a maximum value of 16 μm. The average wear of the inter-element spacers was evaluated to be about 5.5% of their original thickness. The CANFLEX fuel bundle satisfied the acceptance criteria.

Endurance Fretting Test

A 3000-hour fretting-and-vibration endurance test, with 2 intervals at 500 and 1500 hours for intermediate inspections, is being performed under representative in-reactor flow, temperature and pressure conditions. This test is being done to verify that the fretting wear of the pressure tube and CANFLEX bundle is acceptably low under such conditions.

The endurance test is being performed in the KAERI Hot Test Loop. The fuel channel, liner tubes and shield plugs are equivalent to those used in the CANDU 6 design. The method of supporting the end fittings, the arrangement of the feeder pipes, and garter spring supports are similar to those used in a reactor installation. The feeder geometry represents a worst-case feeder, i.e., Channel L-5 with elbows located close to the inlet end fitting, giving poor coolant velocity distributions at the inlet to the liner annulus. During the endurance test, the mechanical vibration characteristics of the pressure tube and the fuel elements were measured by accelerometers and magnetic sensors. Two data acquisition systems were used to collect the basic thermalhydraulic parameters, and to monitor and analyze the mechanical vibration from the accelerometers and velocity probes. To inspect the pressure tube, a video-scope system and casting tool were used. Twelve new test bundles were loaded in the test rig with predetermined alignment angles, to provide the worst turbulence at the bundle junctions, and hence the worst fretting condition. Great care was taken when loading the bundles, to prevent sliding wear on the pressure-tube inner surface by using thin shim stock.

The first 500-hour endurance test was completed at the temperature of 266 °C and inlet pressure of 11.0 MPa, and flow rate of 30 kg/s. After the test, upon opening the fuel channel, the 3 inlet bundles were visually inspected; no fretting marks or evidence of fretting could be seen on any bearing pads. Visual inspection of the spacers on the outer elements also showed no apparent wear. Pressure-tube castings were taken at bearing pad planes of these fuel bundles; only a few witness marks were found. Vibration measurements showed Root Mean Square (RMS) displacement of fuel elements were generally less than 6 μm peak-to-peak.

Bundle Compatibility with CANDU 6 Fuelling Machine

Dimensional compatibility and grappling tests of 4 CANFLEX fuel bundles were done in a Wolsong CANDU 6 fuelling machine under the same operating conditions as those used for the fuelling machine pre-acceptance tests. On completion of two Cold and four Hot tests, the bundles particularly at the end plates were inspected. This was followed by inspection of the fuelling machine separator, magazine fuel-bundle stations, guide sleeve bore and ram adaptor for signs of wear or damage, caused by the CANFLEX bundles. Measurement of the bundles showed no damage or unusual marking to the bundles or fuelling machine. The grappling test of the CANFLEX bundles showed that the CANDU 6 grappling tool satisfactorily engaged on the bundle end plate. These tests confirmed the dimensional compatibility of CANFLEX bundles with the fuelling machines, fuel channels and with the grappling tool.

CONCLUSIONS

Several kinds of out-reactor tests were performed under representative in-reactor conditions to demonstrate the hydraulic performance and mechanical integrity of the CANFLEX fuel-bundle design. The hydraulic performance of the bundle was verified in the fuel-string pressure drop test and the mechanical integrity of the bundle was demonstrated in the bundle strength, refuelling impact, and cross-flow tests. Although the 3000-hour endurance testing is on-going, it is expected from the 500-hour test results that the CANFLEX fuel bundle will show acceptably low to no fretting at the completion of the testing. In addition to these tests, the compatibility of the bundle design with a CANDU 6 fuelling machine was demonstrated. These out-reactor tests are part of the qualification program to verify the mechanical and hydraulic performance of the CANFLEX bundle prior to the irradiation demonstration of the bundle design in a CANDU 6 reactor.

REFERENCES

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3. Chung, M.K. et al., “Operation of the Hot loop Facilities”, KAERI/MR-268/95, Korea Atomic Energy Research Institute, 1996 January.

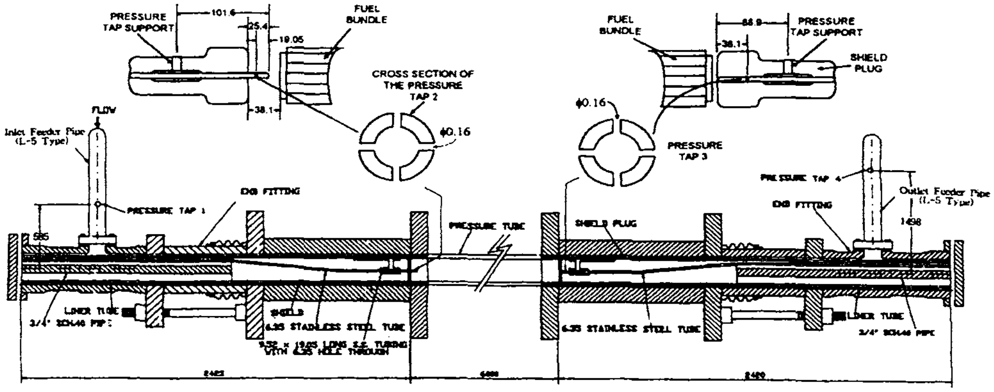

Figure1. Schematic of the Test Rig and Pressure Tap Locations

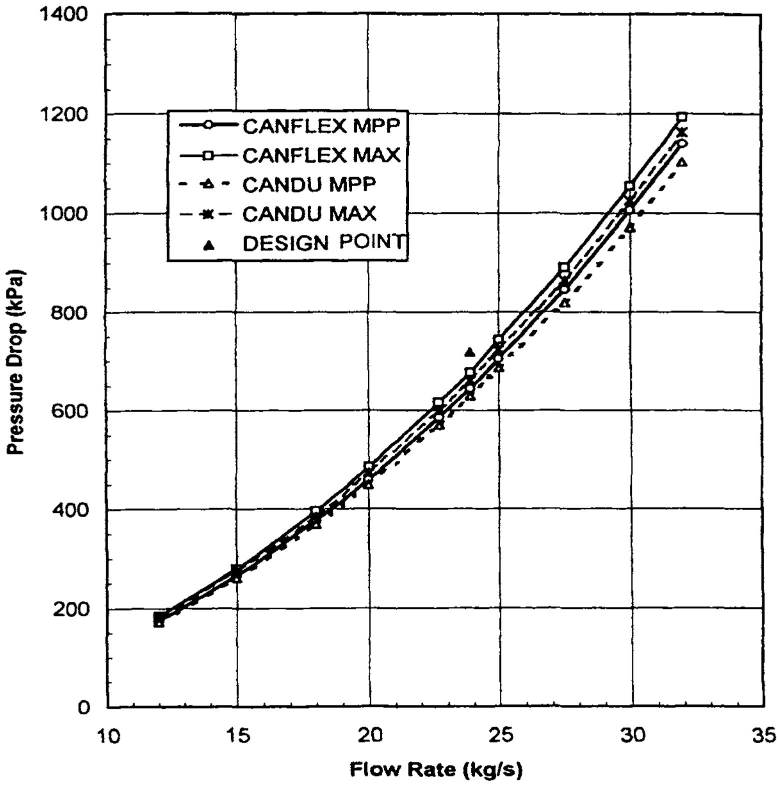

Figure 2. Pressure Loss of the CANFLEX and 37-element Fuel Bundle Strings

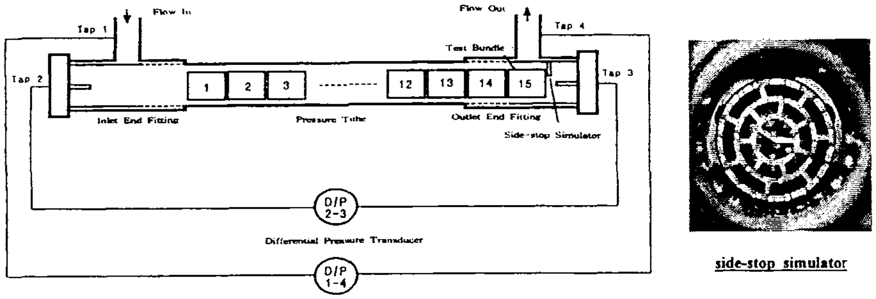

Figure 3. Bundle Strength Test Setup

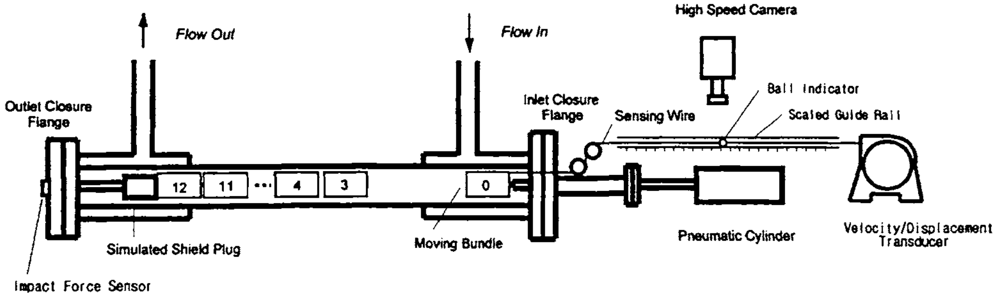

Figure 4. Schematic of the Impact Test Setup

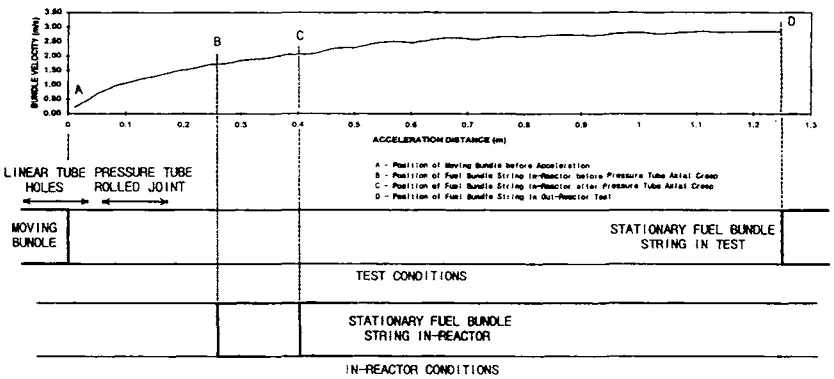

Figure 5. Moving Bundle Velocity Measured by Transducer

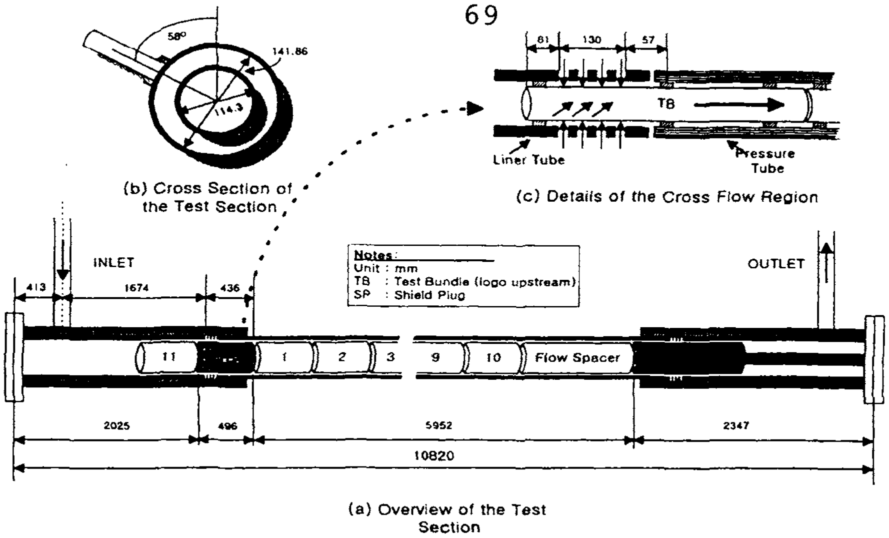

Figure 6. Cross-Flow Endurance Test Setup