REGULATORY REVIEW OF THE CANDU FUEL MODIFICATION PROGRAM IN CANADA

Yujun Guo

Directorate of Assessment and Analysis
Canadian Nuclear Safety Commission
Ottawa, Ontario, Canada

ABSTRACT

Aging of a CANDU nuclear power plant affects various safety margins of the plant. Margin to fuel sheath dryout is one of the safety margins that have been detrimentally affected, leading to a reduced margin to dryout with time. If no proactive actions are taken, the plant will have to de-rate its operation at an earlier time. To postpone the de-rating, the Canadian nuclear Industry has taken multi-initiatives to restore, or partially restore the safety margins that have been eroded due to plant aging. One of the initiatives is modification/re-optimization of the current fuel design, in order to improve the fuel thermalhydraulic performance, i.e., to suppress fuel sheath dryout, whereby offset partially the erosion of margin to fuel sheath dryout.

Several Canadian utilities have already proceeded with the fuel modification program and requested approval of the Canadian Nuclear Safety Commission (CNSC) to load the modified fuel into their reactors. This paper summarizes the CNSC requirements, the review processes, the current status, and the technical challenges associated with licensing review of the fuel modification in Canada.

1. INTRODUCTION

Aging of the systems, structures and components (SSCs) of a CANDU nuclear power plant (NPPs) can have many detrimental impacts on the plant safety. This is represented by degraded safety margins of the SSCs, increased probability of common cause failures, and synergistic/cumulative reduction of safety margins for some design basis accidents (DBAs). These detrimental aging impacts pose major challenges to operation of the CANDU nuclear power plant and, particularly, to maintenance of various safety margins that have been eroded due to aging of the plant SSCs.

Margin to fuel sheath dryout[1] is one of the margins that are detrimentally affected by plant HTS aging. The Canadian nuclear industry has identified three major aging mechanisms responsible for the reduction of margin to dryout [1].

[1] Dryout is a heat transfer phenomenon. Under normal operating conditions, fuel sheath remains wet, and heat transfer from fuel to coolant is high. As a result, fuel sheath temperatures are low. However, under certain accident conditions such as abnormally high channel powers, fuel sheath will no longer be maintained wet, and the fuel will be cooled primarily by a vapour layer next to the fuel. This heat transfer phenomenon is called (fuel sheath) dryout. Because of significantly low heat transfer coefficient of vapour compared to liquid, the fuel sheath temperatures will be much higher. The sheath temperature increase may initiate thermally activated mechanisms that will degrade fuel bundle performance. As many regulatory authorities do, the Canadian Nuclear Safety Commission requires that dryout be prevented during normal operation, anticipated operational occurrences and some of the design basis accidents.

- Pressure tube diametral creeping, which results in an increase in flow bypass between the pressure tube and fuel bundles in the pressure tube, thus a decrease in cooling effectiveness to the fuel bundles. This leads to fuel sheath dryout at much reduced bundle powers.
- Fouling on and plugging of tubes of steam generators (SGs) and heat exchangers (HXs), which reduces heat transfer effectiveness of the SGs and HXs, leading to creeping up of reactor inlet temperatures.
- Flow accelerated corrosion (FAC) and magnetite deposition, which results in changes of hydraulic characteristics such as flow reduction/redistribution in pipes and tubes in the HTS.

All these aging mechanisms contribute to the erosion of effective margin to fuel-sheath dryout. Concerned with the continuous reduction in margin to dryout (and other safety margins) due to plant aging, the Canadian Nuclear Safety Commission (CNSC) requires that all utilities have adequate programs in place to maintain plant safety for long-term operation. If no proactive actions are taken, the CANDU NPPs will have to de-rate their operations at earlier times.

To defer de-rating, the Canadian nuclear Industry has taken multi-initiatives to restore, or partially restore the safety margins that have been eroded due to plant aging. Three major initiatives being taken include

(1) improving analysis methodology to demonstrate larger margins to the current shut-down system (SDS) effectiveness criteria (e.g., prevention of fuel sheath dryout),
(2) revisiting the SDS effectiveness criteria by demonstrating that they are overly conservative,
(3) modifying/re-optimizing the fuel design to increase the margins to dryout, and
(4) changing operating conditions and/or procedures.

Among these initiatives, modification/re-optimization of the fuel makes physical improvement to the fuel thermalhydraulic performance, whereby, offsetting partially the erosion of margin to fuel-sheath dryout.

2. MODIFICATION TO CURRENT FUEL BUNDLE DESIGN AND ASSOCIATED QUALIFICATION ACTIVITIES

2.1. Current 37-Element Fuel Bundle Design

Majority of the NPPs in Canada operate with 37-element bundle fuel bundles (Figure 1). The bundle is about 0.5 m long and 0.1 m in diameter. The 37 fuel elements are arranged in four rings, with 1, 6, 12, and 18 elements in the centre-, inner, intermediate- and outer-ring, respectively. Natural uranium (UO_2) pellets are stacked in the elements of each ring. Geometrical configuration such as ring pitch-circle diameters of the bundle was determined ~30 years ago when the bundle was designed, to yield better thermalhydraulic performance. Twelve or thirteen such bundles are fed in each of the fuel channels in the core, as illustrated in Figure 2.

2.2. Modification to the Current 37-Element Fuel Design

Modification to the current fuel design (Reference design, or 37R) was inspired by observation of the experimental data of dryout powers[2] obtained with a full-scale simulator mimicking a string of twelve 37R fuel bundles [2]. The dryout power data clearly showed that, at majority of the test conditions, initial dryout was detected among a few sub-channels of the string and the dryout did not spread to other sub-channels at low overpowers[3]. This observation indicated that these sub-channels are the limiting ones for the 37R fuel design. Therefore, a modification to the 37R design was proposed by the Industry to increase the flow areas of these limiting sub-channels, whereby, to suppress fuel sheath dryout.

[2] Dryout power is the maximum fuel string power at which initial dryout occurred anywhere in the string.
[3] Overpower is the ratio of bundle string power to dryout power of the string, representing the extent to which dryout power has been exceeded.

The modification is essentially a re-optimization of the fuel design. The objective of the design modification was to produce a fuel bundle design (modified 37-element, or 37M) with improved dryout powers compared to the 37R fuel bundle design. To minimize the impact of this modification on other aspects and to minimize the licensing review complexity, the modification was made to internal fuel arrangement only, and the fuel bundle external configuration interfacing with pressure tubes was retained. The fuel composite also remained unchanged. Therefore, this modification was considered incremental.

Subsequent to the proposed design modification, a full matrix of dryout power tests was conducted with a full-scale bundle simulator of the 37M fuel, in order to quantify the improvement of dryout power of the fuel [3]. Figure 3 illustrates the test result.

2.3. **Qualification of the 37M Fuel**

Two utilities in Canada, Ontario Power Generation (OPG) and Bruce Power, have proceeded with the design modification. Notwithstanding the incremental change of the 37M fuel, as compared to the 37R fuel, both OPG and Bruce Power took various fuel design qualification activities in order to systematically qualify and assess the 37M fuel. These activities include, but are not limited to, the followings.

(1) A series of out-of-core thermal-mechanical testing including acoustic testing, endurance testing, cross-flow testing, wash-in and wash-out testing, pressure drop testing, and interlocking testing;
(2) A full matrix of dryout power testing, as mentioned previously;
(3) Supplemental assessments/analyses for other areas where testing is not warranted;
(4) Assessment of bundle manufacturing and transportation;
(5) Fuel demonstration irradiation (DI) in limited fuel channels before a full-core loading;
(6) Safety analyses and assessments for DI, transition core and full-core loading for normal operation, anticipated operational occurrences (AOOs) and postulated design basis accidents (DBAs);
(7) Assessment of impact on station operation.

The objectives of the fuel design qualification/assessment activities were to

(1) confirm that the 37M fuel design has similar or superior thermal-mechanical characteristics as compared to the 37R fuel;
(2) demonstrate that, for DBAs, the impact of use of the 37M fuel on plant safety consequences is nil or acceptable; and
(3) quantify the increases in safety margin for transition and full core implementation.

3. REGULATORY REVIEW OF FUEL DESIGN AND MODIFICATION

3.1. Regulatory Requirements

The CNSC has set clear requirements and expectations on fuel designs. The applicable requirements and expectations are given in the following documents.

- RD-337, *Design of New Nuclear Power Plants,* Canadian Nuclear Safety Commission, November 2008 [4].
- RD/GD-369, *Licence Application Guide: Licence to Construct a Nuclear Power Plant*, Canadian Nuclear Safety Commission, August 2011 [5].
- NS-G-1.12, *Design of the Reactor Core for Nuclear Power Plants,* IAEA Safety Standards, 2005 [6].

Although these documents are established for new nuclear power plants, they equally apply to modifications to the SSCs including fuels of the existing power plants. While details can be found in these documents, examples of the regulatory requirements and expectations pertinent to the fuel design modification are as follows:

"Fuel assemblies and the associated components are designed to withstand the anticipated irradiation and environmental conditions in the reactor core, and all processes of deterioration that can occur in normal operation and AOOs."

"Fuel design limits are established to include, as a minimum, limits on fuel power or temperature, limits on fuel burn-up, and limits on the leakage of fission products in the reactor cooling system. The design limits reflect the importance of preserving the cladding and fuel matrix, as these are the first barriers to fission product release."

"The design accounts for all known degradation mechanisms, with allowance being made for uncertainties in data, calculations, and fuel fabrication."

"Fuel design and design limits reflect a verified and auditable knowledge base. The fuel is qualified for operation, either through experience with the same type of fuel in other reactors, or through a program of experimental testing and analysis, to ensure that fuel assembly requirements are met."

Meeting these requirements/expectations is assured through stipulation of Licensing Conditions (LCs) in the utilities' licenses [7]:

"*Prior to loading any fuel bundle or fuel assembly into a reactor, the licensee shall obtain written approval of the Commission, or of a person authorized by the Commission, for the use of the design of that bundle or assembly*."

An approval is granted based on a thorough review of the safety cases submitted against the criteria established by the CNSC.

3.2. Regulatory Review Criteria

In line with the above regulatory requirements and expectations, a suite of regulatory review criteria has been developed at the CNSC and documented in the Staff Review Procedures (SRPs). Review criteria under the SRP for reactor core thermalhydraulic design [8], which is one of the most relevant SRPs to review of the 37M fuel modification, are described below as an example.

The SRP for reactor core thermalhydraulic design states that reactor core and associated coolant, control, and protection systems should be designed with appropriate margin to ensure that:

a) The fuel sheath is not damaged as a result of normal operation and AOOs,
b) Fuel sheath damage in an accident is never so severe as to challenge the subsequent barrier, e.g., pressure tube in CANDU design, and
c) The number of fuel sheath failures is not underestimated for postulated accidents.

More specific review criteria, derived from the above regulatory expectations, are provided below. These derived criteria are not a substitute for the CNSC regulations, and compliance with them is not a requirement. However, any deviations of the design features, analytical techniques and procedural measures that an applicant proposed from the review criteria should be identified, evaluated, and justified on how they meet CNSC expectations.

- The core thermal-hydraulic design should demonstrate that there is at least a 95-percent probability at the 95-percent confidence level that the surface heat flux of the hot fuel element anywhere in the core does not exceed critical heat flux (CHF) during normal operation or AOOs.
- Prediction methods of CHF and related thermal margin parameters should be applicable to all normal operation and AOO conditions and be validated against appropriate experimental data covering those conditions.
- Single-and two-phase flow distributions in reactor core, including flow channels and/or subchannels and reactor vessel (if applicable), should be properly calculated.
- Where design tools, methods, and computer codes are used in the design, they should be identified, should be verified and validated using representative, reliable and qualified experimental data, and should be used within the range of validation.
- The core thermal-hydraulic design should thoroughly address uncertainties of various limiting parameters predicted.
- The core thermal-hydraulic design should address possible core power and flow oscillations and thermal-hydraulic instabilities.

3.3. Information and Data Expected in Licensee's Submissions

The SRPs also describe in details the information expected from the licensee for review. The expected information related to review of the 37M fuel modification is as follows:

- Fuel design and qualification activities including detailed design documents, experimental programs, experimental data, and assessment results in support of the design modification;
- Fuel manufacturing changes;
- DI fuel inspection results obtained in fuel bay and in hot cells;
- A suite of safety analysis results for DI, transition core and full-core implementation;
- Implementation plans including monitoring/surveillance activities during core conversion.

3.4. Regulatory Review Procedure

The SRPs also specify detailed review procedures for conducting the technical review. Following the procedures, review of the 37M fuel was conducted by a team comprising technical specialists from various disciplines relevant to the 37M fuel design [9]. The integral review objectives of the 37M fuel were to verify that

- the fuel is fully qualified, through a program of experiments and analyses, for loading into the reactors,
- dryout power and resultant safety margin improvements claimed are creditable,
- the safety analysis provides assurance that consequences of accidents are within the applicable limits and that the impact on risk, if any, is minimal, and
- adequate provisions are in place during the transition from 37R to 37M fuel core so that negative occurrences or trends in performance of fuel or interfacing systems could be detected and corrected in a timely fashion

The integral review was supported by various topical assessments covering eight topical areas [9], as listed in Table 1.

3.5. Review Results

An integrated assessment report [10] was produced for OPG and Bruce Power separately, based on the multi-discipline review of the submitted information. The assessment report concluded that

- the 37M fuel has been adequately qualified for the purpose of commencing a full-core implementation in the OPG (Darlington NGS) and Bruce Power reactors,
- introduction of the 37M fuel bundles to the reactors will not impose any adverse impact on the interfacing systems,
- the safety analysis submitted provided assurance that consequences of accidents are within the applicable limits and that the impact on risk is minimal,
- adequate provisions are in place for the transition from the current 37-element bundle core to the 37M bundle core so that any negative occurrences or trends in performance of fuel or interfacing systems would be identified and corrected in a timely fashion, and
- safety improvements of the 37M fuel, as compared to the 37R fuel, has been confirmed. Quantification of the improvements continues under regulatory review and scrutiny. Capitalization of the safety margin improvements is pending completion of the regulatory review and completion of 37R-to-37M fuel core transition.

4. IMPLEMENTATION STATUS OF THE 37M FUEL

Based on the above review results, the CNSC first granted approval of DI fuel loading into two pre-selected fuel channels in a unit of OPG's Darlington reactors. The first DI bundles were fuelled in 2010 following the normal fuelling scheme of four-bundle shift. The last DI bundles were discharged from the DI channels in early 2012. The discharged DI bundles were then inspected in fuel bay and in hot cells.

With the positive DI fuel inspection results, the CNSC subsequently granted approval of full-core loading of the 37M fuel into OPG's Darlington reactors. The full-core loading started in mid 2012 following the normal fuelling scheme.

Bruce Power was also granted approval of full-core implementation in its Station A reactors which commenced in March 2013. Regulatory review of Bruce Power request for implementation in its Station B reactors is underway.

5. TECHNICAL CHALLENGES IN REGULATORY REVIEW

The approval of full-core loading of the 37M fuel at OPG and Bruce Power was granted in two stages: immediate commence of full-core loading of the 37M fuel, and delayed capitalization of the safety margin improvements. The delayed capitalization of the safety margin improvements is due to the challenges in review of the safety margin quantification.

The safety margin is quantified using a complex process to statistically account for variations of a large number of operational parameters such as reactor core power profiles and thermalhydraulic conditions. This process also addresses various uncertainty sources through statistic analysis. Rigorous assessment of such a complex statistic process remains challenging in the regulatory review.

Critical heat flux (CHF) correlations that are implemented in the computer codes are a key element to quantification of margin to dryout. Since these CHF correlations are empirical, and data-fitting based, scrutiny of the underlying dryout power experimental data has been one of the focal areas in the review. The dryout power data was produced in an experiment program comprising a number of series of CHF tests on full-scale CANDU fuel bundle simulations. Such CHF tests are complex, and the test results are subject to various uncertainties. The regulatory review is to assure that the test repeatability and reproducibility are demonstrated, and the residual experimental uncertainties are adequately accounted for.

6. REMARKS

Nuclear plant aging has eroded various safety margins of the plant. The Canadian regulator has required the Canadian utilities to have programs in place to ensure long-term safe operation of the plants. Modification to the current fuel design is one of the actions that the Canadian utilities have undertaken to restore or counter balance the reduction in safety margins.

The regulator has set requirements and expectations on the fuel design modification activity. Thorough regulatory reviews of the fuel design modification against the requirements and expectations ensure safety of the reactor operation.

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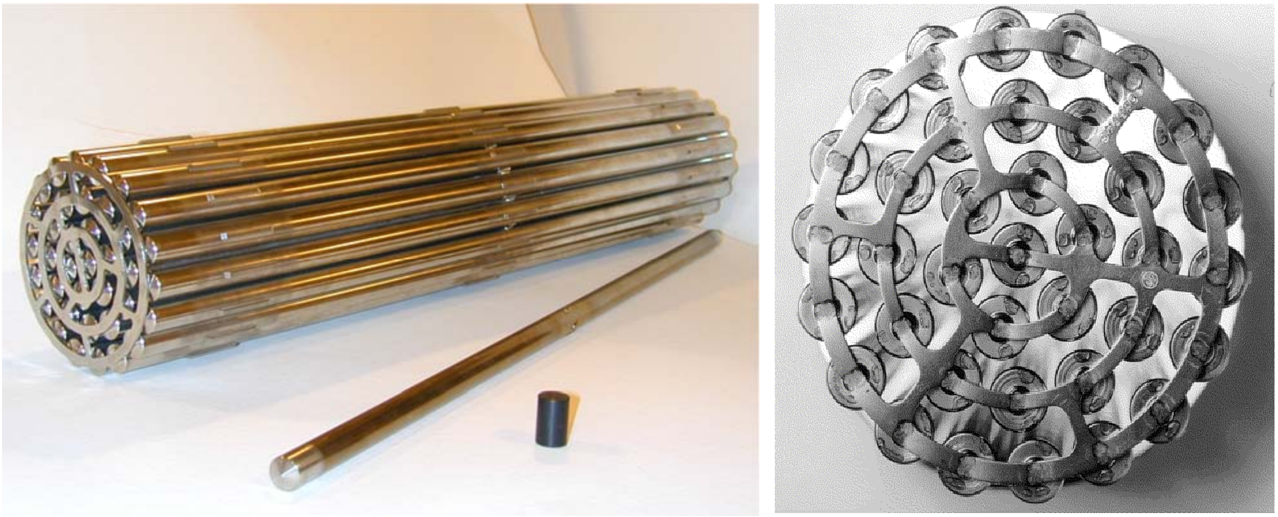

Figure 1. Current 37-Element Fuel Bundle Design

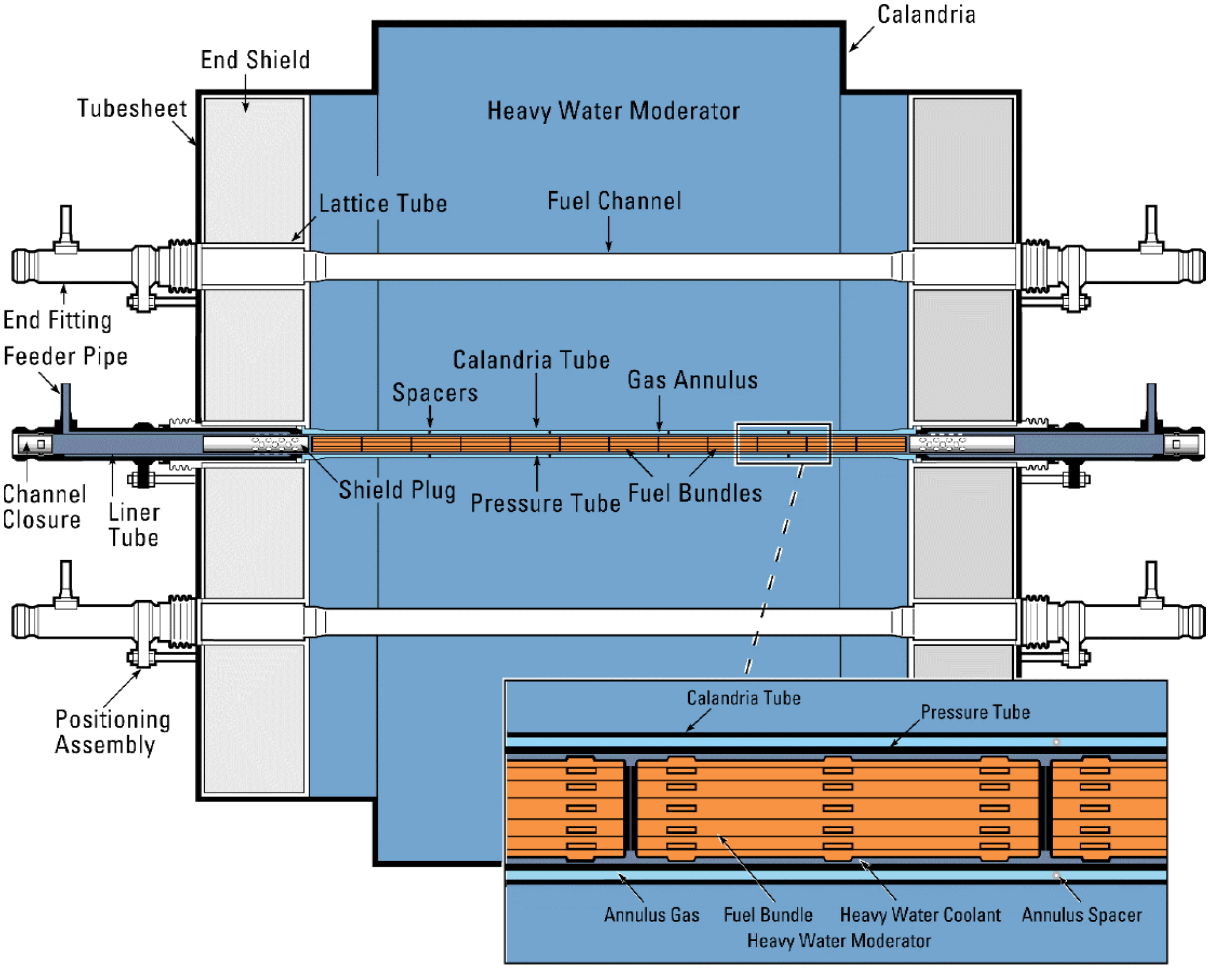

Figure 2. Illustration of CANDU Fuel Channel Arrangements

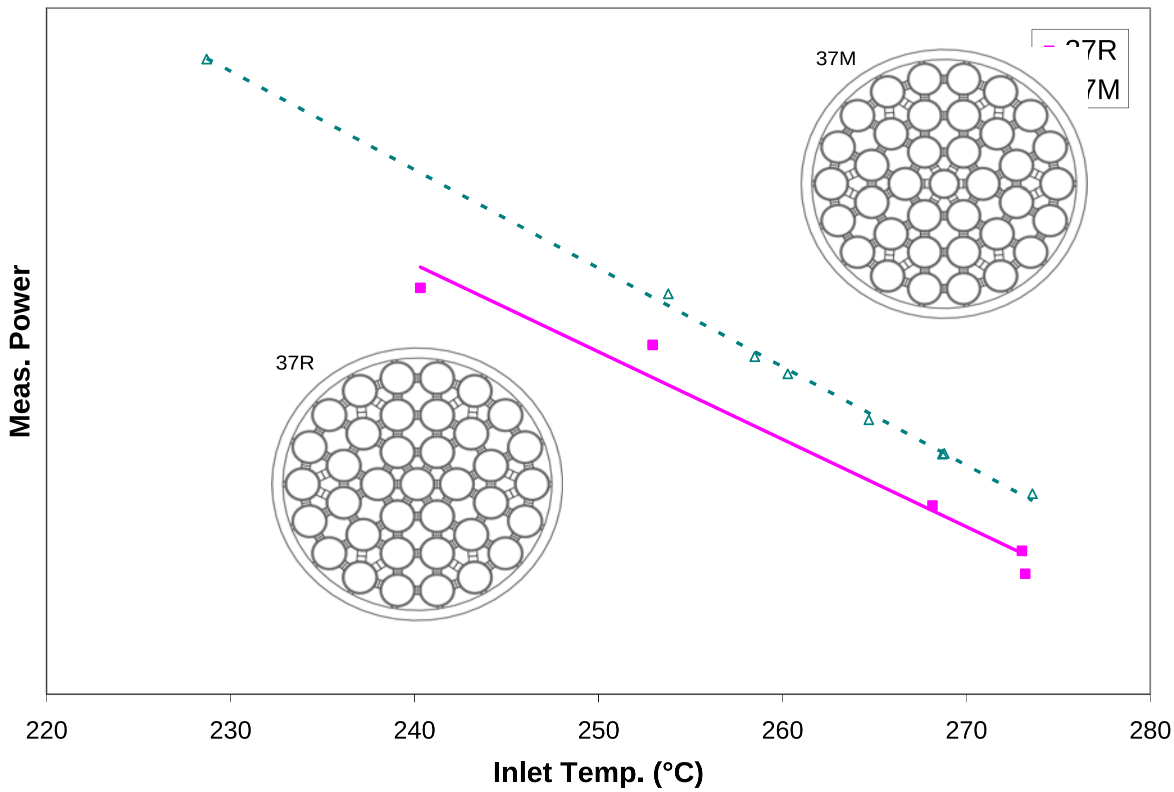

Figure 3. Illustration of the Design Modification and Associated Dryout Power Improvements

Table 1. Review of Topical Areas

Topical Review	Objective
(1) **Reactor physics**	To confirm that - reactor physics codes and data used in design assessment and safety analysis are adequate, - reactor physics assessments in support of the transition and full-core implementation of the 37M fuel are adequate, and - introduction of the 37M fuel to reactors will not result in unacceptable impacts on reactor control, fuel management or trip coverage.
(2) **Fuel thermal-hydraulics**	To confirm that - thermalhydraulic design of the modified fuel bundle is demonstrably supported by experimental evidence, - the design provides acceptable margins of safety during normal operation and AOOs considering full range of axial flux shapes, coolant conditions, and fuel channel conditions (creep) that are expected during normal operation and AOOs, and - more specifically, the pressure drop, CHF and post-dryout (PDO) heat transfer data are consistent, reliable, and adequate to support the thermalhydraulic performance.

Topical Review	Objective
(3) Fuel thermo-mechanical behaviour	To confirm that - the modified fuel bundle will not be damaged as a result of normal operation and AOOs, and the extent of fuel damage in DBAs is appropriately limited, and - there are no fuel dimensional compatibility issues with any reactor interfacing systems/components.
(4) Fuel-fuel channel interactions	To confirm that operation of this fuel will not pose an unacceptable risk to the structural integrity of fuel channels, and
(5) Verification and validation of safety analysis codes	To confirm that - the capability and credibility of computer codes for use in the 37M fuel safety analysis is demonstrated by adequate verification and validation of the code with respect to the incremental change in fuel bundle design.
(6) Safety cases	To confirm that - computer codes and correlations are used within their ranges of applicability, - implementation of the 37M fuel has no adverse impact on the reactor safety, and - there is adequate safety margin as a result of implementation of the 37M fuel bundles.
(7) Impact on known safety issues	To assess the impact of 37M fuel bundle implementation on CANDU safety issues and Generic Action Items (GAIs).
(8) Operational support	To assess - the plan to monitor, record and assess the operational parameters during the conversion of the fuel type, including back out provisions for possible negative results, and - whether the possible defects in the 37M fuel bundles will have adverse impact on key HTS SSCs.