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Canada

Advancements in Probabilistic Approaches for CANDU Components and Systems in Canada

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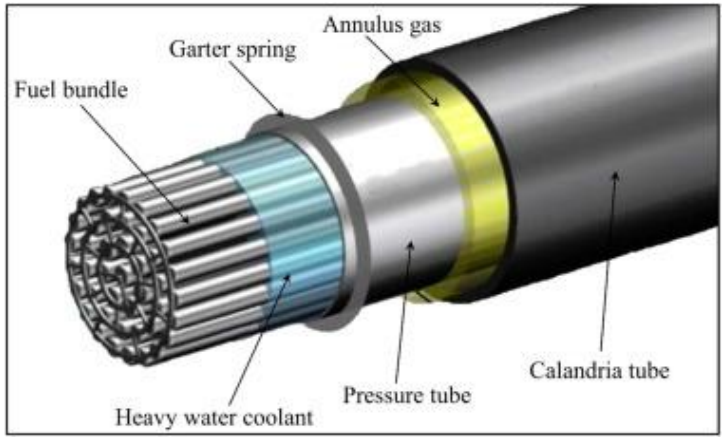
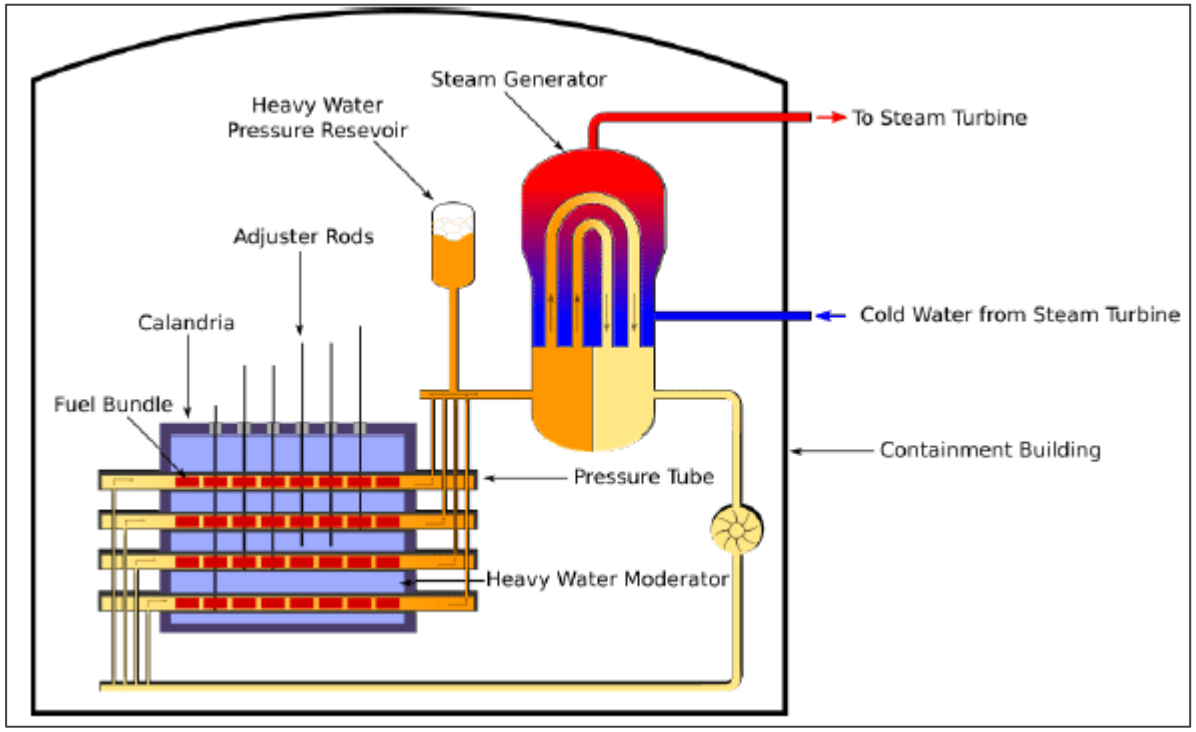
Outline

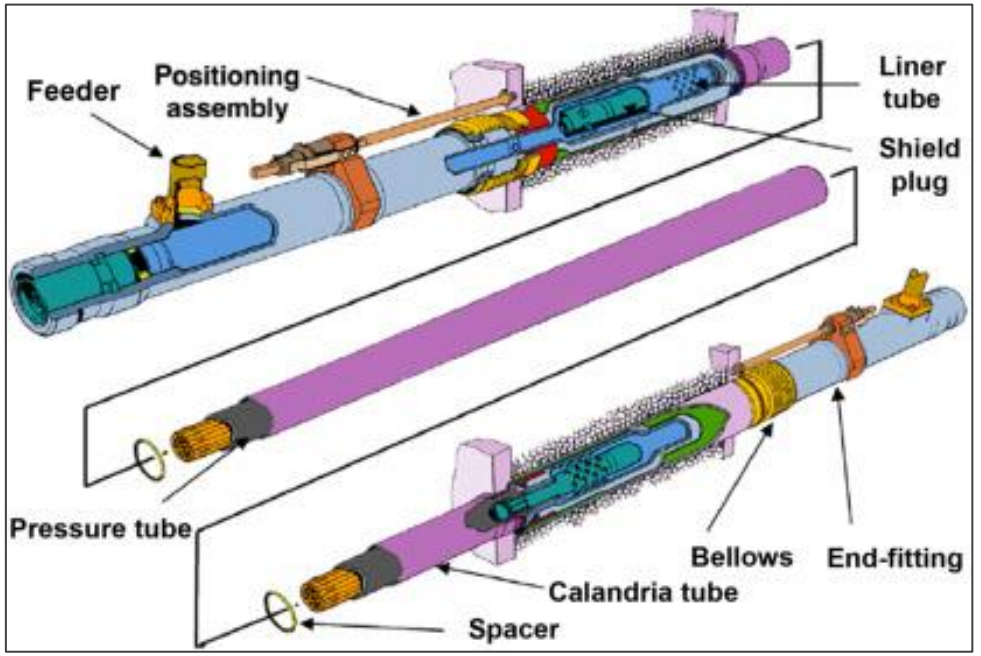
- Introduction
- Pressure tube evaluations
- Uncertainty analysis and simulation convergence
- Feeder evaluations
- Steam generator tube evaluations
- CNSC research projects
- Concluding remarks
- Acknowledgements

CANDU Components and Systems

Multiple fuel channels, feeders and steam generator tubes







Pressure Tube Periodic Inspections

Clause 12 of CSA N285.4: Fuel Channels – Supplementary Inspection

- **Clause 12.2** PT Volumetric and Dimensional Inspections
- **Clause 12.3** PT Hydrogen Equivalent Concentration Determination
- **Clause 12.4** **Clause 12.5**
- **Clause 12.6** Evaluation of Plant Operating Events

Pressure tubes are periodically inspected, including volumetric and dimensional in-field examinations

CSA Standard N285.8

CSA N285.8: Technical Requirements for In-Service Evaluation of Zirconium Alloy Pressure Tubes in CANDU Reactors

Clause 5
Evaluation of Detected Volumetric Flaws

Clause 6
Evaluation of PT-CT Contact

Clause 7
Assessment of Reactor Core
- Protection against Fracture
- Degradation Mechanisms
  - Core Assessment
  - PT-CT Contact
- Leak-before-Break (LBB)

Clause 8
Evaluation of Material Surveillance Measurements

Probabilistic methods are permitted for evaluation of pressure tubes under Clause 7

Evaluation of Pressure Tubes

- CSA standard N285.8 is applied for detailed evaluations of pressure tube inspection findings
  - All requirements of this standard must be satisfied
- The intent of each requirement must be satisfied including while adopting probabilistic methodologies
- Pressure tubes experience in-service degradations and change properties over operating time

Operation of Pressure Tubes

- Pressure tube material made of Zr-2.5 Nb picks up deuterium during operation
- Brittle particles, hydrides, are developed over time
  - Fracture toughness is reduced
- Pressure tubes creep over time and sag with calandria tube
  - The gap between the pressure tube and calandria tube could be decreasing
- More refined methodologies are desired for fitness for service demonstration
  - Probabilistic evaluations have been introduced

Probabilistic Assessments

- Provisions for pressure tube reactor core assessments with probabilistic methodologies are included in CSA standard N285.8
- CSA standard N285.8 is adopted in Canada for reactor licensing

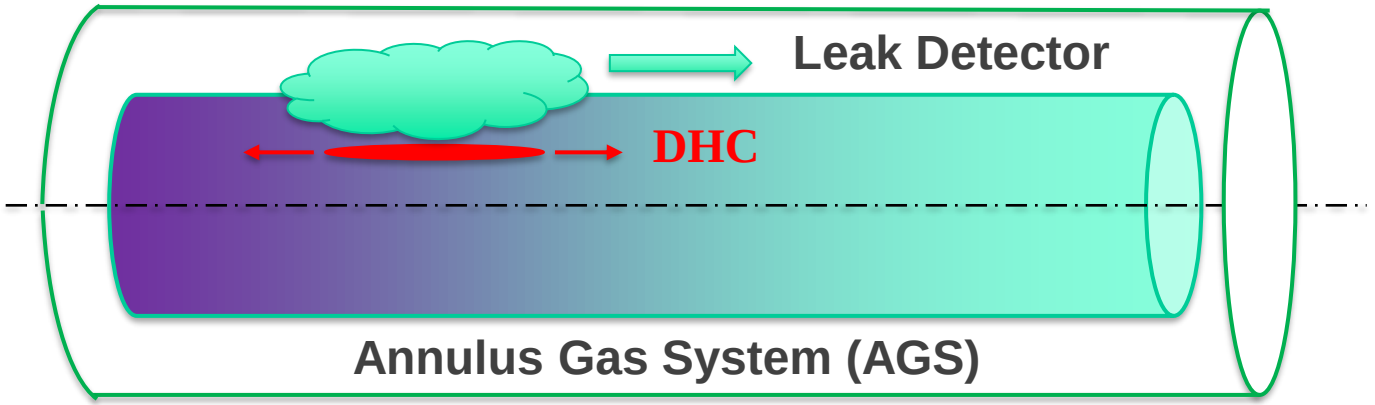
Clause 7 of CSA Standard N285.8 requires reactor core evaluations:

- Reactor core for flaws
- PT-CT contact based on reactor core
- Leak-before-Break (LBB)
- Fracture protection

Probabilistic Core Assessment for Flaws

- Probabilistic core assessment addresses uninspected pressure tubes
- Probabilistic core assessment methodology was accepted by CNSC staff
  - Present inspection data is used to project future reactor conditions, including uninspected pressure tubes
  - Pressure tube failure frequencies are estimated
- Probabilistic acceptance criterion of pressure tube failure, $H_{all\text{-}ig}$, of 0.010 occ/year was accepted by CNSC staff for combined degradation mechanisms

Probabilistic Leak-before-Break



- Probabilistic LBB (PLBB) ensures that sufficient leak detection capabilities and procedures are in place to safely reactor shut down
- Conditional probability of pressure tube rupture given growing though-wall crack with sequence of events
  - Defence in Depth (DiD) consideration

PLBB Acceptance Criteria

- Two methodologies used based on either most limiting pressure tube or reactor core
- Pressure tube crack initiation frequencies, F_{TWC}, were estimated based on pressure tube operating experience for present pressure tube batch

$$P(Failure|TWC) \times F_{TWC} \leq H_{all}$$

$$0.10 \times F_{TWC} \leq 0.010 \text{ occ/y}$$

- CNSC staff accepted conditional probability of failure given growing through-wall crack, of 0.10 for single worst pressure tube $P(Failure|TWC)$ and 0.05 for reactor core

Probabilistic Fracture Protection

- Fracture protection addresses the risk of pressure tube rupture from an undetected surface (partial) or through-wall crack
- Fracture protection for pressure tubes is used to establish reactor P-T operating envelop
- Probabilistic fracture protection methodology establishes lifetime reliability targets for most limiting pressure tube and entire pressure tube core
  - A risk-informed framework is adopted, which also uses insights from deterministic fracture protection evaluation

PT-CT Contact Probabilistic Evaluation

Pressure tube to calandria tube gap is measured during maintenance activities and loose spacers are re-positioned as needed

Pressure tube reactor core is evaluated to demonstrate operability

Under Clause 7, probabilistic evaluation of reactor core PT-CT contact demonstrates that predicted pressure tube failure frequencies are below acceptable per degradation mechanism

Annexes G and H of CSA N285.8

Informative Annex G
on **uncertainty analysis in probabilistic evaluations**
was published in the 2021 Edition of
CSA standard N285.8

Influential sources of uncertainty are identified and a quantitative measure of the impact of these uncertainties on probabilistic evaluation results is assessed to the extent practicable

Informative Annex H

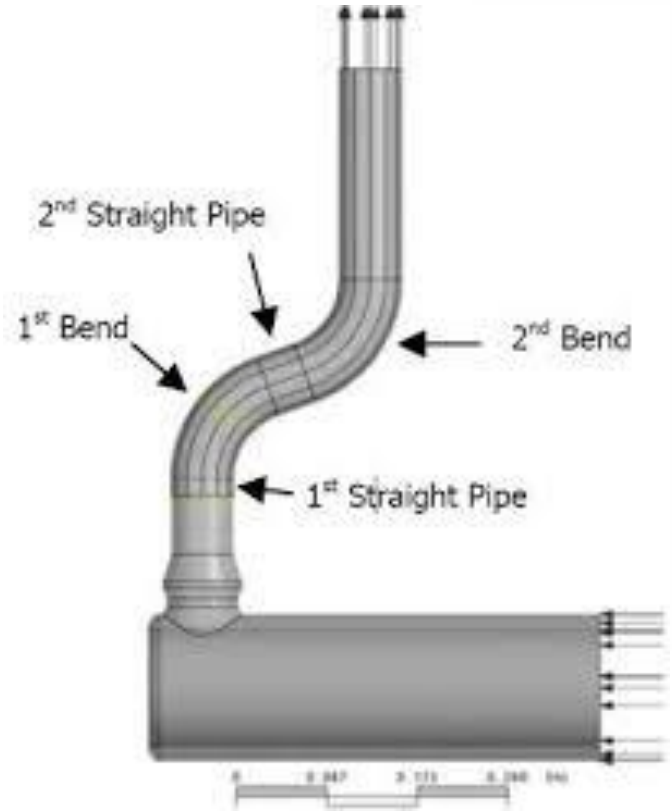
on **the acceptable number of simulations for probabilistic assessments** was published in the 2021 Edition of
CSA standard N285.8

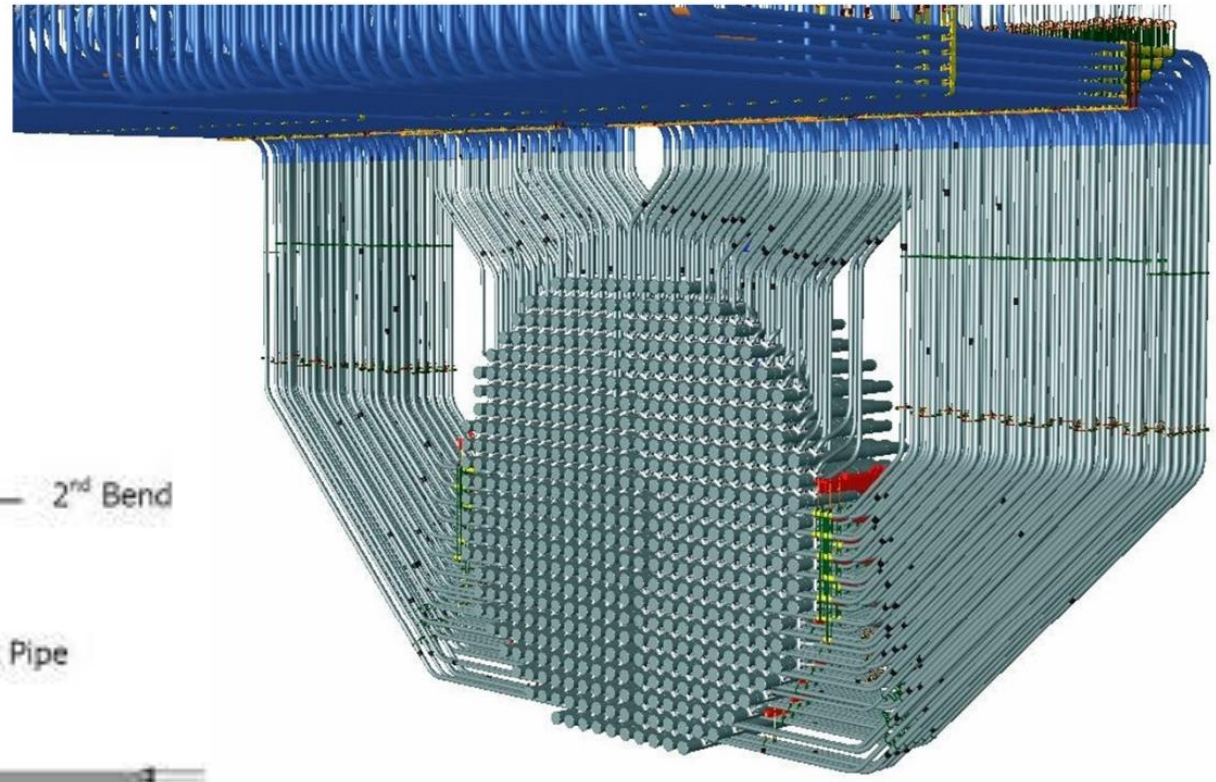
- Minimum required number of simulations
- Convergence criterion used based on evaluation of confidence limit

CANDU Feeders

CANDU feeders manufactured from carbon steel are susceptible to Flaw Accelerated Corrosion (FAC)

Feeder pipe general wall thinning and local wall thinning





Feeder Periodic Inspections

Clause 13 of CSA N285.4: Fuel Channel Feeder Pipes – Supplementary Inspection

Clause 13.2
Feeder Pipe Wall Thickness Measurement

Clause 13.3
Feeder Pipe Visual Inspection

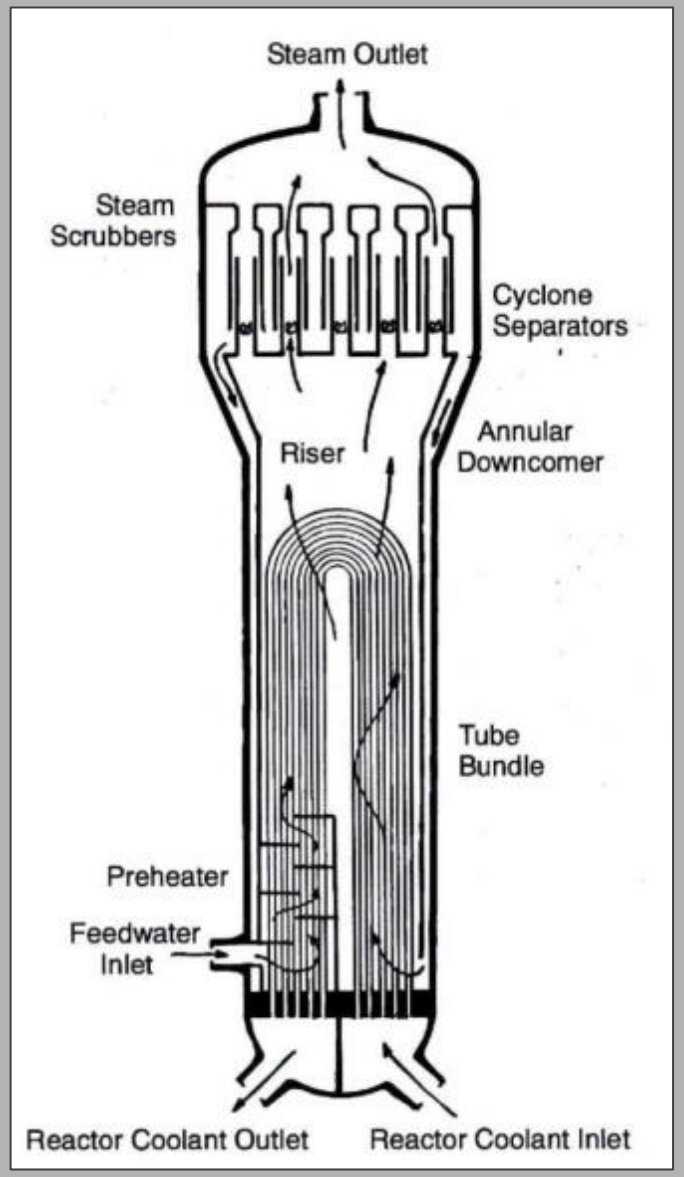
Clause 13.4
Volumetric Inspection of Feeder Piping

Feeder pipes require supplementary inspections followed by fitness for service demonstration to remain in service

Feeders Fitness for Service

- CNSC staff accepted Feeder Fitness for Service Guidelines
  - Provisions for probabilistic evaluations included
  - Probabilistic acceptance criteria have yet to be established
- Some reactors with feeders are in extended operation
- Condition monitoring and operational assessments are performed
- Fitness for service is presently demonstrated strictly on deterministic basis

CANDU Steam Generators



- Steam generator design varies from station to station
  - 515 MWe to 880 MWe
- Number of steam generator tubes increases with increasing power from ~2500 to ~4600
- Materials used are Alloy 400, Alloy 600, and Alloy 800

SG Tubes Periodic Inspections

Clause 14 of CSA N285.4: Steam Generator (SG) Tubes – Supplementary Inspection

Clause 14.2
Volumetric Inspection of Tubing

Clause 14.3
Secondary-Side Tube and Tube Support Visual Inspections

Clause 14.4
Metallurgical Examination of Tubing

Volumetric inspections of steam generator tubes are executed periodically for degradation mechanisms including fretting and others

SG Tubes Evaluations

- Number of flaws in reactor units that exceed specified flaw depth is estimated
  - Flaw depth at Maximum Tolerable Flaw Size (MTFS)
  - Flaw depth at Flaw at Risk of Leakage (FAROL)
- Condition monitoring and operational assessments
- Probabilistic approach is used to assess distribution of flaw depths
- Probabilistic approach is adopted for estimation of flaw growth rate over time

Probabilistic LBB for SG tubes

- Fitness-for-Service Guidelines for Steam Generators and Preheater Tubes were accepted by CNSC staff with conditions
  - Provisions for probabilistic LBB are included
  - Acceptance criterion for probabilistic LBB for steam generator tubes has yet to be fully justified
- Probabilistic LBB for steam generators and preheater tubes has yet to be used in licensing applications

Regulatory Research Projects

CNSC has funded and successfully completed several research and confirmatory projects.

- **R563.1** - Evaluation of Probabilistic Leak-before-Break Methodologies for CANDU Pressure Tubes
- **R564.1** - Review of PRAISE CANDU Probabilistic Fracture Mechanics Code
- **R690.1** - Best Practices for Probabilistic Fracture Mechanics Evaluations
- **R706.1** - Probabilistic Assessments: Principles and Computational Methods

Concluding Remarks

Probabilistic evaluations play an important role in extended operation of CANDU reactors

Probabilistic assessments are presently used on a routine basis

CNSC staff accepted probabilistic methodologies for pressure tube evaluations of Core Assessments, Leak-before-Break, Fracture Protection, and PT-CT contact

CNSC staff concurred with probabilistic acceptance criteria for Core Assessments, PT-CT contact, and Leak-before-Break.
The acceptance criterion for Fracture Protection was accepted with conditions

Acknowledgements

Operational Engineering Assessment Division (OEAD) colleagues, particularly Sankar Laxman and Konstantinos Tsembelis, are acknowledged for contributing to progressive advancements and improvements of probabilistic approaches in licensing applications in Canada

APPENDIX A

This appendix offers responses to the provided upfront panelist questions

Panel: The evolving perception of probabilistic applications in the nuclear regulatory environment

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Question #1

Q: How much has the perception of probabilistic approaches changed over the last three years in your agency?

A: The last three years have seen the increasing use of probabilistic approaches in reactor licence compliance verification. The probabilistic approaches are regarded as more detailed assessment methodologies, although defence in depth principles should be maintained.

Question #2

Q: Have some of the requirements changed to allow increased use of probabilistic analyses?

A: There were no recent changes to the existing requirements to stipulate the use of probabilistic evaluations in fitness for service demonstration. The provisions for probabilistic approaches have been accepted for major components and systems for a considerable time.

Question #3

Q: Compared to three years ago, how do regulatory staff feel about using or reviewing applications with probabilistic analyses?

A: More practical experience and information have been obtained over time while continuing improvements have been made. Staff is technically comfortable with reviewing probabilistic evaluations.

Question #4

Q: What is your regulatory agency's approach toward new technologies such as machine learning and artificial intelligence?

A: Currently, there is no regulatory application of such methodologies in fitness for service demonstration. Some activities have been ongoing at research sites to assess the applicability and readiness of such novel technologies.

Question #5

Q: What would be the role of probabilistic vs. deterministic analyses for the licensing of new reactors (e.g., SMR, non-light water reactors)?

A: Deterministic or probabilistic analyses will be assessed when submitted for a reactor licensing application.

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