THE INVESTIGATION OF UFM APPLICATION TO CANDU CONTROL

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Abstract

This paper assesses the feasibility of using an ultrasonic flow meter (UFM) for the feedwater measurement used in steam generator level control of CANDU plants, instead of the traditional flow meter. The UFM provides enough capabilities to replace the traditional flow meter. In addition, the UFM provides the capability to increase reactor thermal power by using the method of measurement uncertainty recapture (MUR) power uprate. Therefore, the introduction of UFM into CANDU provides two benefits at one time, cost reduction by eliminating the traditional flow meter and increased power by MUR power uprate.

Keywords:
Feedwater flow measurement, Reactor power uprate, Steam generator level control, Thermal power measurement uncertainty, Ultrasonic flow meter

1. Introduction

As the year-to-year power demand in Canada increases, nuclear energy continues to play an essential role in providing secure, stable and affordable electricity. Nuclear energy remains cost-competitive compared to other energy resources while eliminating greenhouse gas emissions. In December 2005, the Ontario Power Authority (OPA) released its report on future power needs for Ontario, entitled 'Supply Mix Advice and Recommendation' [1]. In this report, the OPA recommends that the share of nuclear in Ontario's supply mix remains the same as its current level to ensure the reliability and availability of electricity for the next 20 years. The report also suggests a variety of nuclear options: refurbishing existing units, rebuilding on existing sites and undertaking "new build" plants.

In the last decade, great progress has been achieved in developing new technologies applicable to nuclear power plants, especially in the field of computer-based instrumentation and control. An Ultrasonic Flow Meter (UFM) is one of these technologies, which enables a significantly more accurate flow measurement, compared to the traditional flow meters. In addition, the UFM has no fouling issues due to aging, thereby retaining its accuracy through the life of the plant.

Hitachi and AECL have initiated a feasibility study on UFM applications to enhance CANDU performance, focussing especially on the MUR reactor power uprate for CANDU. Hitachi has developed the UFM application technology over the last ten years in Japan and AECL has widespread CANDU technology and licensing experience. Thus, the collaboration of these two companies provides a good fit for introducing this technology into CANDU.

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The main objective in this paper is to assess the feasibility of using a UFM for the feedwater measurement used in steam generator level control as well as MUR power uprate in CANDU.

2. Overview of Current CANDU 6 Design

1) Steam generator level control

The steam generator level is affected by steam demand changes and reactor power changes. The purpose of the steam generator level control (SGLC) function is to maintain the water level at or near a specified setpoint in the steam generator against the disturbances. The SGLC has two major functions. The first is to provide control of the mass balance in the steam generator while keeping the water level within the operational limitation. The other is to provide control of the level setpoint by accounting for swell or shrinkage in the steam generator during load variations.

To realize these functions the SGLC consists of three main components; the level feedback term, the steam generator power term including the swell/shrinkage term, and the steam and feedwater flow term. The level feedback term compares a level signal with a level setpoint and sends a corrective control signal to position the feedwater control valve. The steam generator power term develops a steam generator setpoint based on neutron power with a specified time constant, since steam generator level varies according to reactor power level. The swell/shrinkage term makes a correction to the setpoint generated by the steam generator power term based on the rate of the neutron power with a specified time constant, since the swell/shrinkage in the steam generator is caused by the rate of change of the steam flow, which depends on the rate of change of reactor power. The steam and feedwater flow terms provide a correction based on the comparison between the steam flow and the feedwater flow, since they should be the same to maintain a constant mass balance in the steam generator at constant reactor power. Due to the inaccuracy of the steam and feedwater flow measurement at low reactor power, the steam and feedwater flow terms are only used when the flow is above 20% F.P. See Figure 1.

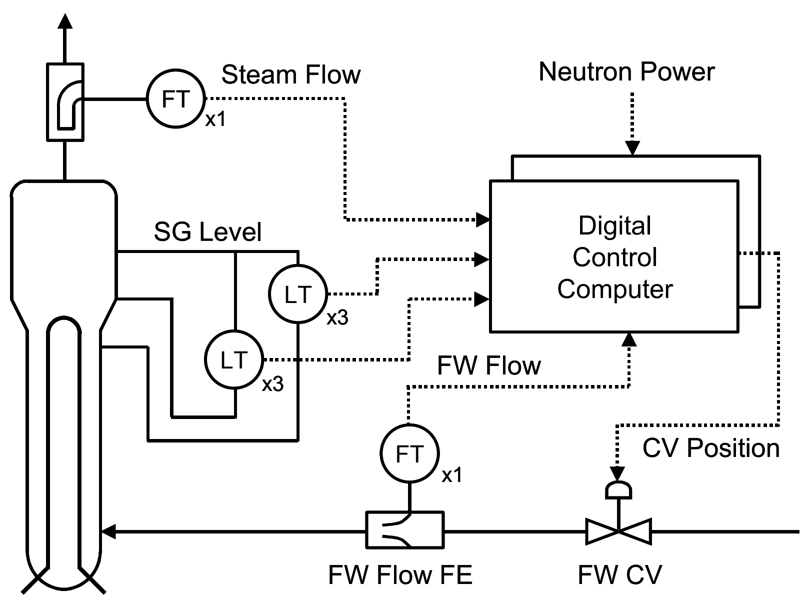

Figure 1 Typical SGLC Signal Flow

The feedwater flow is measured by a flow element located outside the rector building. The feedwater flow signals are provided to the digital control computer for the purpose of the SGLC as well as the reactor thermal power calculation, described later in this paper. The flow element itself is calibrated to within ±0.25% in accuracy or better.

Each steam generator has its own SGLC program in the digital control computer and SGLC program execution is required every 2 seconds.

2) Thermal power calculation

The reactor regulation system includes the basic functions of bulk power regulation and flux tilt control. Thermal power calculation is a part of the reactor regulation system, which is executed every 2 seconds in the digital control computer.

At lower reactor power level the RTDs, located at the reactor inlet and outlet headers, are used for thermal power determination. However, at higher powers when boiling occurs in the higher power channels and voids appear in the reactor outlet headers, the header temperature measurements by the RTDs do not provide good estimates of reactor thermal power. The reactor thermal power above 70% FP, therefore, is calculated based on the secondary side measurements only. The steam flow, the feedwater flow, and the feedwater temperature are used to calculate the reactor thermal power P_B based on the following secondary side heat balance equation:

$$P_B = W_s \cdot (h_s - h_f) + W_{FW} \cdot (h_f - h_{FW})$$

Where

W_s	:	The steam flow
W_{FW}	:	The feedwater flow
h_s	:	The steam enthalpy
h_f	:	The liquid enthalpy of H_2O at saturation condition
h_{FW}	:	The feedwater enthalpy

The feedwater flow measurement used for the thermal power calculation is carried out by the same flow element as used for the SGLC. Therefore, the uncertainty of the traditional flow element impacts on the reactor thermal power measurement uncertainty.

3. The UFM Application

1) LEFM Chordal system

The LEFM Chordal system, manufactured by Caldon Inc., is an intrusive UFM system that uses the transit-time measurement principle. The LEFM Chordal system uses eight pairs of transducers embedded in a Spool Piece Metering Section (SPMS) per one flow measurement. A pair of transducers forms one chordal path and measures a time difference for an ultrasonic pulse to travel upstream versus downstream, which is proportional to a local flow velocity along the chordal path. Using four pairs of transducers, which chordal paths form one measurement plane in the SPMS, a mass flow rate is calculated based on the four local velocities. Using the remaining four pairs of transducers in the same SPMS, which chordal paths form the other measurement plane, another mass flow rate is calculated based on the four local velocities measured by the these four pairs of transducers. The LEFM Chordal system averages these two mass flow rates calculated on the two measurement planes in the SPMS, and finally obtains a mass flow rate based on the eight chordal paths, which is insensitive to hydraulic disturbances like cross flows or swirls [2].

The mass flow rate calculation described above is executed in a processing unit of the LEFM Chordal system. See Figure 2. The processing unit has two redundant Central Processing Units (CPUs) and 2n Acoustic Processing Units (APUs) when applied to n-loop flow line configuration. An APU controls four pairs of transducers on the same measurement plane in a SPMS and calculates a mass flow rate based on the four local velocities along the four chordal paths. Thus, two APUs associated with the SPMS are employed to obtain a mass flow rate based on the eight chordal paths.

The mass flow rate calculation (eight-chordal-based) is designed to employ the two redundant CPUs, so that it enhances the reliability of the LEFM Chordal system. At first, one CPU collects a mass flow rate (four-chordal-based) from one of two APUs associated with a SPMS. At the same time, the other CPU collects a mass flow rate (four-chordal-based) from the other APU associated with the same SPMS. Then, the two CPUs communicate their complementary data to each other by the inter-connecting network between them. Finally, each CPU calculates a mass flow rate (eight-chordal-based) using the mass flow rates (four-chordal-based) at the same time.

The whole process of calculating a mass flow rate in the LEFM Chordal system is executed within 50ms, which includes the APU execution, the CPU execution, the data communication, etc.

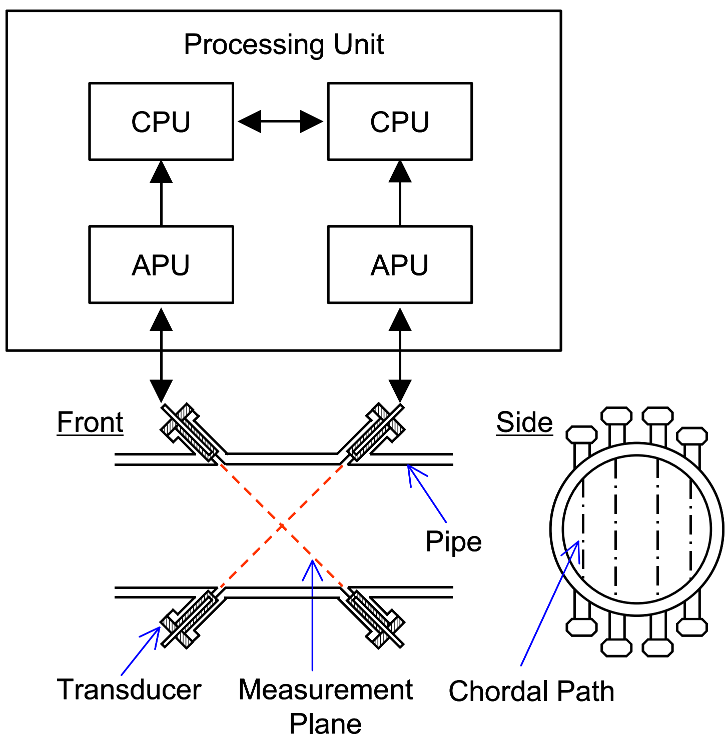

Figure 2 Conceptual Data Processing in the LEFM Chordal System

Due to the fact that the LEFM Chordal system has the features of intrusive mounting, transit-time with multi chordal path, and data processing described above, it provides higher accuracy and reliability in the feedwater flow measurement, compared to the external type UFMs. Table-1 shows the typical features of a LEFM Chordal system applied for feedwater flow measurement. The feedwater flow measurement uncertainty can be as low as ±0.28%, which represents all the uncertainty factors, including the UFM device itself, so that the thermal power measurement uncertainty can be as low as ±0.30%.

Table-1: LEFM Chordal system features for FW flow measurement application

Items	Description
Conditions	
- Nominal pipe size (diameter)	30.48 to 91.44 cm (12 to 36 inches)
- FW flow pressure uncertainty	0.103 MPa (15 psi or less)
- FW temperature limitation	Max 240.5 °C (465°F)
Performances	
- FW flow range	0 to 100%
- FW flow measurement uncertainty	±0.28%
- Thermal power measurement uncertainty	±0.30%
- Temperature uncertainty	±0.28 °C (±0.5 °F)

2) Application to SGLC and thermal power calculation

A typical CANDU 6 with four steam generators is assumed in the following discussion. In addition, a distributed control system (DCS) used for data acquisition and control functions is assumed. DCS control functions are divided into a number of independent partitions through a probabilistic safety analysis, so that the resultant partitioning prevents functions in one partition from being affected by failures in another partition. All partition stations use dual-redundant controllers. According to a preliminary study, five control partitions are identified, in which the SGLC in steam and feedwater partition and thermal power calculation in reactor partition are independently implemented in the DCS [3].

The LEFM Chordal system with eight APUs and two CPUs in the processing unit is proposed for the four-loop feedwater flow line configuration. Having a dual transmitter for the steam flow meter, the proposed system provides the fully redundant configuration in terms of the SGLC. See Figure 3. A mass flow rate (four-chordal-based) calculated at an APU is used as an input signal to SGLC and a mass flow rate (eight-chordal-based) calculated at a CPU is used as an input signal to thermal power calculation. See Figure 4. For example, APU-A1 calculates a mass flow rate at feedwater line A by the four pairs of transducers on the one measurement plane in SPMS-A, and it sends the mass flow rate to a dual-redundant controller used for the steam and feedwater partition and CPU-1. At the same time, APU-A2 calculates a mass flow rate at feedwater line A by the other four pairs of transducers on the other measurement plane in SPMS-A, and it sends the mass flow rate to the dual-redundant controller and CPU-2.

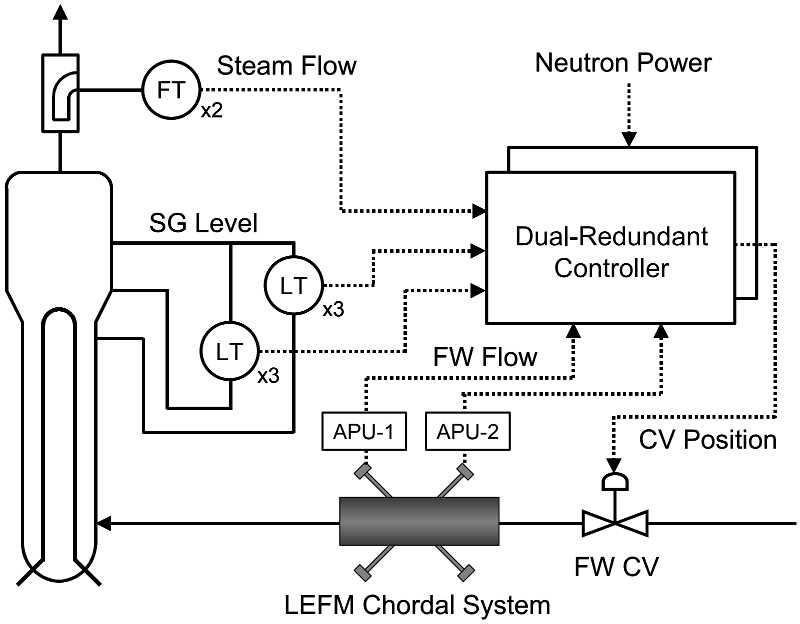

Figure 3 LEFM Chordal System Application to CANDU 6

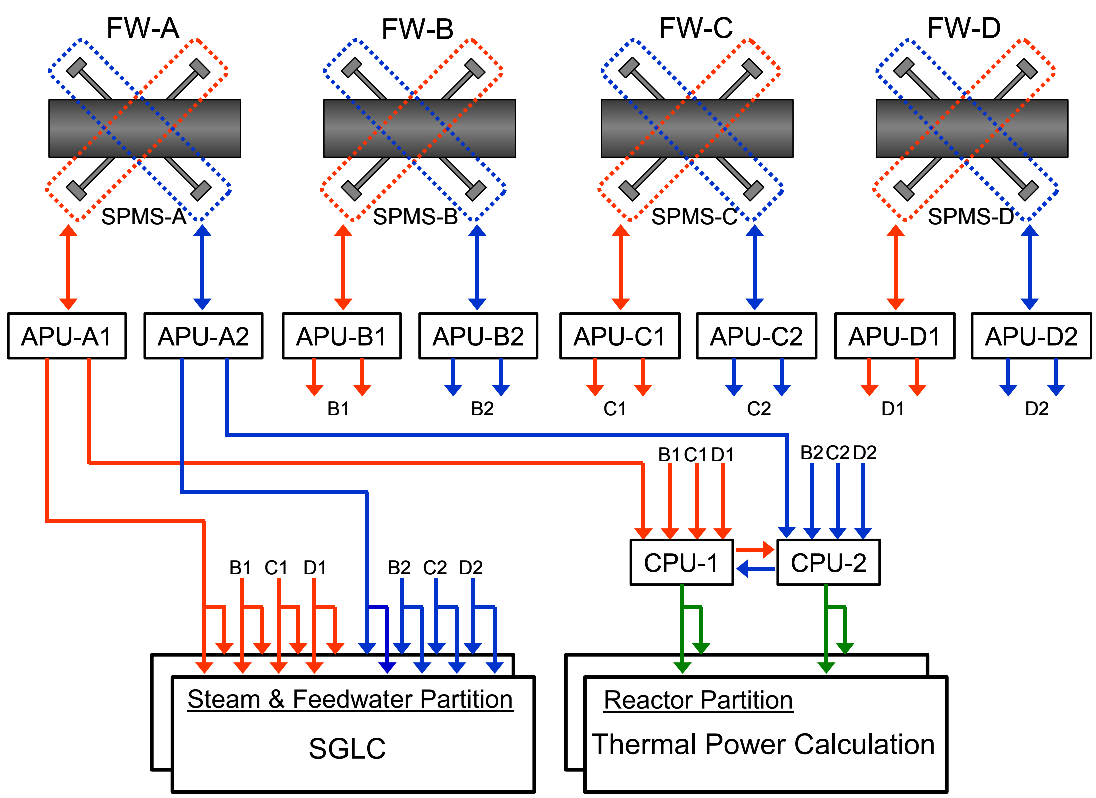

Figure 4 Signal Processing in the LEFM Chordal System Application to CANDU 6

For the other three feedwater lines B to D, the mass flow rate calculations using the dedicated APUs are similarly executed, and the results are sent to the dual-redundant controller, and CPU-1 or CPU-2 in the same way. The dual-redundant controller executes each of the four SGLC programs using their respective mass flow rate and produces output signals to position each of the four feedwater control valves.

The LEFM Chordal system can execute the feedwater flow calculations within 50 ms. Taking 20 samples for smoothing the calculation result from the LEFM Chordal system, for instance, the smoothed data of feedwater flow rates can be updated every 1 second. Since the SGLC program is required to execute every 2 seconds, the LEFM Chordal system has the capability to provide more than enough response performance required for the feedwater flow measurement input to the SGLC. Figure 5 shows a comparison of feedwater flow measurement data performed by the APU and the flow nozzle meter in a load rejection test in a nuclear power plant. It suggests that the APU has equivalent response performance to the traditional flow meter even in the transient condition.

The LEFM Chordal system can provide the feedwater flow measurement with an uncertainty of ±0.28% and it has no fouling issues that can lead to increased uncertainty, because of the measurement principle it uses. Even in the four-chordal-based case, the feedwater flow measurement can achieve ±0.5% uncertainty [4]. On the other hand, the traditional flow meter typically achieves a total uncertainty of around ±1.0%, including the flow element calibration error of ±0.25%. In addition, the traditional flow meter may experience some fouling over time, thereby requiring maintenance and recalibration on a regular basis to maintain and ensure the initial accuracy of the device.

As for the thermal power calculation, all the APU calculation results are shared with CPU-1 and CPU-2 by means of the communication network between CPU-1 and CPU-2. The two CPUs independently calculate mass flow rate in each of the four feedwater flow lines. Finally, the outputs from CPU-1 and CPU-2 are used as input signals to the thermal power calculation performed by the reactor partition every 2 seconds, instead of the traditional feedwater flow meter inputs. As mentioned above, the LEFM Chordal system exceeds the response performance and accuracy required for the thermal power calculation.

Because of the dual-redundant configuration described above, the LEFM Chordal system can be available to maintain the SGLC function and the thermal power calculation function even following a single component failure, and still provide more reliable feedwater measurements compared to the current CANDU 6 design using the single traditional flow meter as shown in Figure 1. For example, in the case of an APU-A1 failure, the dual-redundant controller retains its function using input signals from APU-A2, and the thermal power calculation function associated with feedwater line A is performed based on the four chordal paths.

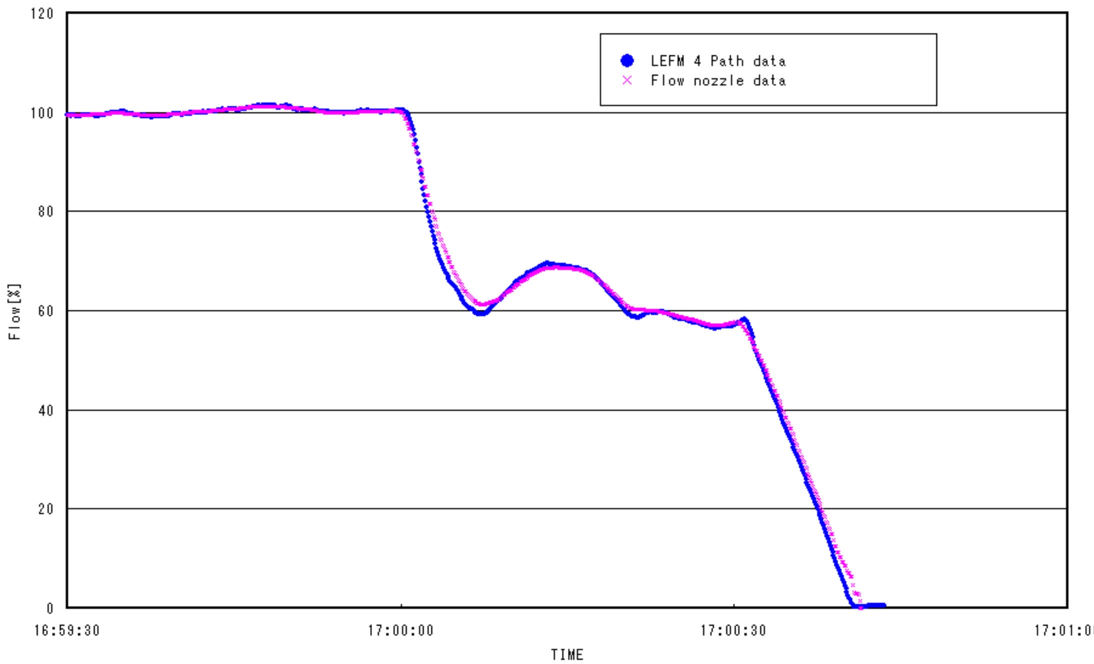

Figure 5 A comparison of feedwater flow measurement data by the APU and the flow nozzle meter in a load rejection test in a nuclear power plant

3) Application to MUR power uprate

The MUR power uprate has been developed in the US and the US NRC provides all utilities with a standard guidance issued in July 31, 2000 [5]. Nuclear power plants are licensed to operate at a specified reactor thermal power. The regulator requires the licensees to assume that the reactor operates continuously at some power level beyond the licensed power when performing safety analyses. This assumption is required to ensure that thermal power measurement uncertainty is adequately accounted for in the safety analyses. The assumed power margin in the safety analyses is based on considerations associated with the thermal power measurement. If the licensees can justify a smaller margin for thermal power measurement uncertainty by using more accurate instrumentation to calculate the reactor thermal power, then a smaller thermal power uncertainty may be assumed in the safety analyses. The method can be applied for CANDU as well.

The safety analyses in typical CANDU 6 design is carried out at 103% FP. The current 3% margin represents a measurement uncertainty associated with reactor thermal power, most of which comes from the feedwater flow measurement uncertainty based on using a traditional flow meter.

By introducing the LEFM Chordal system for the feedwater flow measurement, the thermal power measurement uncertainty can be reduced to about 0.5% (2 sigma). Thus, reactor thermal power could be raised theoretically by as much as 2.5% FP without compromising the safety margin and the licensing basis of their facility. Even allowing for a 1% uncertainty for power fluctuations against the current 3% margin, the thermal power could be increased by 1.5% by taking credit for the improved accuracy of the LEFM Chordal system flow measurement [6].

4) Cost benefit

The LEFM Chordal system can meet requirements for the SGLC application, so that traditional flow meters can be eliminated. At the same time, the reactor thermal power may be increased by MUR power uprate. Therefore, the introduction of the LEFM Chordal system into CANDU plants, especially New-builds, could provide two cost benefits at one time: the cost reduction by eliminating the traditional flow meter and increased power by the MUR power uprate.

4. Discussions

The LEFM Chordal system has the capability to be utilized for the SGLC even in some single failure cases like an APU failure. Nevertheless, an elbow tap implementation in a feedwater line could be one of the back-up options to ensure the SGLC function. The detailed consideration on how to incorporate the elbow tap measurement into the SGLC based on the LEFM Chordal system should be evaluated.

5. Conclusions

The UFM technology applied to feedwater flow measurement in CANDU is proposed for the purposes of the SGLC as well as MUR power uprate. The LEFM Chordal system, manufactured by Caldon Inc., has enough capabilities to meet the functional and performance requirements for both of these applications, replacing the traditional flow meters. It can execute the whole processing for obtaining a mass flow rate within 50ms and provide an overall feedwater flow measurement uncertainty of ±0.28%. In addition, the SGLC function can be available even with a single failure in the LEFM Chordal system because of the dual-redundant configuration.

Therefore, the UFM introduction into CANDU, especially New-builds, can provide two benefits at one time: cost reduction by eliminating the traditional flow meter and getting more power by MUR power uprate.

6. References

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