Identification of Essential Parameters for Eddy Current Based Measurement of Pressure Tube to Calandria Tube Gap in CANDU® Reactors

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Agenda

- Inspection Qualification
- Pressure Tube-to-Calandria (PT/CT) Tube Gap Measurement
- Technical Justification for Gap Measurement
- Identification of Essential Parameters
- Experimental Results
- Uncertainty Analysis
- Summary
What is Inspection Qualification?

- An evaluation that determines whether the objectives stated in the Inspection Specification have been achieved for a given inspection system.
- Review performed by subject matter experts provides direction concerning the effectiveness of the inspection against the Inspection Specification.
- Central document under review is the Technical Justification, which provides evidence of how well the inspection objectives have been met and identifies any limitations in the inspection system.
Preparation for Qualification

1. Identification of essential parameters.
2. Determine how essential parameters vary under inspection conditions.
3. Evaluation of the effect of this variation on the desired outcome of the inspection.
4. Identification of physical parameters, which may affect the inspection outcome, but are not a directly measured quantity.
5. Assessment of the variability of these identified parameters under inspection conditions and their impact on the desired outcome of the inspection.
Pressure Tube-to-Calandria Tube Gap

Calandria Vessel

PT/CT Gap

Calandria Tube (CT) - Zr-2

Fuel Channels

Pressure Tube (PT) - Zr-2.5% Nb
Pressure Tube-to-Calandria Tube Gap Measurement

• Accomplished by a transmit-receive eddy current based technique applied from the inner diameter (ID) of the PT.
• Utilizes ultrasonic measurements to compensate for effects of PT wall thickness (WT) variations on the eddy current signal.
• In-reactor measurements consist of rotational scans at a fixed pitch or interval.
• Gap is estimated at each rotational position from the eddy current response incorporating information on measured PT ID and WT with design value for CT ID as input.
Generation of Eddy Currents

Transmit Coil
Magnetic Field
Receive Coil
Pressure Tube
Gap
Eddy Currents
Calandria Tube
Lift-Off
Gap Measurement Configuration

- Gap Surface Riding Probe
- Calandria Tube
- Pressure Tube
- Maximum Gap
- Minimum Gap
Technical Justification for Gap Measurement

- Main document produced as part of the qualification process (assumes Procedures, Inspection Specification and training material already exist).
- Identification and evaluation of physical parameters (essential parameters) associated with eddy current based measurement of pressure tube-to-calandria tube gap\(^1\).
- Variability of these parameters on the inspection outcome evaluated.
- Method based on an uncertainty analysis using multiple variable inputs and testing the sensitivity of the system output.

\(^1\)Jang, K., ‘CIQB Instructions for the Contents of a Technical Justification Rev. 0’, CIQB-INS-03, 2008.
Physical Basis for PT/CT Gap Measurement

- Physical basis provides justification for choice of parameters associated with procedure/equipment with regards to detection/sizing of the particular parameter to be measured with reference to essential parameters.

- For eddy current based measurement, the application of the skin depth relation helps identify intrinsic material parameters.

\[ \delta = \sqrt{\frac{\rho}{\pi f \mu}} \]

\( \delta \) – skin depth, \( \rho \) – resistivity, \( f \) – frequency & \( \mu \) – permeability
Identification of Essential Parameters

- Materials (pressure tube, calandria tube, tool).
- Temperature at which measurements are performed.
- Equipment (Example: eddy current instrument, tool)
- Data Analysis (Example without details for gap determined from multi-parameter input),
- System Calibration (multiple calibration facilities designed to simulate in-reactor inspection conditions). Each needs to be characterized.
- Minimization of variation in lift-off.
- Personnel
Evaluation of Essential Parameters

Inputs

- Calibrated Eddy Current Response
- PT Diameter
- PT Wall Thickness

Output

- Estimated Gap

Assumptions: Constant resistivity for PT and CT, constant CT diameter and wall thickness, circular PT, all represented in a calibration facility.
Evaluation of Uncertainty based on Variation of Essential Parameters

• Gap measurement requires input of multi-variable parameters, the variability of which needs to be identified and potential impact on inspection outcome evaluated in order to identify final sensitivity to inspection parameters.

• Given large number of variables, sensitivity tests were performed by experimentally varying parameters over range expected under in-reactor inspection conditions and gap measurement output was evaluated.

• Error analysis was performed looking at outcomes due to variation of parameters in order to obtain an estimate of the uncertainty in the measurement.
Experiments Evaluating Sensitivity of Gap Measurement to Variability in Essential Parameters

- **Systematic error**, as well as error induced by variation of essential parameters **PT resistivity**, **CT resistivity**, and **heat transport temperature** characterized through experiments.

- Comparison between Gap system output and B-Scan of mockup-flooded PT/CT annulus at varying radial positions and gap was used to estimate systematic error. Systematic error was found to be gap-dependent.

- Gap between pressure tubes with varying resistivity and uniform-resistivity calandria tubes scanned and relationship between PT resistivity and gap output determined.
Experiments Evaluating Sensitivity of Gap Measurement Continued ....

- Mockup heat transport temperature varied to estimate effect of varying heat transport temperature on output gap. Both PT resistivity and eddy current coil resistivity affected by change in heat transport temperature.
- Effect of calandria tube resistivity on output gap determined by varying calandria tube temperature, employing relationship between calandria tube temperature and resistivity and examining change in output gap.
- Calandria tube temperature varied by wrapping calandria tube in a floodable jacket with varying temperature.
Uncertainty Analysis

• Uncertainty and bias in error input parameters were used to characterize the uncertainty and bias in output gap.

• Error input parameters defined by systematic error and error due to variation of essential parameters.

• Where $Y$ is gap measurement error and $X_1+...+X_4$ are error contributions from input parameters.

• Error bias $y=x_1+...+x_4$, where $x_1,...,x_4$ are mean input parameter errors.

• Error uncertainty $2\sigma(y)$ computed through $\sigma(y)=(\sigma^2(x1)+...+\sigma^2(x4))^{1/2}$

Reference: JCGM, Evaluation of measurement data – Guide to the expression of uncertainty in measurement. 1st Ed. 2008,
Final Preparation

- Internal/External review.
- Feedback decision: Is inspection goal met or are further:
  - Experiments, knowledge of variables, modeling or inspection refinement required?

Experimental Results → Uncertainty analysis generates overall uncertainty
Essential Parameter Variability → Has Inspection Specification been met?
Modeling → Yes → Submission for Qualification
No
Summary

• Steps taken in preparation for inspection qualification of a many parameter inspection system outlined for specific example of PT/CT gap measurement.
• Essential parameters were identified and varied experimentally to represent variations under in-reactor inspection conditions.
• System response and essential parameters were input into the algorithm that provides estimate of PT/CT gap as an output.
• A multi-parameter uncertainty analysis used to obtain an estimate of the overall uncertainty of estimated gap obtained with the inspection system.
• Results incorporated in Technical Justification, which is used to demonstrate that Inspection Specification requirements met.
• Final internal review, prior to submission to CIQB for review and qualification, performed.
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Questions?