# SUPPLEMENTAL RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

**APR1400 Design Certification**

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

**Docket No. 52-046**

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| **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** |

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## 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.

<u>Used Measured Test Conditions for RV Inlet Location from Reference 1</u>

| 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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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.

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**Impact on DCD**

There is no impact on the DCD.

**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 $\eta$ are arbitrary constants. $r$, $\theta$ and $z$ are the radial, circumferential and axial coordinates, respectively. $\alpha$, $\beta$, $\tau$ and $\omega$ 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. $\omega_p$ 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. <u>Mathematical Formulae for Pump-Induced Periodic Loads on the other Components</u>

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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## Question No. 03.09.02-10

DCD Tier 2, Section 3.9.2.3.1.1 states that the random hydraulic forcing function is developed by experimental methods and the forcing function is modified to reflect the flow rate and density differences based on an analytical expression found in Reference 45. However, the staff did not find an expression that is physically suitable to modify the random turbulent flow loadings represented by power spectrum density. In accordance with GDC 1 and 10 CFR 52.47, the applicant was requested to provide a description of the experimental methods and the analytical expression that modified the random forcing functions.

## Response

The wording used in the DCD Tier 2, Section 3.9.2.3.1.2 was intended to indicate that the random hydraulic forcing function is developed based on the System 80 CVAP testing data. A DCD markup is attached to include a more accurate description. Reference 45 used in DCD Tier 2, Section 3.9.2.3.1.2 provides several expressions for the normalized power spectral density (PSD) which are of the following form:

$$\frac{G_p(f)}{\rho^2 V^3 D_H} = \overline{G_p}(F) = \text{a function of } F$$

where,

$f$ = frequency
$\rho$ = Fluid density
$V$ = Velocity
$D_H$ = Hydraulic equivalent diameter

$G_p(f)$ = PSD
$\overline{G_p}(F)$ = Normalized PSD
$F$ = Dimensionless frequency $\left(=\frac{fD_H}{V}\right)$

The expressions show that $G_p(f)$ is related to the fluid properties ($\rho$ and $V$) when the normalized PSD is restored to the original PSD. The forcing function is modified when required to reflect the flow rate (velocity) or density differences between the testing data and the design.

**Supplemental Response**

The expressions are found on pages 233 through 236 of Reference 45 used in DCD Tier 2, Section 3.9.2.3.1.2. Equations 8.67 through 8.72 of Reference 45 include the normalized PSD of the same form mentioned in the response.

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**Impact on DCD**

The DCD Tier 2, Section 3.9.2.3.1.2 will be revised 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.

### 3.9.2.3.1 Hydraulic Forcing Function

#### 3.9.2.3.1.1 Deterministic Forcing Function

An analysis based on a hydrodynamic model is used to obtain the relationship between RCP pulsations in the inlet ducts and the deterministic pressure fluctuations on the core support barrel. A detailed description of this model and subsequent solution are given in References 41 and 42. The model represents the annulus of coolant between the core support barrel and the reactor vessel. In deriving the governing hydrodynamic differential equation for the model, the fluid is taken to be compressible and inviscid. Linearized versions of the equations of motion and continuity are used. The excitation on the hydraulic model is harmonic with the frequencies of excitation corresponding to pump rotational speeds and blade passing frequencies.

The dynamic force on the upper guide structure assembly is due to flow-induced forces on the tube bank. The deterministic components of these forces are caused by pressure pulsations at harmonics of the pump rotor and blade passing frequencies, and vortex shedding due to crossflow over the tubes.

The in-core instrumentation (ICI) nozzles and the skewed beam supports for the ICI support plate of the lower support structure are excited by deterministic and/or random, flow-induced forces. The deterministic component of this loading is due to pump-related pressure fluctuations and vortex shedding due to crossflow.

Data from the System 80 preoperational test (References 43 and 44) is used to determine the magnitude of these pulsations at the pump rotor and blade passing frequencies and their harmonics.

based on the System 80 preoperational test (Reference 44)

#### 3.9.2.3.1.2 Random Forcing Function

The random hydraulic forcing function is developed ~~by experimental methods~~. The forcing function is represented in the form of power spectral density together with associated coherence area. The forcing function is modified to reflect the flow rate and density differences based on an analytical expression found in Reference 45.