

# Introduction to an Analysis Methodology for Channel and Bundle Power Operating Limits in a PHWR

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## 1. Introduction

Thermal safety evaluation of a reactor core is a fundamental analysis area for ensuring fuel integrity under both normal operating and accident conditions. In pressurized heavy water reactors (PHWRs), evaluation approaches that consider thermal-hydraulic differences among individual fuel channels are required. Variations in channel flow rate, power distribution, and geometric characteristics of inlet and outlet feeder pipes may lead to different thermal-hydraulic behaviors among channels, which can influence local thermal margin reduction.

The current Operation Technical Specifications (OTS) of the Wolsong Nuclear Power Plant define operating limits for Channel Power (CP) and Bundle Power (BP). These operating limits are specified in the Wolsong OTS Section "3/4.2 Power Distribution Limits[1]." The limits are established to ensure that all channels maintain acceptable thermal margins and are used as key boundary conditions for both normal operation and safety analyses.

The Channel Power Limit is fundamentally based on maintaining an equivalent dryout margin for all channels. While this approach provides balanced safety margins across the core, differences in channel flow and power conditions result in variations in coolant exit quality and enthalpy rise characteristics. In particular, low-flow channels allow relatively larger enthalpy increases, making it difficult to identify the most limiting channel using only power or flow criteria under accident conditions.

During core design, channel flow rates and feeder diameters are adjusted to maintain similar outlet conditions among channels. However, complete thermal-hydraulic uniformity cannot be achieved due to limited feeder diameter combinations and orifice configurations. These geometric and hydraulic differences become important considerations in limiting channel selection and operating limit evaluation.

Conventional safety analyses have typically relied on representative single-channel models for trip coverage evaluations. However, a structured description of evaluation approaches is needed to confirm that channel and bundle power operating limits maintain consistent safety performance under diverse thermal-hydraulic environments. In particular, clarification of evaluation

procedures considering operating limit conditions is beneficial.

In this paper, an analysis methodology used to evaluate channel-wise Channel Power (CP) and Bundle Power (BP) operating limits under assumed aged operating conditions is introduced. Considerations for limiting channel selection based on equal dryout margin concepts are described, together with a single-channel evaluation approach for channel and bundle power operating limits. Modeling configurations and evaluation procedures consistent with accident analysis practices are also presented. The objective of this paper is to provide a methodological reference supporting understanding of the linkage between operating limit concepts defined in the OTS and their application in safety analyses.

## 2. Channel Power Limit Methodology and Safety Evaluation

The primary objective of channel power limits is to ensure that all channels within the core maintain an equivalent level of safety. This prevents localized reduction of thermal margins in specific channels by maintaining identical dryout margins across the core. While this approach ensures balanced safety margins, it also introduces differences in thermal-hydraulic conditions among channels.

When maximum allowable channel powers are determined to equalize dryout margins, coolant exit quality in low-flow, low-power channels becomes higher than in high-flow channels. This implies a larger allowable coolant enthalpy rise in low-flow channels and results in relatively higher allowable power increase ratios compared with time-averaged operating power. Consequently, identifying the most limiting channel during accident conditions requires a systematic selection process rather than simple comparison of power or flow parameters.

Although channel flow rates, channel powers, and feeder diameters are adjusted during core design to maintain similar outlet conditions, inlet feeders are limited to three diameter types and outlet feeders to four types. Together with orifice installation differences, complete thermal-hydraulic similarity among channels is not achieved. These geometric differences therefore represent important factors in limiting channel selection.

### 3. Limiting Channel Selection

Channel power limits are defined such that identical dryout margins are maintained for all channels. Under this design principle, low-flow channels may exhibit higher coolant exit quality and enthalpy rise than high-flow channels, and the limiting channel may vary depending on accident type. Therefore, a systematic methodology is required for selecting channels with relatively higher vulnerability rather than assuming a single representative channel.

Although the reactor core is designed to produce similar outlet conditions during normal operation, differences in feeder diameter combinations and orifice configurations introduce thermal-hydraulic variations among channels. Under equal dryout margin conditions, lower-flow channels allow higher enthalpy rise and larger allowable power ratios relative to time-averaged operation. Accordingly, enthalpy rise characteristics are considered a primary criterion for single-channel selection.

Channels exhibiting relatively large enthalpy increases within similar flow and power groups are preferentially selected, since larger enthalpy rise corresponds to increased coolant temperature and potential reduction of thermal margins. Bundle enthalpy rise, defined as bundle power limit divided by channel flow rate, is also considered an important parameter because higher values indicate increased fuel temperature rise potential under maximum power conditions.

Spatial location and connection configuration are additionally considered. Peripheral channels generally exhibit lower flow characteristics, while channels connected at higher header elevations may experience degraded cooling performance due to possible flow stratification and steam ingestion. Channels with higher feeder connection elevation and shorter feeder lengths are therefore included as candidates.

Channels with large ratios between channel power limits and time-averaged power are also considered due to their greater allowable power excursion during transients. Furthermore, channels susceptible to power peaking when both channel and bundle limits are simultaneously applied are included. Channels important for safety system actuation or instrumentation signal interpretation are also incorporated regardless of purely thermal-hydraulic representativeness.

Accordingly, limiting channels are selected by comprehensively considering enthalpy rise characteristics, operational margin relative to power limits, spatial effects, potential flow stratification influence, and safety evaluation representativeness.

### 4. Single-Channel Modeling Methodology for Channel/Bundle Power Operating Limits

#### 4.1 Modeling Framework

A single-channel CP/BP limit model is described for evaluating thermal-hydraulic behavior and fuel thermal response under operating limit conditions. The model configuration is presented to provide an analysis environment consistent with accident analysis frameworks, allowing channel flow, fuel heat transfer, and structural thermal behavior to be represented within a unified system. Identical modeling principles and nodalization schemes are applied to all analyzed channels to ensure comparability.

#### 4.2 Modeling Assumptions

To reflect long-term operation effects, burnup-related structural and fuel property changes are included. Pressure tube deformation and fuel property variations are considered to account conservatively for potential impacts on heat transfer characteristics and thermal margins.

Model input parameters and heat transfer correlations are selected to maintain consistency with existing safety analysis methodologies, enabling direct comparison between evaluation results.

#### 4.3 Thermal Modeling

Fuel heat transfer analysis distinguishes between fuel rods with different geometric characteristics. Central and peripheral fuel rods are modeled independently, and a grouped fuel modeling approach is applied to conservatively evaluate localized heating under possible flow stratification conditions.

The pressure tube and surrounding structures are divided into multiple circumferential sectors to represent temperature asymmetry and local heat transfer effects. Heat transfer mechanisms include conduction, convection, and radiation to capture thermal interaction under elevated temperature conditions.

#### 4.4 Power Modeling

Fuel power distributions identical to those used in accident analyses are applied to maintain consistency between operating limit evaluation and accident simulations. A hot-pin concept is adopted to evaluate local peak heat load conditions. Separate representations of conservative fuel characteristics and bundle-average properties are applied to simultaneously evaluate peak and average thermal responses.

### 5. Evaluation Methodology for Safety Analysis Operating Limits

The validity of safety analysis operating limits is evaluated using a single-channel-based accident analysis approach. While conventional trip coverage analyses relied on representative channels, additional single-channel evaluations are performed to confirm that established channel and bundle power limits satisfy

safety criteria across diverse thermal-hydraulic conditions.

Each selected limiting channel is assumed to operate at channel and bundle power limits prior to accident initiation. Evaluations are performed from two perspectives: preservation of validity of existing trip coverage analyses and assessment of the influence of operating limits on single-channel thermal-hydraulic behavior.

System behavior is assumed to remain consistent with existing safety analysis results, and reactor inlet/outlet conditions and core power behavior obtained from system analysis are applied as boundary conditions to individual single-channel models. Safety criteria compliance during accident conditions is then evaluated.

Trip coverage integrity is verified by confirming that sufficient valid trip parameters remain available for each shutdown system. Major accident categories, including loss-of-coolant accidents and secondary-system events, are analyzed to confirm that established safety criteria remain satisfied under revised operating conditions.

Through this procedure, it is systematically verified that channel and bundle power operating limits satisfy both shutdown system requirements and thermal-hydraulic safety criteria under accident conditions.

## **5. Conclusions**

This paper introduced a single-channel-based analysis methodology used for evaluating Channel Power (CP) and Bundle Power (BP) operating limits in a PHWR. The operating limits are based on power distribution limits defined in the Operation Technical Specifications of Wolsong Units 2, 3, and 4, and the methodology is described with consideration of aged operating conditions.

It was shown that maintaining identical dryout margins across channels can produce differences in coolant enthalpy rise and exit quality due to variations in channel flow and geometry. The study described the need for comprehensive limiting channel selection considering enthalpy rise characteristics, operational margins, spatial effects, and potential flow stratification influences.

Modeling configuration, input assumptions, and evaluation procedures using accident analysis boundary conditions were presented to provide a structured description of thermal-hydraulic response evaluation under operating limit conditions.

The methodology introduced in this paper can serve as a reference for understanding the relationship between operating limit concepts defined in technical specifications and their application in safety analyses, and may be used as a supporting reference for future evaluations involving operating limit conditions.

[1] Wolsong Units 3 and 4 Operation Technical Specifications.

## **REFERENCES**