Synopsis - The Comprehensive Vibration Assessment Program (CVAP) for AP1000 Reactor Internals

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CAV WORKSHOP
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Outline

- Background of CVAP
- AP1000 Reactor Vessel Internals (RVI) Background
  - Geometry
  - Historical Precedent
- Flow Induced Vibration (FIV) Excitation Mechanisms
  - Turbulence
  - Acoustics
  - Vortex Shedding
- Digital Signal Processing
- Methodology for CVAP Predictions and Test Acceptance Criteria
Background – Nuclear Regulator Requirements

• U.S. NRC Regulatory Guide 1.20 – Comprehensive Vibration Assessment Program for Reactor Internals during Preoperational and Initial Startup Testing

• Four (4) Primary Elements for CVAP to meet Reg. Guide 1.20
  1) Vibration Analysis Program
     • Predictions
     • Acceptance criteria
  2) Vibration Measurement Program
     • Full-scale, Full-flow, Approximate operational temperatures
  3) Inspection Program
  4) Documentation of Results
     • Pre-Test report with predictions and acceptance criteria
     • 60-day Post-Test report – basic results (can load fuel afterwards)
     • 180-day Post-Test report – full FIV analysis report
  5) Schedule

Present work is focused on the Vibration Analysis Program and Test Preparations
## Background – Prediction and Acceptance Criteria

<table>
<thead>
<tr>
<th>Regulatory Guide 1.20 Requirement</th>
<th>Topic of Requirement</th>
<th>Compliance</th>
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</table>
| **Subsection 2.1.2** | Predictions: Hydrodynamic and structural natural frequencies and mode shapes | - Low-frequency system acoustic modal frequencies  
- Structural Modes & Frequencies (System Level FEA and subcomponent FEA) |
| **Subsection 2.1.4** | Design qualification:  
- Must meet ASME code requirements.  
- Stress is primary focus (typically High cycle fatigue related, but not exclusively)  
- Must cover all normal operational scenarios | - Prediction and identification of RVI component structural responses  
- Limiting locations relative to normal operating and test related plant operating configurations  
- Per RVI component |
| **Subsection 2.1.5** | Must compare system and component responses between CVAP and normal operating conditions | General FIV Analysis Methodologies |
| **Subsection 2.1.6** | Predictions at sensor locations (During CVAP Testing):  
- Includes frequencies, mode shapes and amplitudes | Prediction of anticipated structural response at CVAP sensor locations during **CVAP testing**.  
- Low-frequency system acoustic modal frequencies  
- Structural Modes & Frequencies (System Level FEA and subcomponent FEA) |
| **Subsection 2.1.7** | Acceptance Criteria:  
- Related to Stress Must define bases for criteria (Generally High Cycle Fatigue)  
- Must define permissible deviations  
- Must be for limiting stress location on a given component, BUT must related this level to sensor location | Similar to Subsections 2.1.2 and 2.1.6 above  
- Create transfer functions between Max. stress locations for limiting conditions and test sensor locations  
- Considers uncertainties in modeling and measurements |
Per RG 1.20, this is classified as a prototype because its arrangement, design, size, or operating conditions represent a first-of-a-kind or unique design for which no valid prototype exists.
AP1000 Reactor Configuration

- Generation 3+ Pressurized Water Reactor (PWR)
- Flow rate \( (Q) = 315,000 \text{ gpm} \)
- \( T_{\text{cold}} = 535, \ T_{\text{hot}} = 612 \ \text{°F} \)
- Four Reactor Coolant Pumps
- Two Steam Generators
- Direct Vessel Injection

Pilot Plant construction currently nearing completion in China
RVI Overview

Reactor Vessel Closure Head Not Shown
AP1000 Reactor Internals – Historical Precedent

• Although the AP1000 Reactor Internals are classified as prototype due to various first-of-a-kind (FOAK) design features, the *majority* of the AP1000 Reactor Internals design is *similar* to existing plants that have been safely operating for many years.
AP1000 Reactor Internals – Historical Precedent

• Sub-scale model testing
  – $\frac{1}{24}$, $\frac{1}{22}$, and $\frac{1}{7}$ scale tests have been performed for legacy 3-loop and 4-loop plants
  – Demonstrated good agreement between scale model tests and Hot Functional Tests (HFT)* at H.B. Robinson (3-loop), Indian Point (4-loop), and Trojan

• Hot Functional Testing (HFT)* at Trojan has verified the structural adequacy of the AP1000 guide tube design as well as other RVI component configurations

* CVAP testing is a subset of overall plant testing known as Hot Functional Test (HFT)
AP1000 Reactor Internals – Flow-Induced Vibrations

• Excitation Mechanisms
  – Turbulence
    • Cross-flow oscillatory lift/drag
    • Cross-flow direct applied
    • Free and wall bounded jet flow
    • Large Reynolds number (~90E+06) jet impingement and channel flows
  – Acoustics
    • Reactor Coolant Pump Pulsation
    • Turbulence-Induced
  – Vortex Shedding
    – Fluid-elastic instability/Lock-in

The dynamic response of the RVI to flow-induced vibrations is dependent on multiple excitation mechanisms
**AP1000 Reactor Internals – Turbulence**

- The most significant location of Turbulence is in the turbulence channel flow of the Reactor Vessel Downcomer.
- Turbulence jetting through nozzles, buffeting on plates, cross-flow and axial-flow around tubes and tube arrays all occur within the RVI.

**In general, Turbulence dominates the response of the RVI to Flow-Induced Vibrations**

\[
S_{Fy} = \left( \frac{1}{2} \rho U^2 D \right)^2 \cdot \frac{D}{U} \cdot \Phi \left( f \frac{D}{U} \right)
\]

where:
- \( S_{Fy} \) is the generic form of turbulence force PSD
- \( \rho \) is the fluid density
- \( U \) is the flow velocity
- \( D \) is the characteristic dimension
- \( f \) is the frequency
- \( \Phi \) is a function related to the turbulence intensity.
AP1000 Reactor Internals – Acoustics

• Reactor Coolant Pump Pulsation
  – Motor-driven Centrifugal Reactor Coolant Pump pulsates at shaft and blade-passing frequencies
  – **Variable Speed** Reactor Coolant Pump (RCP’s)

• Turbulence-Induced Acoustics at Low Frequencies

Acoustics could excite significant structural modes and thus require extensive analysis.
The acoustic wave equation may be expressed as a combination of the fluid momentum and mass conservation equations:

\[ \nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \]

\[
\left[ i \omega \sum_{i=1}^{n} \frac{L_i}{A_i} + \frac{w}{\rho} \sum_{i=1}^{n} \frac{K_i}{A_i^2} \right] w - \Delta p = \Delta p_B
\]

\[
i \omega p - \frac{c^2}{V} \sum_{j=1}^{m} w_j = 0
\]

**Note:** Acoustic field of entire Reactor Coolant System primary loop calculated

**Summation is accomplished over N nodes and M flow paths**

Acoustics could excite significant structural modes and thus requires extensive analysis.
AP1000 Reactor Internals – Signal Processing

• A test results post-processing and plotting software has been developed that has the following capabilities:
  – Multi-windowing options, filtering options (high, low, pass, notch)
  – Coherent noise reduction (Condition Spectral Density)
  – Autospectra / PSDs
  – Cross-Spectra / Coherence / Phase
  – Circumferential Wavenumber Decomposition
  – Mode shape phase plotter
  – Readily available integration of acceleration to displacement as well as narrowband frequency range definition

• Process/store complete covariance matrix (~ 130 sensors for CVAP + co-process with other plant sensors)

• DAQ/software must make measurement comparisons to acceptance criteria during testing

Preparations for efficient post-processing and plotting of the CVAP Test results
Illustration of Compliance with Regulatory Guide 1.20
Illustration of Compliance with Regulatory Guide 1.20

Maximum Stress Intensity (Limiting Design Condition)

“Predicted” Directional Strain (Limiting Design Condition)

Accommodations are made in the case that the as-tested conditions differ from the limiting design conditions.

Note: There should be small strain gradient in region of sensor placement.

Values here are arbitrary and only shown for purposes of illustration.
Lower Guide Tube Modes

Values here are arbitrary and only shown for purposes of illustration.
Documentation (Reg. Guide 1.20 Required)

- Two (2) separate Post-Test reports Required per Reg. Guide. for submittal to Regulator, per pre-scribed schedule

  - 60-Day Report
    - Tabulation of predictions vs. measurements (benchmarking)
    - Tabulation of measurements vs. acceptance criteria
    - “Confirms” that design is o.k. from an ASME code standpoint

  - 180-Day Report
    - Full FIV analysis report (Exhaustive report of all data and test conditions)
    - Complete benchmarking analyses between measurements and predictions (modal frequencies, shapes and amplitudes)

Confirmatory FIV report must be submitted to Regulator on prescribed schedule
Conclusions

• The Westinghouse AP1000 plant construction is nearing completion and Westinghouse is making preparations for instrumented Hot Functional Testing (HFT) in support of the Comprehensive Vibration Assessment Program

• Extensive analyses are being performed to establish CVAP test predictions and acceptance criteria for which the structural response is driven by various FIV excitation mechanisms, including random turbulence and acoustic phenomena

Flow-Induced Vibrations play a critical role in the completion of the AP1000