Bruce CANFLEX-LVRF Fuel Qualification

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ABSTRACT

A low void reactivity fuel (LVRF) bundle has been developed to reduce void reactivity during a postulated accident, such as a large break loss-of-coolant accident. The LVRF bundles are intended for use in the Bruce Nuclear Generating Station (NGS) B reactors.

The verification activities include tests, analyses and assessments, or a combination of these, enveloping permitted operational and design configurations. Credible fuel damage mechanisms or key performance parameters are systematically evaluated individually and in combination, as appropriate.

This paper describes the detailed implementation of qualification activities demonstrating the mechanical integrity of the LVRF design, including irradiation performance, out-reactor tests and analytical assessments.

1. INTRODUCTION

A low void reactivity fuel (LVRF) bundle has been developed to reduce the coolant void reactivity during a postulated accident, such as a large break loss-of-coolant accident, compared to the current 37-element bundle design. The LVRF bundles are intended for use in the Bruce Nuclear Generating Station (NGS) B reactors following completion of the qualification activities.

The LVRF bundle design is based on the CANFLEX® Mark IV natural uranium (NU) bundle design [1] that has been previously qualified for use in

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CANDU® 6 reactors and that has undergone a successful demonstration irradiation (DI) at Point Lepreau NGS. The LVRF bundle has dysprosium (Dy) in the centre element to reduce the coolant void reactivity, and contains slightly enriched uranium (SEU) in other elements to compensate for the reactivity loss due to the use of poison. Where appropriate, therefore, the qualification results (e.g., irradiation test results) for CANFLEX Mark IV bundles are used in the qualification of the LVRF bundle for use in the Bruce NGS B reactors. As a result, the actual LVRF qualification activities address the unique design characteristics of the LVRF bundle and demonstrate compliance with the Bruce NGS B fuel design requirements.

A design verification plan (DVP) has been prepared to specify the qualification activities and methods that are required to qualify the Bruce B LVRF bundle. Subsequently, various activities have been performed according to the DVP.

This paper describes the detailed implementation of qualification activities, with highlights of results for irradiation performance, some out-reactor tests and analytical assessments.

2. LOW VOID REACTIVITY FUEL BUNDLE DESIGN

The 43-element CANFLEX Mark IV fuel bundle design forms the basis for the LVRF bundle design for the Bruce NGS B reactor. Compared to the CANFLEX Mark IV NU fuel bundle design for use in CANDU 6 reactors, the LVRF bundle includes the following unique design features:

- To reduce the coolant void reactivity during postulated accident scenarios, Dy is added to the centre fuel element of the LVRF bundle. The centre element contains pellets that are fabricated by blending NU and Dy.
- To compensate for the loss of reactivity due to the use of burnable poison material in the centre fuel element, SEU is used for fuel pellets in the fuel elements of the inner, intermediate and outer rings.
- The LVRF bundle end bearing pads are staggered in an arrangement that provides bridging support that is similar to the current Bruce 37-element fuel bundle.
- The bearing pad on an LVRF bundle is higher than that on the CANFLEX Mark IV NU bundle to provide increased critical heat flux

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(CHF), which occurs as a result of the fuel bundle being more centrally located within the fuel channel.

- The end caps of all fuel elements have a square profile, which is similar to that in the current Bruce 37-element fuel bundle. The flat end cap is designed to ensure interfacing compatibility between the outer fuel elements of the LVRF bundle and the Bruce NGS B fuel carriers and fuel latches during loading and unloading from the fuel channel.

3. DESIGN VERIFICATION PLAN

The fuel design requirements for Bruce B LVRF bundles were derived by considering the following 11 items: functional requirements; performance requirements; safety; applicable codes and standards; environmental conditions; inspection and testing; reliability and maintainability; interfacing systems; materials and chemistry; load, load combinations and service limit; and human factors and other design requirements or constraints. The DVP provides a detailed implementation plan, ensuring that the LVRF design reaches an acceptable level of compliance with the fuel design requirements, prior to the planned 24-bundle DI and full-scale implementation in the Bruce NGS B reactors.

The process of design qualification meets the requirements of Canadian Standards Association (CSA) Standard N286.2 [2].

The qualification activities include tests, analyses and assessments, or some combination of these.

These qualification activities are organised into three performance aspects, to provide complete insight into the qualification activities for key performance issues, including credible damage mechanisms that shall be addressed in the fuel design manual:

- Thermal integrity, to confirm that the fuel pellet and sheath will not overheat;

- Structural integrity, to confirm that the critical components of the fuel bundle will not break, nor will fuel bundle geometry lose geometric stability; and

- Compatibility with reactor systems, to ensure that critical parts fit and that they have acceptable interactions with neighbours and other interfacing systems.

When all of the corresponding qualification activities that are linked to a performance aspect are completed and accepted, the fuel bundle is considered to be acceptable for that aspect of performance.

4. COMPUTER CODES

The irradiation performance of LVRF was qualified based on previous irradiation tests for CANFLEX bundles and supplementary analysis using computer codes. The following are the main computer codes used in the qualification analysis:

- ELESTRES [3]: This code is used for element performance analysis, especially for temperature, fission-product release and sheath strain determination; it is also used to provide pre-transient information for reactor safety analysis, as well as for design assessments.

- FEAT [4]: This code is used for local temperature analysis, e.g., temperature peaking in both ends of a bundle, local temperature increases in the sheath as a result of voiding in the braze, and the temperature profile of the bearing pad surface.

- BOW [5]: This code is used to assess bundle deformation in-reactor.

The ELESTRES and FEAT codes have been improved to account for the thermal properties of Dy-doped pellets. These four codes have been qualified, or are currently under qualification to CSA Standard N-286.7 [6].

In addition to these in-house codes, the ANSYS [8] commercial code, which is used for structural analysis, is also used in the qualification analysis.

5. HIGHLIGHTS OF QUALIFICATION RESULTS

Some results for the qualification of the Bruce B LVRF bundle are highlighted below.

5.1 Irradiation Performance of LVRF Elements

A total of eight CANFLEX bundles containing SEU pellets (bundles AJJ, AJL, AJK, AJN, AJM, AKT, AKV and AKW) were irradiated in the NRU reactor as part of the CANFLEX Mark IV fuel bundle qualification. Four bundles (AJJ, AJL, AJK and AJN) were subjected to continuous operation at high power. These bundles achieved sustained maximum powers of 69 to 83 kW/m, which are significantly higher than the peak power of the LVRF elements (which is less than

60 kW/m). The outer-element discharge burnups of the irradiated CANFLEX bundles were up to 555 MWh/kgU, which also significantly exceeds the core-average discharge burnup and the design maximum bundle-average burnup of the LVRF bundle. The other four CANFLEX bundles (AJM, AKT, AKV and AKW) were subjected to power-ramp tests that have been completed in the NRU reactor. The outer elements of these bundles received power increases (e.g., about 30 kW/m) at burnups that are more severe than those expected for LVRF bundles in Bruce NGS B reactors. Therefore, these irradiations provide the basis for the qualification of the LVRF SEU elements.

Supplementary analysis using the ELESTRES code has been performed for specific cases. For the high power envelope where the maximum bundle power is 1035 kW, the maximum sheath plastic strain at the pellet midplane at end of life is less than 1%. For realistic operating cases based on refuelling simulations, the maximum sheath plastic strain at end of life is always negative (i.e. compressed).

5.2 Irradiation Performance of the Dy Element

The preliminary reactor physics assessment for LVRF showed that the central Dy/U element would operate with a relatively low peak linear power to the maximum discharge bundle burnup. The power change for the central element during refuelling is expected to be low. For SEU and NU fuel elements, these power and burnup conditions are considered to be relatively benign and are not expected to fail fuel in a systematic way. The addition of a small amount of ceramic $(U,Dy)O_2$ material is not expected to have an impact on fuel element performance.

5.3 Bundle Strength under Static Loads

As part of the core conversion project for Bruce B reactors, the reference refuelling scheme is changed from fuelling-against-flow (FAF) operation to fuelling-with-flow (FWF) operation, and the current fuel string is re-configured from a fuel-latch-supported 13-bundle string to a shield plug (F3SP)-supported 12-bundle string.

The LVRF bundle string is supported by the F3SP during normal operation and by latches during refuelling operation. In both cases, the LVRF bundle string is subjected to compressive axial loads as a result of the hydraulic drag caused by the coolant, which may cause compression and bowing of the fuel elements and bending of the end plates.

In FAF operation, the downstream ram is also used to push back the bundle string (upstream). During this process, the bundle string is likely to be compressed between the upstream and downstream rams.

For the LVRF bundle and the 37-element bundle cases, the total axial load applied by coolant drag on a fuel string is borne by the fuel elements that are in contact with the four latches.

Previous strength tests have been performed to qualify the CANFLEX Mark IV bundles for use in CANDU 6 reactors. Tests were performed with exaggerated drag loads. Here, a 12-CANFLEX-bundle string was supported on the side stops. For the LVRF bundle string, the actual drag load imposed on LVRF bundles is about half of the drag load used in the test, and the number of outer elements that are engaged with latches is more than that in the tests. As the load imposed on each contacting element is lower, element failure or significant deformation due to hydrostatic drag load is not expected in the LVRF bundle string.

The integrity of the LVRF bundle string under hydraulic drag loading was demonstrated by a comparative assessment between the current Bruce B 13 37-element bundle string under FAF operating conditions and the 12 LVRF bundle string under FWF operating conditions. Finite-element models using the ANSYS code were developed for both types of fuel bundles under hydraulic drag loading conditions.

Analysis results showed that, overall, the stresses and strains for the LVRF bundles are less than those for the current Bruce B 37-element bundles. That is, the maximum equivalent stresses in sheaths and endplate welds of the LVRF bundle were 65% and 82%, respectively, of those for the existing 37-element bundle. The maximum equivalent stress in the endplate welds for the LVRF bundle was 73% of that for the existing 37-element bundle.

For the shield plug support case, we compared the strength of the 12 LVRF bundle string with that of the 12 37-element bundle string under FWF operating conditions, since the 13 37-element bundle string is not supported by a shield plug but by latches even during normal operation. The LVRF bundles showed lower stress levels than the Bruce B 37-element bundles. The maximum stresses in the sheaths, end plates and welds of the LVRF bundle were 74% to 92% of those in the 37-element bundle.

Based on the previous test results for CANFLEX bundles and that the stress and strain are determined to be lower in the LVRF bundle than in the 37-element bundle, it is concluded that the LVRF bundle is less susceptible to potential fuel failure than the 37-element bundle under the influence of hydraulic drag loads. Since there has been no fuel failure of 37-element bundles as a result of hydraulic drag loads in the Bruce NGS B reactors, the LVRF bundle will not fail due to hydraulic drag loads in the Bruce NGS B reactors.

5.4 Bundle Strength under Impact

Refuelling Impact

Impact occurs when bundles are inserted into the upstream end of a fuel channel and the coolant flow causes the bundles to move into contact with the upstream end of the fuel string during FWF operation. For the same design of bundles, the impact can be quantified in terms of the velocity of a moving bundle at impact.

The CANDU 6 CANFLEX Mark IV bundles showed no deformation at an impact velocity of about 3 m/s during the refuelling qualification test. The end-fitting design in Bruce B reactors is different from that in CANDU 6 reactors, and it may affect the acceleration distance of a moving bundle, and consequently, the impact velocity. Aging also affects impact velocity via the axial growth of channels.

However, the refuelling impact tests with the CANDU 6 CANFLEX bundles were performed with an acceleration distance of more than two bundle lengths, which is significant enough to account for the change in acceleration distance in the channel that stems from the different design of the end fitting and aging.

The CANDU 6 CANFLEX test results provide the basis for assessing the integrity of the LVRF bundle under the influence of refuelling impact. No damage or significant deformation to LVRF bundles is expected during refuelling impacts in Bruce B reactors.

A supplementary analysis was performed to quantify the impact velocity of the LVRF bundle during refuelling in Bruce NGS B reactors. Under given conditions for acceleration distance and flow rate, the impact velocity was lower than the impact velocity previously measured during the CANFLEX fuel bundle impact test. The predicted impact velocity was obtained under the conservative assumptions (e.g., maximum pressure drop, maximum flow rate and conservative value of dynamic friction coefficient).

Therefore, LVRF fuel bundles are expected to withstand refuelling impacts without undergoing significant distortion under the current life conditions of the Bruce NGS B reactor.

Start-Up Impact

Following a fuel channel inspection, fuel bundles are loaded off-power and are positioned so that the fuel string is about one inch from the downstream shield plug. When the heat transport system pump starts up, the coolant flow rate increases to its maximum value over a few seconds. During this run-up, the fuel string will slide back towards the shield plug, resulting in a low-speed impact.

Tests have been done in the past to investigate the impulse strength of a thirteen 37-element bundle string under such impact conditions at the full coolant flow rate. The test results revealed no fuel damage or significant deformation at the allowable impact velocity. The LVRF bundle impacts during pump restarts were estimated to be less severe than those previously tested, because of lower flow during the fuel string travel time and contact of 42 elements of the 43-element LVRF bundle with the downstream shield plug.

Based on the above prediction and the results of the previous Bruce tests, the LVRF bundle is expected to withstand impacts against the shield plug without significant damage.

5.5 Sliding Wear

During refuelling operation, fuel bundles are moved from one axial position of a fuel channel to another position in a fuel channel. The axial movement (i.e., sliding) of the fuel bundles causes bearing pad and pressure tube wear.

A sliding wear assessment was conducted to confirm that the pressure tube and bearing pad wear of LVRF bundles are comparable to or less than those of the 37-element Bruce fuel bundles. The assessment methodology was established based on measurements taken in previous out-reactor tests.

Mixed four- and eight-bundle-shift refuelling schemes (i.e., an eight-bundle shift in the outer channels and a four-bundle shift in the inner channels), four-bundle-shift refuelling schemes in all channels and different fuel position dwell times were considered in the assessment. The assessment results are summarised below.

The maximum pressure tube wear depth based on a 30-year lifetime was significantly less than the pressure tube allowance.

The maximum bearing pad wear was significantly less than the bearing pad wear allowance.

The predicted values are comparable to measured values of pressure tube and bearing pad wear for Bruce 37-element fuel bundles; they are also less than the sliding wear allowances.

5.6 Frequency Sweep and Mechanical Endurance

Many mechanical endurance test results with 37-element bundles and CANFLEX Mark IV bundles are available. Along with the results of the previous endurance tests, another endurance test was also needed to show acceptable fretting of the LVRF bundle with its different bearing pad configuration (staggered and tall bearing pads). The test approach for LVRF was to perform a short-term (500 h) endurance test. Previous test results showed that the maximum fretting rate occurred early on in the test.

Flat face shield plugs would dampen the axial vibration of fuel elements caused by pressure pulsations. Nevertheless, pressure pulsation is considered to be a potential bundle damage mechanism for Bruce NGS B reactors. Therefore, the mechanical endurance test was performed with pressure pulsation.

A “traditional” frequency sweep test, similar to that done for the Darlington long bundle/latch support program, was also performed for LVRF bundle/shield plug support prior to the endurance test.

Measurement of vibration amplitudes during variable temperature and frequency sweep (with and without pulsations) revealed that mechanical resonance of CANFLEX-LVRF is similar or better than that of the existing 37-element fuel bundle. The tests show that the LVRF bundles performed as required without failure or gross geometry changes, and the bundles did not cause damage to the pressure tube beyond that of existing fuel.

5.7 Flow Visualisation

A series of flow visualisation investigative tests were performed on the LVRF bundle to confirm that the vibration performance of the bundle with the proposed staggered bearing pad configuration is comparable with that of the Bruce 37-element bundle.

No excessive vibration amplitudes of LVRF bundles were identified over a wide range of frequencies, at room temperature in simulated crept and sagged pressure tubes and over a wide range of flow rates. The displacement amplitudes of the LVRF bundle measured during the testing program were comparable to those measured for the Bruce 37-element bundle in crept and sagged fuel channels of CANDU reactors. The displacement amplitudes of LVRF bundles were within the limits of vibration in design guidelines for room-temperature flow tests. Hence, the LVRF bundle is not likely to have worse fretting behaviour in Bruce NGS B reactors than those of the 37-element fuel bundles in the Bruce reactors.

5.8 Droop

A series of measurements and calculations for the LVRF bundle were performed to determine the droop of the bundle for comparison to that of the 37-element Bruce bundle.

The gap measurements showed that the droop for the fully supported LVRF 43-element CANFLEX bundle is comparable to that of the standard 37-element Bruce bundle. The maximum droop for both bundle types is negligible.

The maximum droop for the overhang case for the LVRF bundle is comparable to that for the standard 37-element Bruce bundle.

5.9 Bent Tube Gauge Passage Tests

Bench testing at AECL's Sheridan Park laboratories has demonstrated that the LVRF bundle with tall bearing pads will pass the bent tube gauge test. This is the same gauge that was used for assessing the 37-element bundle's acceptability for Bruce fuel channel passage.

It was demonstrated that the bent tube gauge test adequately represents the Bruce fuel channel passage requirements for LVRF bundles.

5.10 Compatibility of LVRF Bundle with Bruce Fuel Channel and Fuel Handling

The CANFLEX bundle geometry was examined in both the as-manufactured and irradiated, drooped state, in comparison with the standard 37-element bundle, to assess its compatibility with the existing Bruce fuel channel and the Bruce fuel handling system. In addition, the compatibility of the LVRF bundle with the new tools designed for FWF operation was assessed.

An increase in bearing pad height leads to a bundle with a larger outside diameter. The LVRF fuel bundle with high bearing pads is acceptable with the fuel handling tools, e.g. the new fuel equipment. The latch/endcap interface for the LVRF fuel bundles is specified to be consistent with the 37-element bundle, to ensure reliable interaction with the latches. Therefore, the same latch interaction performance is expected for the LVRF bundle.

5.11 Cross Flow LVRF Bundle with Bruce Fuel Channel and Fuel

The CANFLEX-LVRF bundles in the inlet and outlet cross-flows were tested simultaneously for a period of 18 hours. The test bundles were inspected after 1 and 2 hours, and 18 hours. The test was performed at reactor conditions of temperature (265°C) and, pressure (nominal 10 MPa at inlet), and coolant chemistry, with a flow rate of 32.8 kg/s (light water, equivalent to 36.2 kg/s heavy water). The fuel carrier for the inlet and outlet cross flow test was oriented with the lip in the downward position.

The following conclusions can be drawn as a result of measurements and inspections of bundles in inlet and outlet cross-flow tests:

- There were no failures of the endplate-to-endcap welds.
- There were no cracks in the endplates.
- There was no near-full-surface bearing pad wear.
- The wear per spacer pair for the outer elements of the bundles placed in the inlet cross-flow, after two hours, was within the measurement accuracy of the acceptance criterion.

- The wear per spacer pair for the outer elements of the bundles placed in the outlet cross-flow, after 18 hours, was within the measurement accuracy of the acceptance criterion, except for two element pairs. The maximum element-to-element spacing gap reduction for this bundle was 0.013 inches. The bundle was disassembled and the spacer heights and spacer wear for the elements of interest were also measured individually. The examination of the spacers shows the appearance of small notches on the top of the spacer surface. There was no full-length spacer wear (from 0.0024 to 0.0070 inches) and the fretting was limited to the small regions.
- The total wear of all spacers (measured by both calliper and Pi-tape) for the test bundle in the inlet cross-flow was slightly larger than that of the test bundle in the outlet cross-flow.
- The bundle is also qualified for cross-flow endurance given (a) FAF operation and (b) irradiation effects.

6. CONCLUSIONS

An LVRF bundle has been developed for use in the Bruce NGS B reactors. Some highlights of the qualification activities were presented, demonstrating irradiation performance, bundle integrity during refuelling and bundle characteristics (e.g., vibration motion and compatibility with interfacing systems).

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