Power Uprates Through Ultrasonic Feed Water Flow Measurement – CANDU-Specific Opportunities And Challenges

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Abstract

Ultrasonic Flow Measurement (UFM) technology is approved by the US NRC for use in PWR and BWR plants to achieve power uprates by Measurement Uncertainty Recapture (MUR). While a number of US plants have successfully increased thermal output, application to and approval for CANDU plants has not yet occurred, in part due to insufficient study of licensing issues specific to Canada and the CANDU design. This paper addresses the major technical and regulatory issues and proposes answers to 4 questions about MUR power uprates for CANDU plants: (1) What are the life-cycle issues? (2) What makes a unit a good candidate? (3) What is the typical path forward? (4) What are the benefits?

1. Introduction

In the United States, the NRC requires that LOCA safety analyses assume that reactor power is 102% of the licensed power level. The 2.0% margin is added to "allow for instrumentation error" [1]. Since 1999 (reconfirmed in 2006), the NRC has allowed utilities to "recapture" part of this margin and apply an equivalent power uprate if they could demonstrate that the measurement uncertainty of their feed water (FW) flow measurement instrumentation (used to calculate thermal power) was <2.0%. In other words, investing in a superior instrument authorizes a utility to seek from the NRC a [2.0-(instrument uncertainty)]% increase in its reactor maximum operating power. The basic principle of power uprate by "Measurement Uncertainty Recapture" (MUR), pioneered in 1994-1999 by Caldon Ultrasonics, is shown in Figure 1 below.

Cameron Measurement Systems Division-Caldon© Ultrasonics (CMSD-Caldon) offers an Ultrasonic Flow Meter (UFM) product line that has demonstrated accuracies better than ±0.28%, the Caldon LEFM (Leading Edge Flow Meter) CheckPlus™. The LEFM CheckPlus™ has been applied in the USA and Europe to PWR and BWR Nuclear Power Plants (NPP) to achieve MUR power uprates of 1.4% to 1.7%. Additionally, the system is fully redundant, has high tolerance to perturbations and operates accurately over the full reactor power range. These capabilities make this instrument particularly suitable for nuclear reactor thermal power measurement. MUR uprate project payback periods have been between 1 and 2 years.

The underlying technical and safety bases of these conclusions have been verified and confirmed in two US NRC reports [2] [3]. Furthermore, extensive study of UFM technology by Hitachi, Ltd. [4] has concluded that the Caldon© Ultrasonics LEFM CheckPlus™ UFM is currently the state-of-the-art FW flow measurement system and fully lives up to its claims of high accuracy and dependability.

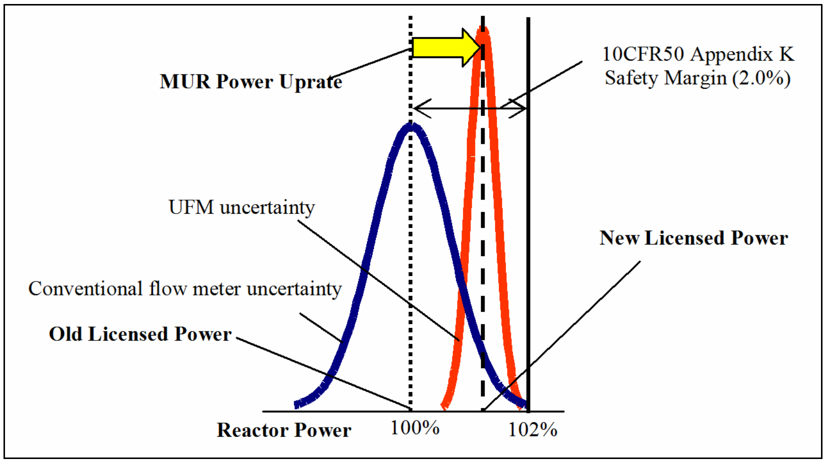

Figure 1 The MUR Power Uprate Concept as Approved by the US NRC

This paper will demonstrate that highly accurate FW flow measurement systems can be used to justify power uprate by measurement uncertainty recapture of part of the CANDU 3.0% Safety Margin. Building on the work by AECL / Hitachi [5] [6] as well as AECL / Hitachi / CMSD-Caldon [7], this paper proposes a comprehensive path forward to a successful and profitable MUR power uprate addressing the particular challenges (technological, safety, regulatory and life-cycle) inherent to CANDU using the combined analytical, engineering, instrumentation and project/construction management expertise of Atomic Energy of Canada Limited, Cameron Measurement Systems Division (Caldon© Ultrasonics), and Hitachi, Ltd. (and its subsidiaries).

2. Current Status and Experience

Prior to the approval of the MUR uprate concept, UFMs had been used in PWRs, BWRs and CANDU reactors to correct venturi biases typically ascribed to venturi fouling. Venturi fouling is the generic name given to time-varying deposition of corrosion products in the venturi throat in the area of the low pressure taps. Because these biases are positive and cause the venturi to read errantly high, operators control the plant to a lower MW output and MWs are "lost". Correction of these biases has been termed "MW recovery".

MW recovery procedures have included on-line or periodic venturi calibrations based upon permanently installed UFMs, or periodic and one-time calibrations based on measurements from temporarily installed UFMs or tracer tests. The US NRC has expressed a negative view toward one-time tests, citing the opportunity for overpower operation caused by the time-variation of the venturi fouling phenomenon, possibly resulting in undetected calibration shifts [2].

MUR uprates using a high accuracy UFM effectively perform both the MW recovery and uprate function in one step since any venturi bias is irrelevant when not used in the power determination calculation.

2.1 USA, Mexico and Europe

Since 1999, 35 plants in the US (25 PWR and 10 BWR) have received NRC approval to use Caldon LEFM UFMs for MUR uprating, thereby gaining 1533.8 MWth, the equivalent of a small reactor's output for a fraction of the cost of a new reactor.

The argument used to convince the NRC to accept the MUR power uprate concept was that the use of a more accurate device (i.e., with a narrower uncertainty distribution) would actually *increase* safety by decreasing the probability of overpower events *even at a higher operating power*. In addition, the following issues were addressed before receiving approval:

- Transferability and traceability of laboratory calibration
- On-line verification of accuracy
- Equipment reliability and failure detection
- Vendor-customer communication and user understanding of system
- Standards and methodology for combination of errors
- Actual uncertainty of nozzles vs. uncertainty values originally assumed in Appendix K of NRC regulations 10 CFR Part 50

The NRC initially approved the MUR power uprate concept in 1999. Following 21 overpower events involving *external* AMAG (Advanced Measurement & Analysis Group, Inc.) and *external* Caldon UFMs, the NRC decided to review its approval of the MUR uprate concept and the UFMs upon which it was based. In 2004 and 2006, Caldon's LEFM Check and CheckPlus™ technology (an in-line technology with sensing equipment in direct contact with the measured fluid) had its approval for MUR power uprates reaffirmed. The analyses showed that while the MUR power uprate concept was sound, the use of external UFM devices could not guarantee the accuracy required to support an MUR uprate. As of the publication date of this paper, *external*-type UFMs may not be used to obtain MUR power uprates.

2.2 Japan

Prior to 2000, the Japanese regulator had allowed utilities to generate electricity from NPPs only by the rated electric power. Since 2000, Japanese utilities have been allowed to operate their NPPs by the rated reactor power. This change to plant operation policy required the utilities to monitor and manage thermal power output with more accuracy and higher reliability.

Originally, UFM technology was applied for the recalibration of FW flow measurement instruments that have fouling issues when operating at rated electric power. In addition to this recalibration issue, Hitachi also investigated the possible future use of UFM technology for MUR power uprating and to meet the requirements of thermal power management under operation by the rated reactor power. In the late 1990s, Hitachi R&D on UFM applications to FW flow measurement in NPPs identified Caldon's technology as superior to all other UFM models then available.

Hitachi has led several other R&D efforts as well as joint studies with Japanese utilities. Hitachi conducted LEFM external performance field tests for the purpose of recalibration of FW flow nozzles. LEFM Chordal performance tests were also conducted aimed at future MUR applications based on the LEFM Chordal technology. For example, Hitachi evaluated the LEFM Chordal accuracy during the Hamaoka-5 (H-5) ABWR construction phase (specifically, 2001-2004) and confirmed a thermal power uncertainty of 0.3%. H-5 has been in service since 2004 with an LEFM Chordal permanently installed on the FW lines collecting field data in actual operating conditions. Currently in Japan, LEFM Chordal systems are permanently installed and working at the H-5 ABWR and 3 PWRs; in addition, Hitachi is planning to install the LEFM Chordal system at 3 other units.

In 2005-2007, the Atomic Energy Society of Japan (AESJ) established a working group, in cooperation with the Japanese nuclear regulatory board, to develop the Power Uprate Roadmap for Japanese NPPs, including application of the MUR concept. This working group has made a performance assessment of several UFMs for MUR applications, and they have confirmed LEFM Chordal's superiority to the other UFM technologies [8].

The MUR uprate concept has not yet been approved in Japan.

3. Typical MUR Implementation Schedule

Extensive experience by CMSD-Caldon and Hitachi, Ltd. has demonstrated a consistent project timeline for MUR power uprate implementation using Caldon UFMs in PWR, BWR and ABWR NPPs. Figure 2 shows the typical MUR implementation schedule for an LEFM CheckPlus™ (✓+) system based on experience in the US and Europe.

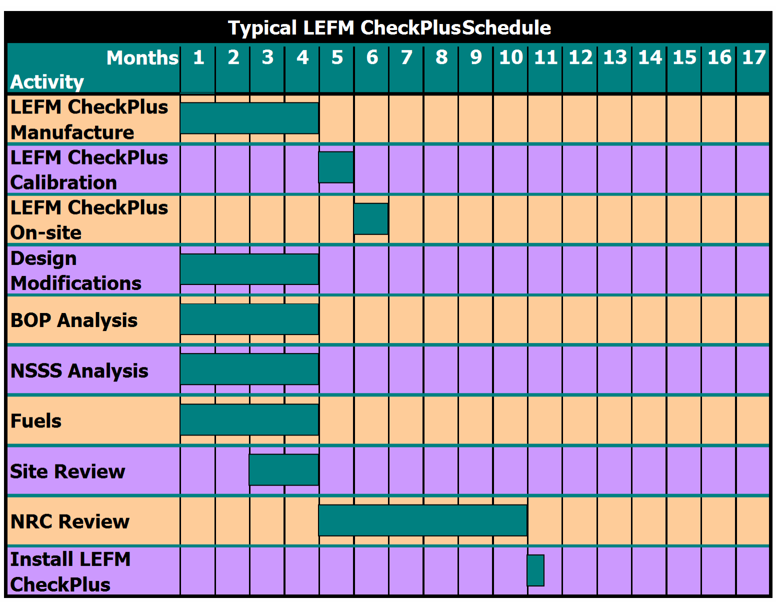

Figure 2 Typical MUR Implementation Schedule per Current CMSD-Caldon Experience

As described in the previous section, the Japanese utilities are still in a pre-MUR implementation stage (pending the METI final report on MUR power uprates), but the MUR implementation schedule would be generally similar to those so far experienced by CMSD-Caldon in the USA and Europe.

Typical MUR uprates are completed within one year of project kick-off. Together with the short payback period, the time from investment to payoff is typically less than 2 years.

3.1 Dealing with the Existing Venturis and Any Other UFM System

In principle, the installation of a high accuracy FW UFM makes any other FW flow instrument redundant and unnecessary. In practice, the additional cost of removing existing instruments coupled with the reluctance to remove a "tried and true" solution means that 2 (or more) FW flow meters may be operating simultaneously. While only one signal is needed for reactor thermal power control and one for process control (e.g., Steam Generator Level Control), the existence of 2 independent sources of raw data may involve some changes in operating procedures and plant operator interface screens and controls. Typically, utilities opt to use the UFM for reactor power control (and to justify a power uprate) as well as to calibrate their existing venturis, which continue to be used for process control.

In the case of an existing external UFM (e.g., AMAG Crossflow or Caldon External LEFM), utilities usually either remove the instrument (replacing it completely with the LEFM CheckPlus™) or leave it in place for reference purposes.

4. MUR Implementation for CANDU

Based upon the experiences of CMSD-Caldon and Hitachi, Ltd. (see above), a typical CANDU MUR implementation has been developed. **Note** – We are assuming the LEFM CheckPlus™ solution. Also, we assume that the typical path forward shown below would follow the client utility's meeting with the CNSC and that no impediments to proceeding would have been identified.

4.1 Expected Project Timeline – Refurbishment

Extrapolated from the experiences of CMSD-Caldon and Hitachi along with AECL's expected analysis times, the following typical project tasks specific to CANDU have been identified:

1. Kick-off meeting involving all parties including client utility (1 month)
2. LEFM CheckPlus™ manufacturing and testing (6 months)
3. LEFM CheckPlus™ on-site (1 month prior to outage)
4. Design modifications package (4 months typically required)
5. Safety analysis (review of implications)
6. CNSC review of design modifications package (6 months)
7. Installation of the instrument spool-piece (1 month)
8. Implementation of MUR Uprate (1 month)

Given the abovementioned new tasks and modifications to standard MUR implementation tasks, AECL, Hitachi and CMSD-Caldon have projected an "Expected Typical MUR Implementation Schedule for CANDU" (see Figure 3):

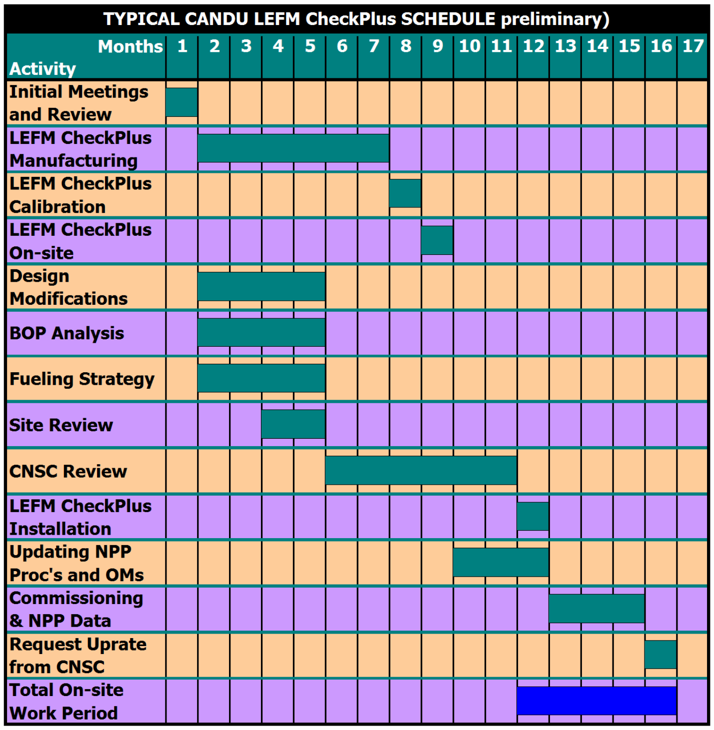

Figure 3 Expected Typical MUR Implementation Schedule for CANDU

For the first application to a CANDU reactor, the authors expect a conservative approach to MUR power uprate implementation by all parties. We anticipate that a review of post-installation monitoring data may be required before a power uprate is implemented. After the first few projects, we expect that uprate approval will be applied immediately after UFM installation and plant start-up.

4.2 Expected Project Timeline – Maintenance Outage

When installing a FW UFM during a maintenance outage rather than during a refurbishment (re-tubing) outage, any work on FW lines must respect outage heat sink requirements. For CANDU6 stations that feature two primary heat transport system loops, each cooled by two steam generators (SG), only one SG per loop may be emptied at any one time. This requirement means that the FW piping to at least one SG per loop must be operational at all times, limiting UFM spool-piece installation to only 2 FW lines at a time, thus requiring additional installation time. This restriction based on heat sink availability would not apply to installation during a refurbishment outage because the core is de-fuelled.

4.3 Expected Power Uprate

In the CANDU safety analysis, a 3.0% safety margin accounts for both uncertainty in the reactor power (as determined from secondary-side thermal power measurements used for calibration of reactor power) and for a refuelling ripple allowance of 1.0%. In this analysis, bundle powers are increased by 3.0% to account for the total reactor power uncertainty and the allowance for refuelling. The uncertainty in the secondary-side thermal power measurements includes the following components grouped into 2 main types:

A. FW flow measurement uncertainties including:
   1. Venturi calibration uncertainty
   2. Venturi calibration "drift" between recalibrations

B. Uncertainty in other boiler power components including:
   1. Exit steam enthalpy uncertainty (composed of boiler pressure measurement uncertainty, boiler pressure fluctuations and steam exit quality error)
   2. FW enthalpy uncertainty (based on FW temperature uncertainty)
   3. Reheater enthalpy uncertainty
   4. Reheater flow measurement uncertainty
   5. Primary circuit heat losses
   6. Pump heat uncertainty

One must note that FW flow measurement uncertainty dominates the uncertainty calculation.

By using the LEFM CheckPlus™ Chordal System for FW flow measurement, the thermal power measurement uncertainty can be reduced to about 0.5% (2 sigma) or less. Thus, reactor thermal power could potentially be raised by as much as 2.5% without compromising the safety margin and the licensing basis of an existing facility. Even allowing for an additional 1.0% uncertainty for power fluctuations ("ripple") during refuelling (plus all other uncertainties) against the current 3% margin, the thermal power could be increased by at least 1.5% by taking credit for the improved accuracy of the LEFM Chordal system flow measurement.

4.4 Areas Impacted

The existing venturi flow elements are installed on the 12-inch Class 6 NPS FW lines, downstream of the Level Control Valves and upstream of the Boiler Secondary Side. Installation of an LEFM involves cutting a section of the FW pipe and welding a prefabricated spool-piece on each of the FW lines. Installation is not seen as a significant obstacle, although some additional details (e.g., need for SG drainage) will require further assessment.

4.4.1 Physical Modifications and Installations

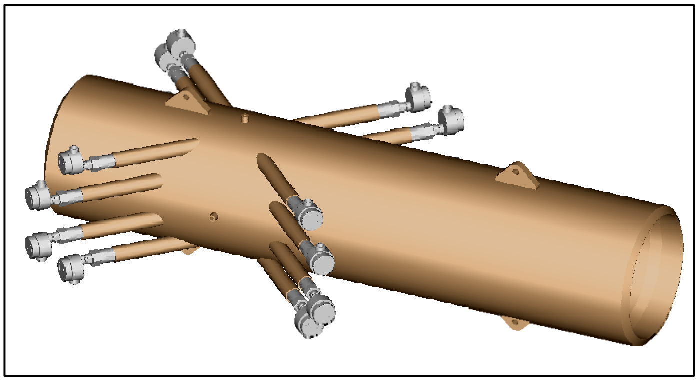

Figure 4 LEFM Spool-Piece

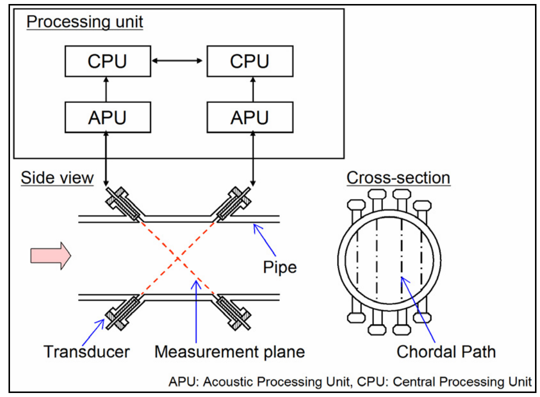

Figure 5 LEFM Control Network

- Cut out a section of FW pipe and weld the UFM spool-piece into place.
- Install the local panel for the LEFM CheckPlus™.
- Install and connect cable for Class II (EPS) Power Supply and for control interface with LEFM Acoustic Processing Unit (APU).
- Install cabling between the LEFM CheckPlus™ and the LEFM APU cabinet.

4.4.2 Instrumentation & Control and Software Impacts

Currently, 4 FW flow meters exist, one for each SG. Each of these flow meters generates a 4-20mA signal that is looped through the monitoring devices identified in Table I.

Table I – Typical Feed Water Flow Signals and Devices in CANDU6

Monitored Inputs	**FT-1**	**FT-2**	**FT-3**	**FT-4**	**Comments**
66432-DCCX	AI-2530	AI-2531	AI-2532	AI-2533	
66432-DCCY	AI-2530	AI-2531	AI-2532	AI-2533	
Flow indicator	FI-1	FI-2	FI-3	FI-4	Located in the main control room on panel 66110-PL10
FY-50	FY-50	FY-50	FY-50	FY-50	This calculates the total flow of all 4 flow meters

We assume that the existing venturi-type flow meters will not be removed and their signals will continue to be monitored. The addition of the LEFM CheckPlus™ signals will require the design of 4 new instrument loops with each of the loop monitoring devices (in the table above) replicated and included in the new loops. Panel 66110-PL10 (located in the main control room) will have to be modified to include these new flow indicators. New device tags will have to be assigned to the DCCX and DCCY computers to represent these new inputs.

Four more device tags will have to be added to the CRT display to represent the LEFM flow meters (we assume that the LEFM flow meters will be tagged F-5, F-6, F-7 and F-8):

- 64323-F-5 / F-6 / F-7 / F-8 – Boiler 3311-BO1 / 2 / 3 / 4 feed water flow

If desired, the SG level control program can be modified to accept the LEFM signals rather than the venturi signals.

Considering the parameters and limits affected by addition of LEFM to the FW lines, a programming specification (PS) document detailing the necessary software modifications would be prepared before LEFM installation. The usual QA and V&V procedures for such a software change would be in force.

4.4.3 Operating Manuals

Plant operating manuals (OMs) will require modification to address the use of new alarms, displays and controls in both normal and abnormal conditions. While important and requiring careful attention, these changes can be handled in the same manner used for all plant changes and are not seen as a significant obstacle to LEFM addition.

The OM changes will reflect the addition of a more accurate FW flow measurement and calorimetric power determination: (1) any references to 100% power will show the new 100% operating power limit, and (2) the operators will now be provided with a instrument health indication on their power calorimetric calculation.

The LEFM is designed for complete redundancy: two independent communication buses, CPUs, APUs, and power supplies insure that for any single failure, a high accuracy mass flow and temperature measurement is available for each pipe. In "Maintenance" Mode, the LEFM mass flow accuracy is better than ±0.5%, compared to the normal mode accuracy of ±0.3%, particularly in installations with multiple FW loops such as CANDU reactors. Each system is analysed to determine operational accuracy in both "Normal" and "Maintenance" modes.

The LEFM self-diagnostics, which check timing measurements, dimensions, hydraulics, and software/hardware operation, completely insure that any failure is alarmed to plant operators by way of a measurement quality status.

4.4.4 Human Factors

The LEFM CheckPlus™ was designed with special attention to human factors. Troubleshooting, diagnostics and data are all displayed on intuitive touch-screens for easy operation and interaction. Operators typically do not need to see or use these screens, however; feed water flow, temperature, and status are displayed much as they were prior to the uprate.

As with OM changes (see 4.4.3), the new LEFM equipment will require some changes to control room instrumentation in the areas of alarms, displays, and controls. These changes are not extensive and can be accommodated within existing panel space using stand-alone instrumentation or within existing display and annunciation systems. While these changes are important and require careful attention, they would be handled in the manner used today for plant changes and are not seen as a significant obstacle to adding an LEFM UFM.

4.4.5 Instrument Maintenance and Maintainability

The LEFM CheckPlus™ system essentially eliminates the maintenance burdens associated with conventional (nozzle-based) feed water flow instruments (e.g., periodic calibration, inspections and cleaning all requiring plant shut down). Unlike conventional flow instruments, the system's calibration can be confirmed on line (i.e., while the instrument is in operation). Specifically, the instrument can confirm automatically that the velocity profile in service is within the calibration basis and that uncertainty of the transit time measurements is within the expected accuracy. Additionally, the instrument can confirm that internal pipe dimensions have not changed beyond the design basis.

All UFM maintenance can be performed while the instrument is installed and operating. Mean time to repair any component is less than one shift and should not interrupt operation or affect uprate availability. Transducer life exceeds five years and degradation is readily flagged by the self-diagnostics. Should a transducer require replacement (a failure which is automatically annunciated) that transducer can be replaced while the system continues to operate. Finally (see 4.4.3 above), the system is designed for complete redundancy.

4.5 Licensing Issues

At the time of writing, an exploratory meeting with the CNSC had not been scheduled. At this first meeting, the AECL-Hitachi-Cameron team hopes to elicit some reactions from the CNSC and so guide its subsequent presentations to the CNSC and other activities. We expect that subsequent representations to the CNSC would be made by the utility with support from AECL, Hitachi and CMSD-Caldon.

5. Preliminary Business Case for Generic CANDU6 in Canada

In CANDU plants, the safety margin between the analyzed power and the operating power is 3%, which covers not only instrument uncertainties but also transient variations in the operating power level. The 3% margin requirement limits the power at which CANDU plants operate for a period of roughly 5000 Effective Full Power Days (EFPD) or about 14 years at full power. After approximately 5000 EFPD of exposure and in the absence of any mitigating action, plant operation may become limited by potential changes in pressure tube dimensions due to radiation-induced diametral creep, and power may have to be reduced to ensure fuel integrity under postulated accident scenarios. Under these conditions, the impact (on the plant's maximum operating power) of the measurement uncertainty recapture of a portion of the 3.0% safety margin is relatively minor. Thus the aggregate return of an MUR uprate on a CANDU plant will depend on the age of the pressure tubes (i.e., the time left before de-rating must be considered).

Three net present value (NPV) uprate scenarios have been considered (1.5%, 2.0% and 2.5%), since instruments other than the FW mass flow and FW temperature instruments also affect thermal power uncertainty and the allowance for transient variations might also be plant-specific. Figure 6 shows the results of this preliminary analysis:

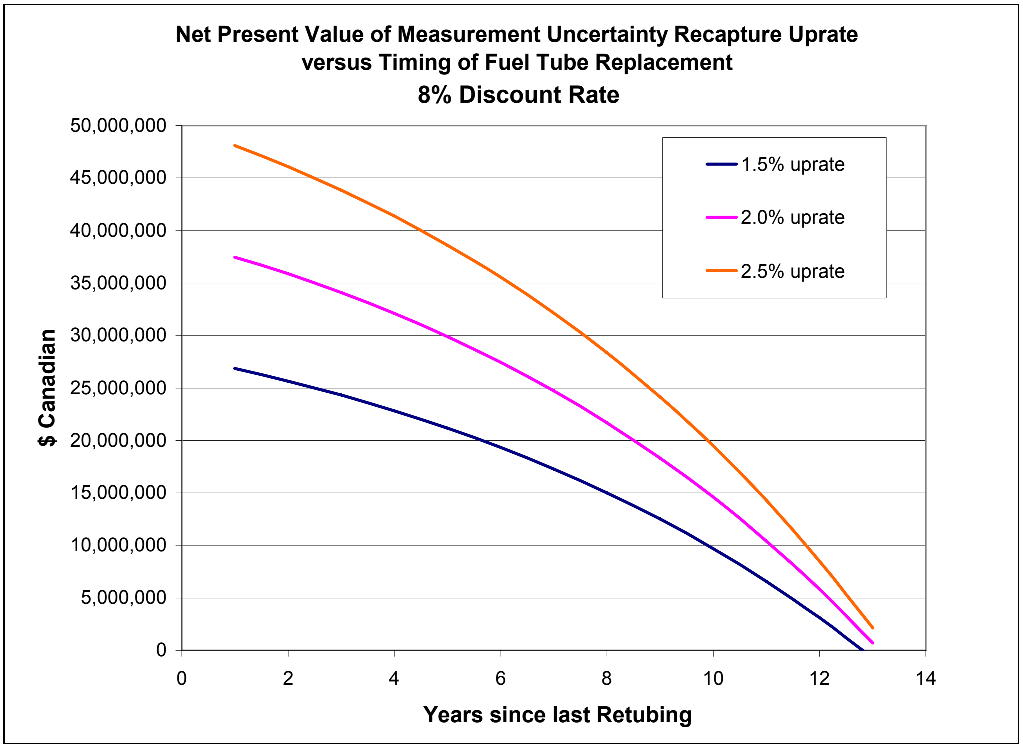

Figure 6 Preliminary and Generic CANDU6 MUR Uprate NPV vs. Time Since Last Retubing

The analysis was based on the following assumptions and considerations:

- CA$50 (net value) per MW-hr (the net value of power at the plant fence, CA$53, less a CA$3 assumed fuel cost).
- 8% discount rate.
- The total uprate project implementation costs being subtracted from the returns. These costs include the LEFM CheckPlus™ ultrasonic equipment, installation of the equipment, cabling and operating impact analyses.
- Testing of the sensitivity to project cost of the net present value of the returns. (For plausible variations the change in returns was only 1 to 2 %.)
- Estimating and including the shortening of pressure tube life due to the increased power.

The analysis demonstrates that, for plants about to perform or having just performed a pressure tube refurbishment, the CA$27-48 million return (present value) is a compelling argument for executing the project. Clearly and unsurprisingly, returns are highest if the UFM MUR uprate takes place soon after refurbishment; however, even with only 2 or 3 years until pressure tube deformation may require derating, proceeding with the project still provides a positive return.

6. Conclusion

The purpose of this paper was to demonstrate that highly accurate FW flow measurement systems can be used to justify power uprates by measurement uncertainty recapture of the CANDU 3.0% Safety Margin. By combining the knowledge, expertise and experience of Atomic Energy of Canada Limited, Hitachi, Ltd. and Cameron Measurement Systems Division (Caldon© Ultrasonics) the authors consider that they have effectively summarized all issues and challenges and presented herein a realistic and sound plan that justifies application of MUR power uprates to CANDU. While the licensing issues could not be explored with the CNSC in time for publication, the authors consider that past experience and practice in the USA backed up by the available technical and analytical arguments amply justify an optimistic view with respect to eventual licensing of uprates by MUR using highly accurate UFM technology.

7. References

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