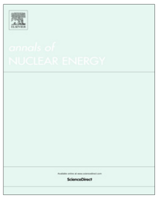
Annals of Nuclear Energy 83 (2015) 181–187

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



ROP margin improvement options for CANDU reactors

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ARTICLE INFO

Article history:
Received 28 January 2015
Received in revised form 26 March 2015
Accepted 27 March 2015

Keywords:
Regional overpower protection
CANDU
Detector layout
Handswitch position

ABSTRACT

Over the past few years, Candu Energy Inc. (a wholly owned subsidiary of SNC-Lavalin Inc., which acquired the assets of Atomic Energy of Canada Limited's Commercial Reactor Division) has been continuously developing and evaluating various options to improve the regional overpower protection (ROP) margin in aged CANDU 600 MW (CANDU 6®) reactors. This paper presents results from applying a couple of margin improvement options to a generic aged CANDU 6 reactor, namely ROP detector layout optimization and application of a revised handswitch position designation. Application of these options requires no change to the ROP analysis methodology, statistical approach or acceptance criterion. As such, any increase in ROP margin associated with these options carries little or no licensing risk and are not expected to require more than one standard outage to implement.

1. Introduction

In the CANada Deuterium Uranium (CANDU®[1]) reactor design, the regional overpower protection (ROP) systems (which are also known as the neutron overpower protection or NOP systems (Levine et al., 2002; Chung et al., 1980)) protect the reactor against excessively high power in the fuel which could lead to fuel or even fuel channel failures. In order to have a substantial margin to failure, the systems are designed to protect against dryout.[2] The power increase in the core could be caused by either a localized power peaking within the core (for example, due to improper channel selections for fueling) or a general increase in the core power level during a slow-loss-of-regulation (SLOR) event.

The CANDU 600 MW (CANDU 6) design is equipped with two ROP systems. Each system consists of three independent safety channels. Each safety channel includes a number of fast-responding, self-powered flux detectors which are distributed throughout the core within vertical and horizontal assemblies. Each system can initiate reactor trip on one of the two independent, fast acting shutdown systems using a two-out-of-three trip logic. The shutdown system number 1 (SDS1) is a rod-based shutdown system and consists of cadmium shutoff rods (SOR) which are located at the top of the reactor. The rods are released into the core when this shutdown system is actuated. In a standard CANDU 6 design, the SDS1 ROP system consists of 34 self-powered, platinum-clad, straight individually replaceable (SIR) detectors which are located in 16 out of the 26 available vertical assemblies. It should be noted that these vertical assemblies are also shared with other flux detectors used for reactivity control and flux mapping. The second shutdown system, shutdown system number 2 or SDS2, is a liquid-poison-based shutdown system. The SDS2 is connected to highly concentrated gadolinium solution which is stored in high pressure tanks. The gadolinium solution is released into the moderator when the SDS2 is actuated. In a standard CANDU 6 design, the SDS2 ROP system includes 24 detectors of the same types as SDS1 which are located in 7 out of 9 available horizontal assemblies. The three safety channels for SDS1 are designated as channels D, E, and F; while for SDS2 they are designated as channels G, H, and J. Fig. 1 shows a diagram of the shutdown systems in CANDU 6 reactor.

In order to protect the reactor from an overpower event, the ROP trip setpoint (TSP) for these detectors is calculated probabilistically using the ROVER-F code (Kastanya and Caxaj, 2010). A brief overview of how the TSP is calculated is presented in Section 2. For any detector, once its reading goes beyond the TSP value, it will trip the safety channel it belongs to. Then for each shutdown system, once two of the safety channels trip the shutdown system will be actuated.

The ROP TSP value needs to be calculated periodically throughout the life of the reactor to capture the changes in reactor conditions. For example, as the reactor ages the geometry of the fuel channel slowly departs from the corresponding design

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[1] CANDU is a registered trademark of Atomic Energy of Canada Limited, used under exclusive license by Candu Energy Inc.

[2] Dryout is a condition in which the heat transfer coefficient from the fuel is reduced significantly from the normal operating value due to coalescence of small bubbles in the coolant into a vapor film enveloping the fuel element. This elevates the fuel temperature to a level higher than the desired temperature.

http://dx.doi.org/10.1016/j.anucene.2015.03.048
0306-4549/

Nomenclature

CANDU	CANada Deuterium Uranium
CCP	critical channel power
CP	channel power
DLO	detector layout optimization
HFD	horizontal flux detector (assembly)
HSP	handswitch position
IHB	Inverse Heat Balance
NOP	neutron overpower protection
OID	onset of intermittent dryout
PT	pressure tube
ROP	regional overpower protection
SDS	shutdown system
SIR	straight individually replaceable
SOR	shutoff rod
SLOR	slow loss of regulation
TSP	trip set point
VFD	vertical flux detector (assembly)

specifications at the beginning-of-life. One parameter which has a direct impact on the ROP TSP value is the pressure tube (PT) diametral creep. As the PT starts to creep (*i.e.*, experience an increase in its inner radius), a "bypass" path for coolant flow is created around the upper portion of the PT cross-sectional area as the fuel bundle resides on the lower portion of the PT cross-sectional area. This phenomenon reduces the amount of cooling to the fuel bundles in this fuel channel. This will reduce the critical channel power (CCP), which is the power level at which an onset of intermittent dryout (OID) starts to develop. The reduction in the CCP value will eventually require a reduction in the ROP TSP value to maintain the appropriateness of the safety margin provided by the ROP systems. A progressive reduction in the ROP TSP value will eventually result in a need for a reduction in the maximum operating power level. This is a challenge faced by all operating CANDU reactors around the world.

In order to mitigate this problem, Candu Energy Inc. has investigated two options which will allow the operating stations to recover some of the ROP margin. The two options are ROP detector layout optimization (for both shutdown systems) and application of a revised handswitch position designation. Section 2 of this paper provides an overview of the methodology used for probabilistic calculation of the ROP TSP value. Some details about the two ROP TSP enhancement options are also presented in this section. An overview of the development of a generic aged thermal hydraulic model of a CANDU 6 reactor is also presented in this section. Section 3 presents some results from implementing these two options. Finally, Section 4 closes this paper with some conclusions.

2. Methodology

2.1. Overview of the ROP TSP calculation

An ROP system is designed to have a high probability that it will actuate a reactor trip before OID in any fuel channel, thus providing a large margin to the safety requirement of protecting the reactor from the relevant overpower events. It should be noted that using OID as a criterion is also conservative. Prevention of OID provides a high degree of confidence that actual dryout is prevented. The means to evaluate whether OID could occur is through ROP analyses, which are performed by considering two quantities, namely the margin-to-dryout[3] (MTD) and the margin-to-trip (MTT). The former is defined as the ratio between the channel power at which the onset of intermittent dryout will first occur (the corresponding channel power level is called the critical channel power or CCP) and the actual channel power (CP). The MTT is defined as the ratio between the reactor power at which the ROP system will actuate the shutdown system and the actual reactor power. The relation between these two quantities can be expressed by the following inequality:

$$\mathrm{MTT} \leqslant \mathrm{MTD} \qquad (1)$$

which could be expanded to:

$$\frac{\mathrm{TSP}}{\Phi} \leqslant \frac{\mathrm{CCP}}{\mathrm{CP}} \qquad (2)$$

where TSP is the trip set point, Φ is the detector reading, CCP is the critical channel power, and CP is the channel power.

In the design and operation of the ROP system, a nominal flux distribution (and, hence, power distribution) refers to the one produced by a core configuration where all devices are at their nominal position. The departure in the neutron flux distribution from this nominal distribution can be categorized into two types:

a. *Flux shapes*. The flux shapes are defined as various flux and power distributions caused by changing the device configuration (including zone-controller fills) or changes in the xenon distribution from the nominal distribution.
b. *Ripples*. Ripples are defined as variations in the core power distribution that are due to fueling and changes in the burnup distribution. The ripples used in the ROP can be generated from core-follow simulations or come from operating data from the plant.

The basic ROP safety requirement can then be expanded using these two definitions. The requirement is that for any flux shape k and ripple q, each safety channel must trip before the power in any fuel channel reaches the critical channel power for that fuel channel. This means that the detector locations, detector channelizations in the safety channels, and the trip set point (TSP) must be determined carefully such that for each flux shape considered, there is at least one detector $j_{p,i}$ in each safety channel i which satisfies the following expression:

$$\mathrm{TSP}(j_{p,i}) \leqslant \Phi(j,k) \times r_{\mathrm{CPRL}}(k,q) \qquad (3)$$

where $\mathrm{TSP}(j_{p,i})$ is the installed trip set point for protecting detector j (the subscript p is used to emphasized that it is a protecting detector), in voting logic channel $i; \Phi(j_{p,i})$ is the normalized[4] detector reading at detector j for flux shape k (and may include several calibration terms depending on plant operation); and, $r_{\mathrm{CPRL}}(k,q)$ is the minimum critical power ratio (*i.e.*, the MTD) for flux shape k and ripple q. This is the basic deterministic equation for determining the trip set point value.

Since each component involved in determining the TSP value has some uncertainties related to its value, the deterministic approach for calculating the TSP value is no longer applicable. Therefore, a probabilistic calculation is required. In order to determine the TSP value, a probabilistic approach is utilized by the ROVER-F code which is used in the ROP TSP analysis for CANDU

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[3] "Dryout" in MTD actually corresponds to the onset of intermittent dryout (OID).

[4] The detector reading is normalized to the detector reading for the nominal case and thus is invariant to ripple variations.