SUPPLEMENTAL RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

APR1400 Design Certification

Korea Electric Power Corporation / Korea Hydro & Nuclear Power Co., LTD

Docket No. 52-046

RAI No.:	**151-8078**
SRP Section:	**3.9.2 – Dynamic Testing and Analysis of Systems Structures and Components**
Application Section:	**SRP 3.9.2**
Date of RAI Issue:	**08/10/2015**

Question No. 03.09.02-9

As a result of the audit conducted beginning on June 30, 2015, the staff identified additional detailed information that should be docketed to support the staff's safety finding associated with this section because Tier 2, Section 3.9.2.3.1 does not describe the hydrodynamic model or the method of calculating the forcing functions. In accordance with GDC 1 and 10 CFR 52.47, the applicant is requested to (1) describe how, within the hydrodynamic model, pump pulsation pressure fluctuation was translated to loads on RVI components; and (2) to clarify whether measured test data from one or four pumps were used and justify that the assumption of in-phase pressure fluctuation from four pumps operating is conservative.

Response

(1) The pump pulsation pressures for the RVI components are obtained using the test data for the following representative locations based on the valid prototype CVAP test data (Reference 1):

- RV Inlet Nozzle Location
- Control Element Assembly Guide Tube
- Incore Instrumentation Guide Tube
- Upper Guide Structure Support Plate
- Control Element Assembly Shroud

The RV inlet nozzle location data is used as input in solving the wave equation on the core support barrel (Reference 2). The other location data are also used for obtaining the pump pulsation pressures for the other RVI components as follows, which is described in Reference 2.

- Perpendicular pressure wave: when the pressure wave axis is perpendicular to the axis of the component
- Parallel pressure wave: when the pressure wave axis is parallel to the axis of the component.

The pump pulsation pressures for the RVI components are transferred as input to the structural response analysis. The overall procedure showing the hydraulic load analysis methodology is shown in Figure 3-1, Summary of Analytical Methodology of Reference 2.

(2) The measured data for all available conditions are taken from the valid prototype CVAP test data in accordance with the following steps:

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Accordingly, the assumption of in-phase pressure fluctuation from four pumps is conservative.

Used Measured Test Conditions for RV Inlet Location from Reference 1

Test Condition (PVMP #)	No. of Pumps
1	1
2	2
3	3
4	2
5	2
6	3
7	2
8	3
11	3
12	2
14	2
15	4

Supplemental Response

The analysis methodology for pump induced periodic loads shown in Figure 3-1 of Reference 2 is divided into two parts; the first part pertains to the Core Support Barrel (CSB) and the flow skirt surrounded by the downcomer region and the second part pertains to the other reactor internal components. The detailed analysis methodologies for the two parts are described separately in the following:

a. CSB and Flow Skirt

The pump induced periodic loads for the CSB and the flow skirt are determined using DPVIB. The program is used for analysis of acoustic pressure pulsation in the annulus of the downcomer region. The mathematical model for the program refers to Reference 3, which derives the relationship between the pulsating pump pressure in the inlet ducts and the pressure fluctuations on the CSB outer wall. The summarized description of the model and the flow chart for the calculation is provided in the Attachment.

b. Other components

The pump induced periodic loads for the other reactor internal components (e.g., the upper guide structure, the lower support structure, etc.) are determined using test data and simple mathematical formulae with trigonometrical functions. Because of the complicated configuration inside the CSB, it is impossible to use a mathematical model. The mathematical formulae are shown in the Attachment.

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Second Supplemental Response

This response is being supplemented to add a description of the DPVIB computer program into DCD section 3.9.1 since it was used to provide fluid mode frequencies, the pressure distribution, and Fourier coefficients that resulted in the loads on the CSB support which is considered important to safety.

References

1. CEN-263(V)-P, Rev.1-P, A Comprehensive Vibration Assessment Program for Palo Verde Nuclear Generating Station Unit 1 (System 80 Prototype), Combustion Engineering, Inc., January 1985.

2. APR1400-Z-M-NR-14009-P, Rev.0, Comprehensive Vibration Assessment Program for the Reactor Vessel Internals, KEPCO & KHNP, November 2014.

3. Penzes, L.E., Theory of Pump-Induced Pulsating Coolant Pressure in Pressurized Water Reactors, Nuclear Engineering and Design, Vol. 27, pp.176-188, 1974.

Impact on DCD

DCD Tier 2, Section 3.9.1.2.2.5 will be added as indicated in the Attachment.

Impact on PRA

There is no impact on the PRA.

Impact on Technical Specifications

There is no impact on the Technical Specifications.

Impact on Technical/Topical/Environmental Reports

There is no impact on any Technical, Topical or Environmental Reports.

Analysis Methodology for Pump Induced Periodic Loads

Pump induced periodic loads are separately calculated using totally different 2 methodologies according to reactor internal component location. The reactor internal components are divided into the following 2 groups.

- The Core Support Barrel (CSB) and the flow skirt surrounded by the downcomer region
- Other components not located near the downcomer region

To determine the pump induced periodic loads on the components surrounded by the downcomer region, pressure distribution exerted on the CSB outer wall and the flow skirt is calculated using DPVIB. And to determine the loads on the other components, mathematical formulae with trigonometric function are used. In this attachment, the summarized description (including mathematical model) for DPVIB and the mathematical formulae for pump induced periodic loads on the other components are provided respectively.

1. Description for DPVIB

(1) Mathematical Model

The pressure measured near the inlet duct is related to the deterministic pressure fluctuations on the CSB according to the following hydraulic model. The inlet duct pressure is used to define a forcing function in the model.

The pressure pulsations through the inlet ducts resulting in the pulsation loads on the CSB are defined by the following equation.

$$\nabla^2 P - \frac{1}{C_0^2}\frac{\partial^2 P}{\partial t^2} = \nabla \cdot \overrightarrow{P_d}$$

Where, P is the pressure and C_0 is the sonic velocity. t is the time. $\overrightarrow{P_d}$ is the volumetric driving body force (forcing function).

If the right hand side is eliminated, the general wave equation for free vibration is obtained.

$$\nabla^2 P - \frac{1}{C_0^2}\frac{\partial^2 P}{\partial t^2} = 0$$

The analytical model for the downcomer region can be expressed as follows.

$$\mathrm{P}(\vec{r}, t) = R(r)\Theta(\theta)Z(z)T(t)$$

Where, $R(r)$, $\Theta(\theta)$, $Z(z)$ and $T(t)$ are respectively the solutions for the radial mode, circumferential mode, axial mode and time equations.

The solutions are as follows.

$$R_{ms}(r) = J_m(\tau_{ms}r) + \eta_{ms}Y_m(\tau_{ms}r)$$
$$\Theta_m(\theta) = q\cos(\alpha_m\theta)$$
$$Z_n(z) = a\sin(\beta_n z) + b\cos(\beta_n z)$$
$$T(t) = e^{i\omega t}$$

Where, J_m and Y_m are Bessel functions of the first and second kind. a, b, q and η are arbitrary constants. r, θ and z are the radial, circumferential and axial coordinates, respectively. α, β, τ and ω are variable separation constants.

For describing forced vibration, the forcing function, $\overrightarrow{P_d}$, is assumed to be a periodic pump pulsation as follows.

$$\overrightarrow{P_d} = -\hat{r}P_0\cos(\omega_p t)$$

Where, P_0 is a constant volumetric driving force. ω_p is a pump forcing frequency. And the sign, '-', indicates the inlet flow direction opposite to the radial direction with the origin at the cylinder center.

From the above wave equation and the forcing function, the pressure distribution in the downcomer region is determined by the following analytical solution.

$$P(\vec{r}) = \sum_{n,m,s}^{\infty} C_{nms}Z_n(z)\Theta_m(\theta)R_{ms}(r)\cos(\omega_p t) = \sum_{n,m,s}^{\infty} C_{nms}Q_{nms}\cos(\omega_p t)$$

Where, C_{nms} is Fourier coefficient and it is given as follows.

$$C_{nms} = \frac{C_0^2}{\omega_{nms}^2 - \omega_p^2}a_n b_m c_{ms}$$

$$a_n = \frac{\int_{z_1}^{z_2} Z_n(z)\,dz}{\int_0^L Z_n^2(z)\,dz}$$

$$b_m = \frac{\int_{-\Delta\theta}^{\Delta\theta} \Theta_m(\theta)\,d\theta}{\int_0^{2\pi} \Theta_m^2(\theta)\,d\theta}$$

$$c_{ms} = \frac{\int_{r_1}^{r_2} \delta(r - r_2) R_{ms}(r) r \, dr}{\int_{r_1}^{r_2} R_{ms}^2(r) r \, dr}$$

For the detailed mathematical model, refer to Penzes' paper (1974).

(2) Calculation Process

The flow chart of DPVIB is shown in Figure 1. The calculation process consists of 3 steps of preparation, calculation and output generation as shown in the figure.

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(3) Standard DPVIB Input File

The form of standard input file for DPVIB is as below. The index at the head of each line is given to indicate a line number. This input data are just an example.

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(4) Reference

Penzes, L.E., Theory of Pump-Induced Pulsating Coolant Pressure in Pressurized Water Reactors, Nuclear Engineering and Design, Vol. 27, pp.176-188, 1974

2. Mathematical Formulae for Pump-Induced Periodic Loads on the other Components

The pump induced periodic loads on the components, which are not located near downcomer region, are determined for the following 2 cases according to pressure wave axis direction.

- Perpendicular Pressure Wave: when the pressure wave axis is perpendicular to the component
- Parallel Pressure Wave: when the pressure wave axis is parallel to the component

(1) Perpendicular Pressure Wave

When the pressure wave axis is perpendicular to the component, the pressure differential across the component is provided. The pressure pulsation is calculated by the following equation.

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(2) Parallel Pressure Wave

The pressure wave parallel to the component is shown in Figure 3. The one-half wave length can be comparable to the diameter of the component (such as fuel alignment plate) and the pump-induced load on the component is sizable.

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3.9.1.2.2.3 CESHOCK

The CESHOCK program is used to obtain the transient response of the reactor internals and fuel assemblies due to pipe break and seismic loads.

The computer program CESHOCK determines the response of structures that can be represented by lumped-mass and spring systems subjected to a variety of arbitrary-type loadings. Further description is provided in Reference 27.

CESHOCK has been verified by demonstration that its solutions are substantially identical to those obtained by hand calculations or from accepted analytical results via an independent computer code. The details of these comparisons are available in References 26 and 27.

3.9.1.2.2.4 CEFLASH-4B

The CEFLASH-4B computer code (Reference 28) predicts the reactor coolant system pressure and flow distribution during the subcooled and saturated portion of the blowdown period of a LOCA. The equations for conservation of mass, energy, and momentum, along with a representation of the equation of state, are solved simultaneously in a node and flow path network representation of the primary RCS.

CEFLASH-4B provides transient pressures, flow rates, and densities throughout the primary system following a postulated pipe break in the RCS.

The CEFLASH-4B computer code is a modified version of the CEFLASH-4A code (References 29 and 30). The CEFLASH-4A computer code has been approved by the NRC (References 31 through 33). The capability of CEFLASH-4B to predict experimental blowdown data is presented in Reference 28.

3.9.1.2.2.5 DPVIB

The DPVIB program is used to calculate fluctuating pressure distribution in the downcomer region caused by RCP pressure pulsation.

Main inputs of DPVIB are system pressure, temperature and pump forcing frequency. The pressure distribution in the downcomer region is obtained by solving the acoustic wave equation using an analytical method described in Reference 41. The DPVIB program also generates Fourier coefficients that are used in the stress analysis of the CSB.

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