ROP DESIGN FOR ENHANCED CANDU 6 REACTOR

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Abstract

The Enhanced CANDU 6®[1] (EC6®) nuclear power plant is a mid-sized pressurized heavy water reactor design, based on the highly successful CANDU 6 (C6®) family of power plants, upgraded to meet today's Canadian and international safety requirements and to satisfy Generation III expectations. The EC6 reactor is equipped with two independent Regional Overpower Protection (ROP) systems to prevent overpowers in the reactor fuel. The ROP system design, retaining the traditional C6 methodology, is determined to cover the End-of-Life (EOL) reactor core condition since the reactor operating/thermal margin gradually decreases as plant equipment ages. Several design changes have been incorporated into the reference C6 plant to mitigate the ageing effect on the ROP trip margin. This paper outlines the basis for the EC6 ROP physics design and presents the ROP related improvements made in the EC6 design to ensure that full power operation is not limited by the ROP throughout the entire life of the reactor.

I. INTRODUCTION

The Enhanced CANDU 6 (EC6) nuclear power reactor, developed by Atomic Energy of Canada Limited (AECL®), is an updated version of the well-established CANDU 6 reactors which meets Generation III expectations. The EC6 design adapts the inherent safety characteristics of the reference CANDU 6 and further improves the safety margins while enhancing plant operability and maintainability. By incorporating incremental changes to the reference C6 plant design, the EC6 maintains a strong level of provenness.

Similar to the C6 power reactors, the EC6 (Reference [1]) is characterized by on-power fuelling and a relatively large reactor core, resulting in a continuously changing burnup distribution and a potential for slow flux and power oscillations due to xenon variation. It thus needs protection against localized fuel channel and bundle overpower throughout the core for a wide variety of possible core configurations. An overpower is defined as a fuel channel or bundle power in excess of specified safety-related limits.

To provide the protection against overpowers, the EC6 reactor is equipped with two independent and diverse ROP trip systems (Reference [2]), one for each shutdown system. If either ROP system detects an overpower condition in the reactor, it immediately actuates its associated shutdown system, which then rapidly shuts down the reactor so that dryout can be prevented in any fuel channel under any slow-loss-of-regulation (SLOR) reactor condition.

The EC6 design is targeted to have a lifetime capacity factor of 92% with a standard interval of three years between maintenance outages. A key to achieving such a high capacity factor is to avoid reactor power de-rating throughout the entire life of the reactor.

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However, the aging of the primary Heat-Transport System (HTS) in the EC6 reactor affects the total flow rate to the core, flow distribution in a fuel bundle and heat transfer properties of the HTS as a whole. This results in a reduction of the thermal margin, which means the Trip Setpoints (TSP) for the ROP systems also need to be reduced in order to protect the reactor with high trip probability. Therefore, the EC6 ROP systems are designed for EOL core conditions to ensure full power operation throughout the entire life of the reactor to achieve a high capacity factor.

This paper describes the main feature of the EC6 ROP design. The overall ROP systems are briefly presented in Section II, and the design basis as well as the acceptance criteria is given in Section III. The ROP physics design analysis process is discussed in Section IV. The design changes incorporated in the reference C6 plant design to specifically improve the ROP margin are described in Section V. Preliminary results obtained from the latest ROP analysis for EC6 are summarized in Section VI. Finally, the paper concludes with a summary section.

II. ROP SYSTEM

The EC6 reactor is equipped with two ROP systems to prevent the occurrence of fuel damage during operation, i.e., to protect the reactor against local overpower due to localized peaking or a general increase in the core power level during a SLOR event. Each of these ROP systems consists of an array of fast-responding, self-powered in-core flux detectors, appropriately distributed throughout the core and organized into three safety channels. Flux detectors associated with rod-based Shutdown System Number 1 (SDS1) are arranged within the vertical flux detector assemblies, while flux detectors associated with liquid-poison-based Shutdown System Number 2 (SDS2) are arranged in horizontal flux detector assemblies. The flux detector assemblies are located within the relatively cool and low-pressure moderator, between and perpendicular to the fuel channels.

Each ROP detector has a preset TSP. If the signal from any detector in a safety channel exceeds the detector's setpoint, then the safety channel which contains the detector is tripped, and a trip of two out of the three safety channels in an ROP system will trip the associated shutdown system. Thus, the ROP system is designed so that at least one detector in each safety channel will reach its predetermined setpoint before any potential damaging overpower in the fuel. Although a trip is initiated on a two-out-of-three voting logic, for EC6 ROP design purposes the concept of the worst two-out-of-two voting logic is applied, which assumes that the best safety channel is unavailable during the SLOR event. This approach reduces the chance of a spurious trip as a result of failure of a single loop or component. In addition, the triplicated safety channel design allows the independent testing of each trip parameter, from primary transducer to the final release circuit.

The detector locations for each ROP system are carefully optimized to ensure coverage of any flux shape that could arise in the operating reactor, while minimizing any potential for spurious trips and possible restrictions on reactor operating powers due to inadequate margin to trip. A flux shape is defined as the whole core thermal flux distribution obtained for a given assumed operating state and reactivity device configuration. Each flux shape is characterized by possible changes in the reactivity device positions in-core relative to the reference nominal device configuration.

In the EC6 ROP design, platinum clad inconel type detectors are employed for both SDS1 and SDS2. The platinum clad inconel type self-powered detectors are sensitive to both thermal neutrons and gammas. It is implicitly assumed that the change in thermal flux predicted by the physics simulations is directly proportional to the change in neutron and gamma fields expected at the detector sites because both neutron and gamma fields will increase proportionally if local fuel power increases. Dynamic compensation of the detectors is performed by the computerized ROP system to obtain a signal matching the dynamic variation of the power to the fuel.

III. ROP DESIGN BASIS AND ACCEPTANCE CRITERIA

In the operating reactor, variations from the nominal flux and power distribution are expected during normal operation, and must be taken into account in the ROP design. Perturbed power shapes could also occur during various operational conditions such as startup after a long shutdown, shim operation and power manoeuvrings. Other perturbed power shapes could occur as a result of reactivity device malfunction.

III.A. Design Basis

The main safety design requirement for the ROP systems is to prevent fuel sheath dryout in any fuel channel during a SLOR event. The fuel sheath dryout is to be prevented for a SLOR event starting from various possible flux shapes under normal reactor control or faulted device control conditions.

Each ROP system must actuate a reactor trip before the Onset of Intermittent Dryout (OID) in any fuel channel in order to prevent fuel damages. However, the Critical Channel Power (CCP) related to the OID event cannot be physically monitored. The in-core detector signals are used as the only measurable information. Therefore, the protection of the reactor against regional overpower depends only on the ROP detectors installed in the core. Basically, a flux shape is covered if ROP detectors are able to detect a high local flux in excess of their preset trip setpoints before the dryout occurs in any of the 380 fuel channels. For each flux shape evaluated, the safety design requirement for an ROP system can be described mathematically by the following inequality:

$$\frac{\mathrm{TSP}}{\phi} \leq min\left[\frac{\mathrm{CCP}}{\mathrm{CP}}\right]$$

Where ϕ denotes the detector signal, TSP is the trip setpoint, CCP is the critical channel power and CP is the channel power. The expression, *min*(CCP/CP), is the minimum margin to dryout for all channels in the core.

III.B. Design Acceptance Criteria

The EC6 ROP design acceptance criteria include:

- Each ROP trip instrumentation channel, for both SDS1 and SDS2, provides an effective trip for any SLOR event starting from any designated flux shape. The designated flux shapes are representative of all possible flux shapes that can occur due to changes in the in-core reactivity device positions as a result of normal reactor control or faulted device control conditions.
- The detector trip setpoints are set high enough to avoid spurious trips at expected reactor powers of normal operating transients.
- The probability of an ROP trip before the OID is shown to be greater than 98% for all of the designated flux shapes, with the most effective trip channel assumed to be unavailable at the time of trip. This is consistent with the standard effectiveness criterion specified in design and analysis of ROP systems in traditional CANDU reactors which ensures a high reliability of trip.

- The SDS1 detector signals are taken from only Vertical Flux Detector (VFD) assemblies and the SDS2 detector signals are taken from only Horizontal Flux Detector (HFD) assemblies, to provide physical separation, independence and diversity.

IV. ROP PHYSICS DESIGN ANALYSIS PROCESS

The traditional C6 ROP analysis process, depicted in Figure 1, has been adapted for the EC6 ROP physics design work. To ensure that the targeted high capacity factor is achievable, the ROP systems are designed based on the EOL plant conditions. The standard RFSP (References [3]) time-average equilibrium model and NUCIRC (Reference [4]) model, corresponding respectively to the EOL core configuration and plant ageing conditions for the HTS, are prepared and used for a wide range of flux shape simulations, the core follow to obtain the refuelling ripple data, the calculations of CCP as well as the ROP related uncertainty analysis. Selection and optimization of the in-core detectors, determination of the trip setpoints for both SDS1 and SDS2 are performed by ROVER-F (References [5] and [6]) computer code.

The objective of the EC6 ROP physics design process is to specify the number of in-core detectors needed, the spatial distribution in core, the channelization and the required trip setpoint to cover all of the specified flux shapes.

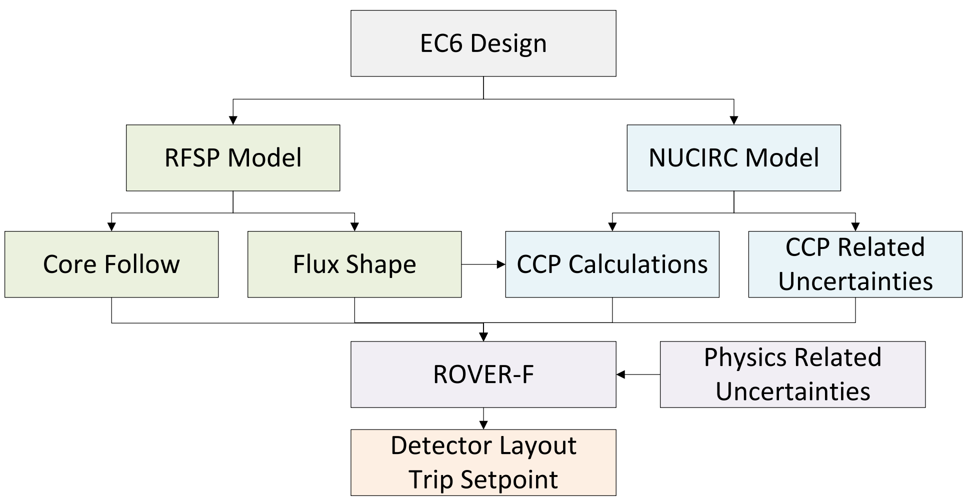

Figure 1 Flow Diagram of ROP Physics Design Process

IV.A. Flux Shapes

When the overpower occurs, the flux and power distribution in the core will affect not only the peak channel and bundle powers, but also how well the ROP flux detectors respond to the overpower condition. Hence, the possible flux shapes that could arise in the reactor are the basic element of the ROP design process. The number and variety of reactivity control mechanisms have a significant impact on the design of the ROP systems. In the EC6 reactor, the following mechanisms are employed for short or long term adjustment and control of reactivity and power levels:

- 6 liquid zone controllers with 14 individual compartments filled with variable amounts of light water are used to continually perform bulk and spatial flux control;

- 11 adjuster rods, grouped in banks and normally inserted in the core, are used to flatten the power shape and to provide positive reactivity upon their removal, such as for startups and shim operation;
- 4 mechanical control absorbers, normally held out of core, may be driven into core to compensate for excess overall reactivity, or dropped into core to initiate a power stepback;
- Addition of poison into the moderator, boron for long-term reactivity adjustments and gadolinium for short-term reactivity adjustments;
- On-line daily refuelling to compensate for the fuel burnup.

A typical layout of reactivity devices is shown in Figure 2. For the EC6, the number of the adjusters is reduced from 21 to 11 relative to C6, mainly to compensate the penalty on fuel burnup due to the increased pressure tube (PT) wall thickness in EC6. Details will be given in Section V.

In order to provide spatial coverage in the ROP design, it is necessary to consider a range of flux shapes that produce flux perturbations in all areas of the core. However, it is not possible to consider all flux shapes that represent all possible device positions during operation since the range of device movement is continuous within control limits, and as a result the number of positions and permutations is infinite. Therefore, the strategy used, as in past ROP designs, is to consider a number of combinations of discrete reactivity control device positions that envelope the range of positions possible under normal and faulted control device conditions.

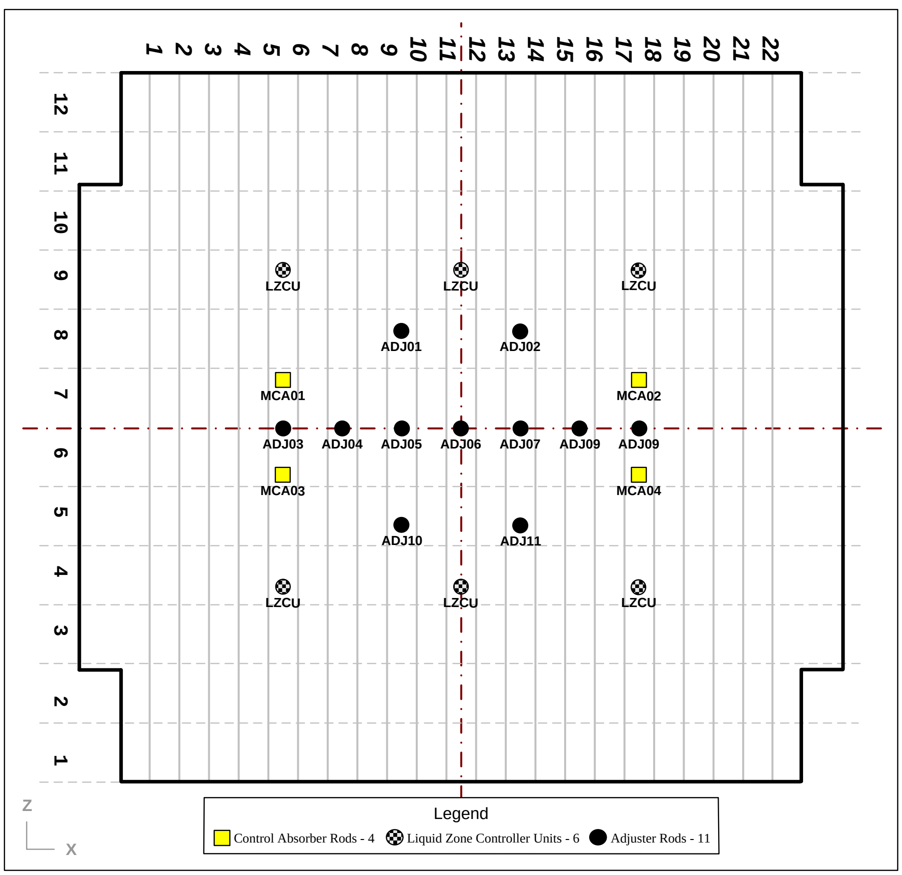

Figure 2 Layout of Reactivity Devices

IV.B. Refuelling Ripple

As in the C6 design, the EC6 design features on-power refuelling where fresh fuel bundles are inserted, while fuel bundles with high burnup are removed. As a result, the core at any instant will have channels and bundles with a mixture of varying irradiations and powers. The resulting variation in individual channel powers from the time average (or reference) values is known as refuelling ripple.

A basic simplification in the ROP design process is to separate the effect of refuelling ripple from the other flux shape variations, i.e., those due to reactivity devices or xenon fluctuations. The perturbation cases used to design the ROP systems are thus based on a smooth time-average model. The effect of refuelling ripple is accounted for by applying the Channel Power Peaking Factor (CPPF) to the ROP detector readings and applying the channel power ripple to the channel powers of each flux shapes. The CPPF can be obtained from the core follow simulations. The channel power data from the core follow simulations are used to generate the channel power ripple dataset needed for the detector layout optimization analysis.

IV.C. Critical Channel Power

EC6 HTS utilizes heavy water to cool the fuel. For the purpose of removing heat from the core, the heat transport pumps provide forced coolant circulation through the fuel channels and the steam generators. In the steam generators, the heat is transferred to secondary side light water to generate steam, which subsequently drives the turbine generator. Similar to the C6, the EC6 HTS configuration features two “figure of eight loops”.

The OID defines the channel conditions under which the heat transfer mode changes from the efficient pre-dryout to transition boiling but with some liquid wall contact still occurring. The CCP is expected to be lower for a crept pressure tube (i.e., a pressure tube with expansion in diameter). Therefore, for the EC6 ROP design, the CCPs are calculated for all the perturbation cases for the EOL conditions including fouled steam generator and feeders which will further decrease the CCP value.

The NUCIRC model for the EC6 EOL plant conditions is used to calculate the CCPs and to perform the CCP-related uncertainty analysis. NUCIRC is a steady-state thermalhydraulic code designed to analyze the heat transport system for various operating conditions and to predict the CCP at fuel dryout in the ROP analysis for CANDU reactors.

IV.D. Uncertainty Analysis

Uncertainties are needed by the ROVER-F analysis to calculate the trip probability. They are categorized according to ROVER-F input structure as follows:

- Detector related group;
- Flux-shape related group; and
- CCP related group.

Each of the above groups includes up to four categories as follows:

- Detector-random uncertainty: random errors that vary from detector to detector (e.g., recalibration errors);

- Channel-random uncertainty: random errors that vary from fuel channel to fuel channel (e.g., uncertainty in channel flow);
- Common-random uncertainty: random in expected value but affect in a common way all fuel channels or detectors (e.g., uncertainty in the total reactor power);
- Bias: systematic error.

The uncertainty values used in the EC6 ROP design are derived from previous C6 ROP studies and operating experience with conservative modifications to take into account design differences for the EC6 reactor.

IV.E. Selection of Detector Layout

The design of the detector layout consists of two parts, one in which detectors are selected by a process using a deterministic allowance for error, and other in which the design is assessed probabilistically.

First, all candidate detectors are deterministically assigned a trip setpoint that allows a minimum number of detectors to cover all designated flux shapes. A detector covers a flux shape if its assigned setpoint is equal to or lower than its required setpoint to prevent OID in a given flux shape; next, a Boolean coverage matrix (true or false) indexed by case (flux shape) and detector number is generated.

This matrix is then reduced to obtain a set of protecting detectors for every flux shape. This set of protecting detectors is used as input to the next step in the design process: the probabilistic design optimization.

The final detector layout is selected from the protecting detector set identified in the deterministic design through an iterative process using a probabilistic calculation and an optimization algorithm. At each stage of the iteration the quality of a proposed detector layout is evaluated by performing a probabilistic assessment. The probabilistic assessment is performed with the ROVER-F computer code which models a hypothetical SLOR event with explicit allowance for the random variation in all important design parameters.

A minimum trip setpoint is determined by the probabilistic calculation to ensure all flux shapes considered in the design will cause a trip before any fuel channel reaches the OID with at least 98% trip probability given the best one out of three safety channels unavailable at trip.

V. DESIGN CHANGES TO IMPROVE ROP MARGIN

V.A. Plant Ageing Effect on ROP Margin

An issue common to all types of nuclear power plants is the ageing of plant equipment. New plants could have substantial operating margins built in when they enter service. The operating margin gradually decreases as the plant equipment is affected by ageing.

During CANDU reactor operation, the conditions of temperature, stress and neutron flux change the dimensions of the pressure tubes. The dimensional changes are seen as expansion of PT diameter, sagging and elongation. The expansion of the PT diameter results in coolant flow by-pass around the fuel bundle, reducing critical heat flux (CHF) which in turn reduces the CCP. This leads to a decrease in CCP with an increasing rate which directly contributes to a reduction in ROP margin.

Other ageing phenomena that also significantly affect the thermal margin are the increases in steam generator (SG) fouling which leads to an increase in the reactor inlet header (RIH) temperature, and an increase in piping roughness which increases the flow resistance.

The reference C6 plant design has implemented the following features to mitigate the ageing effect on ROP margin:

- Improved feeder materials to reduce the flow assisted corrosion, which helps minimize the SG fouling and the feeder pipe roughness;
- Use of a fully welded SG divider plate to minimize the RIH temperature increase;
- Installing the PT with the back end, i.e., the last part extruded during manufacturing, at the inlet to reduce the creep rate.

For EC6 design, many design changes are incorporated to the reference design in order to further enhance the ROP margin.

V.B. Adjustment of Feeder Size

The in-core reactivity device configuration and the reference channel power distribution for the EC6 reactor are different from the reference C6. Feeders have been resized for ~100 channels to re-distribute the channel flow by increasing the flow to limiting channels and reducing the flow to channels with excessive margin. This improves the CCP in the critical channels and thus enhances the ROP thermal margin.

V.C. Increase of Pressure Tube Wall Thickness

The PT diametral expansion is caused by irradiation, stress and temperature. The expansion in diameter can be reduced by increasing the PT wall thickness. The PT thickness is increased by ~18% in the EC6 reactor design.

The drawback of increasing the PT thickness is the penalty on fuel burnup, which is partially overcome by reducing the total reactivity worth of in-core material:

- The adjuster layout has been re-optimized so that the number of adjuster rods is reduced while a balanced core flux and power distribution, and load cycling capability are still maintained.
- The guide tube positioning springs are relocated outside the core. This improves the spring robustness and meanwhile removes parasitic neutron-absorbing material from the core.

V.D. Improvement of HTS Instrumentation Accuracy

Uncertainties related to the calculation of CCP for ROP analysis can be categorized as two types. The first one is associated with the measurement of process parameters. The second one includes all other uncertainties involved in the calculation of HTS conditions leading to the calculation of CCP and ROP setpoints. Improved HTS instrumentation allows for a more accurate determination of the HTS behaviour, reducing the process portion of the uncertainties used in the ROP analysis.

The improvement of the HTS instrumentation includes:

- RIH temperature measurement replaced with narrow range temperature transmitters;
- Addition of differential pressure transmitters to fuelling machines;
- Addition of differential pressure drop instrumentation across the ROH interconnect line orifices;
- Addition of differential pressure drop instrumentation across the boiler;
- Addition of differential pressure drop instrumentation across the pump;
- Relocation of header-to-header pressure drop instrumentation to provide symmetry;
- Enhanced channel flow measurement.

V.E. Digital ROP System

A digital ROP system will be implemented for the EC6 reactor. The analogue components used in the reference C6 design are becoming less common and more difficult to procure. The digital ROP approach minimizes human involvement and errors, reduces signals uncertainties by allowing more frequent and automatic calibration, and performs digital signal processing to improve dynamic response correction. The digital ROP systems in Darlington reactors have proven to be effective.

V.F. Additional Detectors Assemblies and Optimization of Detector Placement

The reference C6 design is limited by the number and location of the HFDs, with no HFDs in the lower part of the core. Thus, coverage of certain flux shapes with a bottom-to-top tilt is less effective. A "virtual detector" scheme, known as "Difference Compensation", was devised to estimate the peak flux values in the lower part of the core based on the available detector signals. However, the applications of this scheme do not always lead to satisfactory results in all situations.

In addition to the existing nine horizontal assemblies in C6, six more locations have been identified and the spatial clearance has been confirmed for the EC6 ROP design. Three out of the six assemblies are located seven lattice pitches below the reactor centreline. Adding detectors on new SDS2 assemblies in the lower core eliminates the requirement for a "Difference Compensation" scheme and provides better coverage for high flux tilts.

The VFD and HFD assemblies are shown in Figures 3 and 4, respectively.

The core detector placements are optimized to take into account the changes in the core configuration, the feeder sizes, detector assemblies and ROP related uncertainties.

VI. PRELIMINARY RESULTS

The physics design process for the ROP systems for the EC6 has been conducted. The main features assumed in this design process are:

- The system is designed for the EOL plant conditions to take into account the ageing effect on the HTS performance;
- One detector is required to trip in order for a safety channel to trip;
- A modified algorithm based on a simulated annealing stochastic optimization procedure is used to determine the detector configuration in the core;

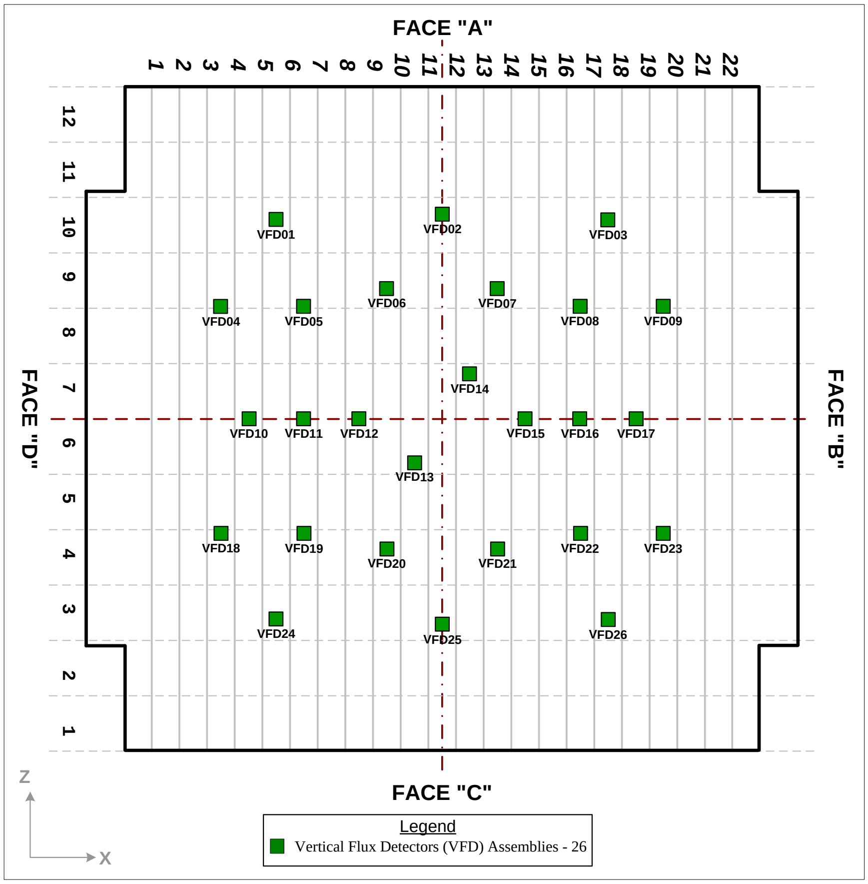

Figure 3 Layout of VFD Assemblies

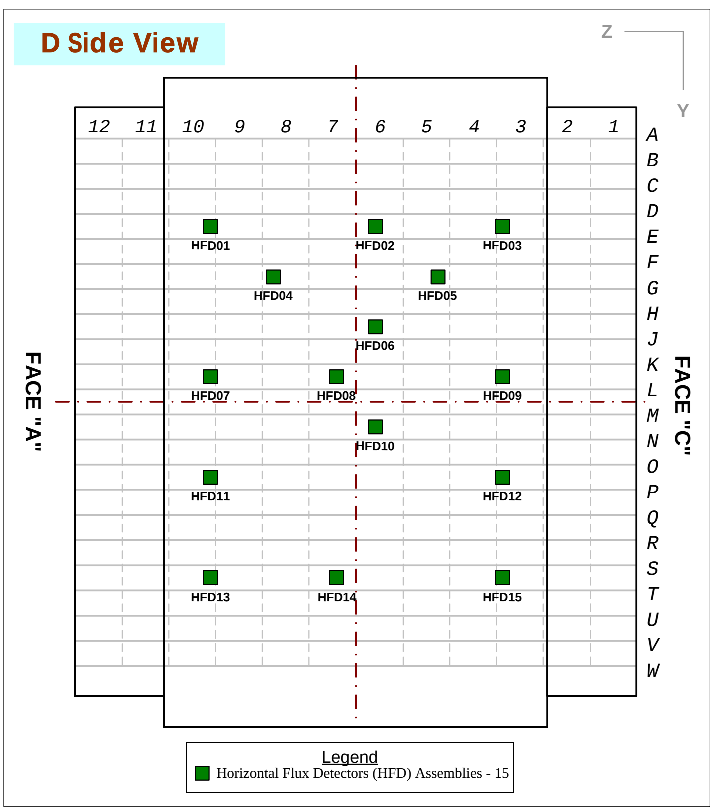

Figure 4 Layout of HFD Assemblies

- There are three safety channels in each ROP system. A two-out-of-three voting logic is applied to initiate a trip, however, the trip probability calculation is based on the worst two-out-of-two channel trip requirement, which assumes that the best channel is unavailable during trip;
- All the designated flux shapes are covered with at least 98% trip probability.

At this moment, the design analysis has been completed only for determination of the handswitch position 1 (HSP-1), the nominal trip setpoint for the ROP systems. The flux shapes used in the analysis are adapted from a generic C6 HSP-1 definition with the exceptions of startup after short shutdown (not a requirement for EC6) and the changes resulting from a reduced number of adjuster rods.

The design of ROP systems has been determined for three instrumentation channels with approximately 50 detectors for both SDS1 and SDS2. Those detectors are appropriately distributed over the reactor core, without any detector overlapping. The "Difference Compensation" scheme is no longer used for the SDS2 because of the presence of an additional three new horizontal detector assemblies in the lower part of the core.

The preliminary results show that the ROP trip setpoints are sufficiently high and full power operation will not be limited by the ROP margin throughout the entire life of the plant.

VII. SUMMARY

The EC6 nuclear power reactor design retains the basic features of the proven C6 design. The EC6 design process ensures that design changes are incremental from the CANDU 6 family of plants. The ROP design of the EC6 has followed this process, retaining the analysis methodology and the benefits from the previous ROP studies and operational experiences, while selecting changes to improve component robustness and system reliability and to further enhance the performance of the EC6 reactor.

So far, the ROP design analysis for flux shapes designated as HSP-1 has been completed. The results show that it is possible to operate the EC6 reactor with no power de-rating at the EOL condition. The future work will look at determination of TSP for other handswitch positions and the robustness of the ROP design. The ROP TSP analysis will be repeated for the initial core and the pre-equilibrium core though the thermal margins are expected to be much higher for those core conditions.

VIII. ACKNOWLEDGEMENT

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