REVISED 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.:	**549-8856**
SRP Section:	**03.12 – ASME Code Class 1, 2, and 3 Piping Systems and Piping Components and Their Associated Supports**
Application Section:	**3.12**
Date of RAI Issue:	**07/07/2017**

Question No. 03.12-19

ASME BPV Section III, mandated by 10 CFR 50.55a, requires that the structural evaluation of systems, structures, and components important to safety consider combinations of various loadings, including dead weight (DWT), pressure, seismic, thermal expansion and transient loads from system operating transients. Topical Report APR1400-Z-M-TR-12003-P-A (ML17129A596), “Fluidic Device Design for the APR1400” and technical report APR1400-K-ANR-14005-P Rev.0 (ML14164A170), “CFD Analysis of Fluidic Device” both discuss the operation and the performance of the safety injection tank fluidic device (SIT-FD). The computational fluid dynamics (CFD) modeling, using full scale experimental data, showed that vaporous cavitation can occur in the center of the exit nozzle and the discharge tube for both large and small flow modes.

a) The staff would like to understand whether and how cavitation effects and vibration originating from the operation of the SIT and its FD have been taken in to account in the structural design evaluation of the SIT, its discharge piping and pipe supports.

b) Also please discuss whether the operation of the SIT with its FD can result in other phenomena, such as water hammer, and how their effects have been accounted for in the structural design of SIT, FD, piping and supports.

c) In addition, please discuss whether the structural evaluation model of the SIT is coupled with the FD. If decoupled, please discuss how consideration for protection against resonance has been accounted for.

Response – (Rev. 1)

a) 1. Resonance due to Cavitation

As discussed in the technical report “CFD Analysis of Fluidic Device,” APR1400-K-A-NR-14005 [1], cavitation was apparent at the discharge tube of the fluidic device.

Cavitation bubbles are created when the static pressure of a liquid locally drops to the vapor pressure of the liquid. The bubbles collapse suddenly in the downstream region where the static pressure exceeds the vapor pressure. When the bubble collapses, non-periodic high frequency noises are generated. Data from numerous experiments show the implosion bubble noises are of about 5 kHz and above [2], [3].

Generally, the possibility of resonance caused by flow induced vibration is investigated by comparing the flow characteristic frequency and the natural frequencies of the components. The natural frequencies of the safety injection tank (SIT) and safety injection (SI) line, including supports, were calculated by using commercial software such as ANSYS and PIPESTRESS. Table 1 shows the natural frequencies of the SIT and safety injection line. Schematics of these structures are displayed in Figures 1-1 and 1-2. The table reveals that the first five modal frequencies of the SIT and discharge piping are less than [ ]TS. Since the cavitation noises are non-periodic and their frequencies are much higher than the modal frequencies of the SIT and the SI line, there exists no possibility of resonance due to the cavitation implosion.

Table 1 - Modal Frequencies of the SIT and SI line (units: Hz)

TS

TS

Figure 1-1. Schematic of the SIT and Fluidic Device

TS

Figure 1-2. Schematic of the SI line

a) 2. Resonance due to Vortex Breakdown

The solid surface in the cavitation zone can be impaired by cavitation erosion if it is exposed for a long enough time under severe cavitation conditions. The SIT with the fluidic device is designed to mitigate the hypothetical large break loss of cooling accident. Since the loss of coolant accident is assumed to occur once during the 60 year operation [4], it is not necessary to take cavitation erosion into account in the design of the fluidic device and discharge tube.

Swirling flow is observed in the flow through draft tubes of hydraulic turbines [5]. If the flux of angular momentum entering the discharge tube is large enough as compared to the flux of axial momentum, a recirculation flow known as vortex breakdown occurs along the centerline of the tube. It has long been recognized that the formation of a vortex breakdown can create flow oscillation in the tube.

Swirling flows inside the fluidic device vortex chamber and vortex breakdown in the discharge tube were observed [1] in the CFD analysis results. Swirling flow increases flow resistance due to the rotational motion. Vortex breakdown also increases flow resistance caused by the flow blockage effect. The fluidic device uses these mechanisms to control the flow rate of safety injection water. Due to the formation of vortex breakdown, flow oscillation is expected to occur in the discharge tube of the SIT. This oscillation can increase the risk of excessive structural vibration when the flow characteristic frequency coincides with the structural frequencies.

Systematic experimental study on the pressure oscillation in draft tubes of hydraulic turbines was conducted by Palde [6]. Those experiments were conducted for the model with wicket gates and various tube shapes. The structure of the test rig to create swirl is similar to the vortex chamber and discharge tube of the fluidic device.

Palde obtained the correlation between draft tube shape and the characteristic frequencies. He used the frequency parameter $(fD^3)/Q$, the momentum parameter $\Omega D/(\varrho Q^2)$, and dimensional parameter L/D to compare experimental results from various tubes. In defining the parameters, f = frequency; D = throat diameter of tube;

Q =volumetric flow rate; Ω =angular momentum flux entering the tube; ρ = density; L =length of tube, respectively.

In order to assess the possibility of resonance caused by vortex breakdown, the CFD analysis results were compared with Palde's draft tube experiments [6]. Palde tested 75 distinct tube shapes. Most of them were simple geometrical shapes or combinations of straight circular cylinders, truncated diverging cones, and circular cross-sectional elbows. However, it is determined that there is not an identical shape corresponding to the fluidic device discharge nozzle in Palde's tests. Therefore, the most approximate shape in the Palde's tests is used to estimate the frequency parameter. Figures 2-1 to 2-3 show the dimensions of the fluidic device compared to Palde's discharge tubes.

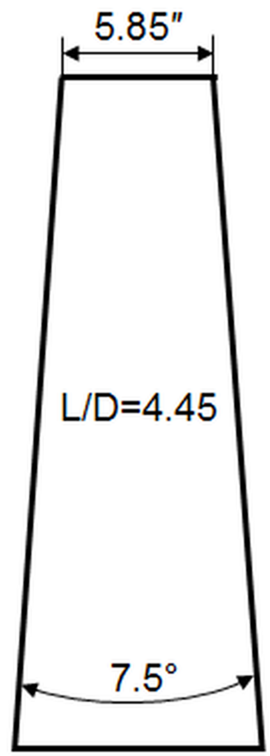

Figure 2-1. Dimensions of Discharge Tube Used in Palde's Experiment

TS

Figure 2-2. Dimensions of SIT Exit Nozzle

TS

Figure 2-3. Dimensions of SIT Discharge Tube Connected to the Exit Nozzle

Figures 3-1 to 3-5 display the tangential velocity distributions obtained from the CFD analyses.

TS

Figure 3-1. Tangential Velocity Distributions for L-CASE1

TS

Figure 3-2. Tangential Velocity Distributions for L-CASE2

TS

Figure 3-3. Tangential Velocity Distributions for S-CASE1

TS

Figure 3-4. Tangential Velocity Distributions for S-CASE2

TS

Figure 3-5. Tangential Velocity Distributions for S-CASE5

Table 2 - Flow Variables and Momentum Parameters Obtained from the CFD Analyses

TS

Table 2 shows the variables and momentum parameters obtained from the CFD analyses for the various flow cases specified in the technical report [1]. Among the variables, Ω is approximated by [ ]TS. V_θ is the tangential velocity at the discharge tube throat.

The frequency parameter is predicted from Palde's experiments for the truncated cone type discharge tube. The momentum parameters are not exactly the same as Palde's data and at smaller flows, (i.e., S-CASE1, S-CASE2, and S-CASE 5 – Figure 3-3, Figure 3-4, and Figure 3-5) the parameters exceed the experimental range. Accordingly, a linear fit based on Palde's data is utilize to estimate frequency parameters.

Figure 4 shows the predicted frequency parameters for the large and small flow cases. The characteristic frequencies associated with the predicted frequency parameters are summarized in Table 3.

As seen in Tables 1 and 3, the frequencies from vortex breakdown are much higher than the structural frequencies of the SIT and SI line. From this fact, it can be

concluded that the probability of structural resonance due to vortex breakdown is very low in the SI system.

TS

Figure 4. Frequency Parameter Predicted from Palde's Experimental Data [6]

Table 3. Frequency Parameters and Predicted Frequencies

TS

The fluidic device was tested over 100 times by KAERI (Korea Atomic Energy Research Institute). In spite of the large series of tests, no damage was found. This further ensures that flow oscillation does not cause serious structural problems in the SI system.

Reference

[1] APR1400-K-A-NR-14005, CFD Analysis of Fluidic Device

[2] C. E. Brennen, "An Introduction to Cavitation Fundamentals," Turbo-machinery & Medical Applications WIMRC FORUM (2011)

[3] J. F. Gulich, Centrifugal Pumps, Springer Verlag (2007)

[4] APR1400 DCD Tier 2

[5] E. Naudascher and D. Rockwell, Flow-induced Vibration: An Engineering Guide

[6] U. J. Palde, "Influence of Draft Tube Shape of Surging Characteristics of Reaction Turbines," REC-ERC-72-24 (1972)

b) Generally, water hammer occurs in piping systems which experience rapid changes in water velocity. Quick isolation valve opening or the gas accumulation in the SIT discharge line may be potential reasons for water hammer.

During pre-operational testing (SIT discharge line isolation valve operation test [DCD Tier 2 14.2.12.1.22]) and SIT blowdown testing (DCD Tier 1 Safety Injection System ITAAC Table 2.4.3-4 9.a), the water inside the SIT is discharged into the reactor vessel. The isolation valve is initially closed to keep the water inside the SIT. The discharge will then be started by opening the isolation valve. The valve, designed with a stroke time of approximately 30 seconds, opens so slowly that water hammer is not expected to occur during the pre-operational testing.

During pre-operational testing, water stored in the SIT is discharged into the reactor vessel. The flow is not compressed on the downstream of the piping because the vessel is empty and open to the containment atmosphere. In a LBLOCA event during a plant normal condition, the SIT discharge line isolation valve is already open. Therefore, a rapid decrease in the RCS pressure induces the quick injection of the water inside the SIT into the reactor vessel. However, the break in the RCS should be so large as to decrease the RCS pressure rapidly. Therefore, the reactor vessel condition could be also regarded as a vessel opened to the atmosphere. Therefore, water hammer is not expected to occur during the pre-operational testing or Large Break LOCA event.

The SIT discharge line is filled with water by gravity from the Safety Injection Filling Tank (SIFT) during the plant overhaul period. With the filling procedure, the air which may be accumulated in the piping is removed through the vent valve. In addition, the SIT discharge line is usually in the pressurized condition. Therefore, there is no possibility of air intrusion from the outside of the piping during normal plant conditions.

c) A structural evaluation model of the SIT for seismic analysis is coupled with the fluidic device because it is installed inside of SIT with support welding. Therefore, a resonance of fluidic device is considered in the seismic analysis for the SIT. Figure 5 shows the structural evaluation model for the SIT, including the FD.

TS

Figure 5. Seismic Analysis Model for the SIT

Supplemental Response based on NRC Feedback

a) NRC noted that KHNP should provide reasonable assurance that vibration effects on the structural integrity of the safety injection line through the initial test program.

KHNP has modified DCD Section 14.2.12.1.22 to state that the safety injection tank subsystem test is modified to assure the vibration effect on the safety injection line (see Attachment).

b) NRC comments on Revision 0 of Question 03.12-19 (b) stated that "water hammer damage has been observed at other plants. The root cause, at least at Palo Verde and Calvert Cliffs, was determined to be due to back leakage of the SI check valve, which led to steam bubble formation in the piping between the check valve and the SI tank."

KHNP has reviewed the material provided by the NRC for applicability to the APR1400. This material has included NUREG/CR-2781, NUREG-0927, NUREG/CR-6519, Information Notice 91-50, Information Notice 97-40, WCAP-15628 (H.B.Robinson), WCAP-15837 (Ginna), and WCAP-16029 (Callaway). As a result of KHNP's review,

the case studies reviewed indicate no direct applicability to potential water hammer events in the Safety Injection System /SI tank of APR1400.

In the APR1400, the voids or steam bubbles formation in the safety injection line during the test and normal operation will not be expected due to the following reasons:

- Venting is provided for safety injection line
- Monitoring is also provided using the pressure instrument when the back leakage occurs through the 1st check valve from the RCS
- All valves are tested periodically following the In-service Test Plan during the plant operation. The test procedures for the Safety Injection System will be prepared incorporating the previous water hammer events
- Normal operating pressure is 610 psig and normal operating temperature is 50~120°F in the piping between the 1st check valve and the SI tank (upstream of 1st check valve). Normal operating pressure is 2,250 psig and normal operating temperature is about 600°F in RV downcomer (downstream of 1st check valve). The boiling temperature is about 490°F under the 610 psig condition. Therefore, the temperature should be higher than 490°F for boiling when the relatively large amount of water volume of 50~120°F are mixed with the small leakage of 600°F. The temperature will be below 490°F if the leakage is within the acceptance range. If the leakage is a large amount that elevated the temperature above 490°F (actually it is not a leakage but a check valve failure), the pressure will also increase over 610 psig and the boiling temperature will increase. The pressure in the piping between the 1st check valve and the SI tank is monitored in the MCR during normal operation, and the alarm is annunciated to the MCR when the pressure is above 1,000 psig, requiring an operator's action.

Based on the above discussion, steam bubble formation in the piping between the 1st check valve and the SI tank is difficult. If a steam bubble may be formed in the piping between the 1st check valve and the SI tank, it is expected that the steam bubble will be immediately condensed by the surrounding relatively cold water. In addition, for the leakage through the 1st check valve, there would have to be another simultaneous leakage (for example, leakage through the check valve at the downstream of the SI tank), since the piping between the 1st check valve and the check valve at the downstream of the SI tank is maintained under water solid condition initially.

However, even though Safety Injection System is designed to prevent water hammer by eliminating possible void, an analysis was performed in response to the NRC's additional comment to confirm that a potential water hammer load are within the design limit. The analyses consisted of the following steps:

1. Pressure calculation due to water hammer (pump run-out condition, pump rated condition, void condition)

2. Force calculation due to water hammer (pump run-out condition, pump rated condition, void condition)

3. Generation of force time history due to water hammer

4. Application of force acting at a point of the piping system (e.g. elbow)

Table 1 summarizes the load combinations using the square root of the sum of squares method. Table 2 summarizes the load definitions.

Table 1 Load Combinations

TS

Table 2 Load Definitions

TS

Table 3 is the results of SI piping analysis by incorporating water hammer. All pipe stresses meet applicable code allowable.

Table 3 Piping Analysis Results by Incorporating Water Hammer

TS

Finally, Table 4 summarizes the support margin by incorporating the impacts of water hammer. A load safety factor (LSF) is applied to the pipe reaction load to determine the support design load. All of the supports on the SI piping subsystem are acceptable in the existing support design.

Table 4 Review of Support Load Incorporating Water Hammer

TS

APR1400 Safety Injection System is designed to prevent the water hammer by eliminating possible void trap in the system based on NUREG/CR-6519. These preventive design features are system pressure instrumentation and SIT level and pressure instrumentation for leakage monitoring, pipe slope and length condition for screening out the steam bubble collapse induced water hammer, high point vent valves, filling tank and periodic surveillance for checking water filled condition.

However, based on NRC feedback, the pressure and dynamic forces on the piping system due to SIT blowdown are calculated. This section evaluates hydraulic load on the SIT discharge piping during SIT blowdown without water hammer to the reactor vessel. A summary of the analysis approach is summarized below.

1) SIT discharges during test condition and actual accident condition. Test condition uses MOV opening which is relatively slow, and the discharge load will be bounded

by accident condition. SIT blowdown when initially isolated during shutdown condition would be the same as test condition.

2) During small break LOCA, Reactor Vessel pressure decrease may not be lower than SIT pressure. If the pressure decreases below SIT pressure, the flow rate will be less than that for large break LOCA.

3) Maximum discharge load will occur when RV pressure decreases abruptly during large break LOCA.

4) The maximum hydraulic load during the SIT blowdown is expected to occur with maximum flow rate at the discharge piping.

5) The dynamic pressure of [ ]TS is calculated based on the NUREG/CR-6519 Equation 4-2. The pressure is applied to the piping structural analysis.

6) The pressure is converted to the force applied to the piping system.

7) The evaluation results of the piping system are summarized in Table 5 and 6. Table 5 is the results of SI piping analysis by incorporating SIT blowdown. All pipe stresses meet applicable code allowable. Table 6 shows the support margin by incorporating SIT blowdown. All of the supports on the SI piping subsystem are acceptable in existing support design.

Table 5 Piping Analysis Results Incorporating SIT blowdown

[ ] TS

Table 6 Results of Support Load by Incorporating SIT Blowdown

TS

Impact on DCD

DCD Tier 2 Chapter 14, Subsection 14.2.12.1.22 will be revised as shown 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 Report.

1.5 To demonstrate valve response to SIAS

1.6 To verify instruments alarm setpoints

1.7 To demonstrate SIT vent valve venting capability

1.8 To demonstrate SIT hydraulic performance

1.9 To verify SIT outlet valve operability in response to maximum differential pressure between SITs and RCS

1.10 To demonstrate "Pull to lock" verification

1.11 To demonstrate valve response to power removed condition

2.0 PREREQUISITES

2.1 Construction activities on the SIT subsystem have been completed.

2.2 Support systems required for the operation of the SIT subsystem are complete and operational.

2.3 Adequate supply of makeup water from the IRWST is available.

2.4 The reactor vessel head and internals have been removed.

2.5 The reactor vessel is filled above the DVI nozzles.

2.6 SIT subsystem instrumentation has been checked and calibrated.

2.7 All lines in the safety injection system have been filled and vented.

2.8 Temporal vibration instrumentation on the SIT subsystem has been installed and calibrated.

3.0 TEST METHOD

3.1 Operate power-operated valves from all appropriate control locations and observe valve operation and position indication. Where required, measure valve opening and closing times.

3.2 Verify power-operated valves fail to the position specified in Subsection 6.3.2 upon loss of motive power.

3.3 Simulate an SIAS signal and observe valve interlock and alarm operation.

3.4 Fill the SITs from the IRWST and observe level indication and alarm operation.

3.5 Pressurize the SITs and observe pressure indication, control, and alarm operation.

3.6 Simulate an SIAS to each SIT and measure the time required for the SITs to discharge their contents to the RCS and measure the flow rate and the flow turndown time by fluidic device.

3.7 Pressurize each SIT to its maximum operating pressure and verify each SIT discharge valve open.

4.0 DATA REQUIRED

4.1 Valve position indications

4.2 Valve opening and closing times, where required

4.3 Position response of valves to loss of motive power

4.4 System response to SIAS

4.5 Setpoints at which alarms and interlocks occur

4.6 Times required for SITs to discharge their contents to the RCS

4.7 Flow turndown times required for SITs

4.8 Flow rate required for SITs when discharging their contents to the RCS

4.9 SIT pressure when stroking valves

4.10 Vibration of SIT subsystem pipes

5.0 ACCEPTANCE CRITERIA

5.1 The SIT subsystem performs as described in Subsection 6.3.2.2.2.

5.2 SIT subsystem valves can be open and closed by their respective hand switches and status is indicated as specified

5.3 Valves stroke time (open and close) without flow should meet required time

5.4 SIT system valves fail to the required position on loss of air and power and go to the position indicated upon restoration of air and power

5.5 Specified valves in SIT subsystem responses to SIAS

5.6 Specified initially closed valves can be power removed from the valve and switches at the MCR and RSR. Also the following initially open valves can close and be power removed at the MCR and RSR

5.7 SIT Subsystem level instrument alarm setpoints are verified

5.8 SIT Subsystem pressure instrument alarm setpoints are verified

5.9 SIT control valve interlocks are verified

5.10 SIT venting capability is demonstrated by each vent valve depressurizing SIT in less than required time

5.11 SIT hydraulic performance is demonstrated by each of the four SITs discharging its contents to the RCS from an initial wide range level and pressure which is provided by vendor, and the resistance coefficients in high flow and low flow mode are within required design range

5.12 Valves response to specified differential pressure between SITs and RCS pressure

~~5.13 The vibration frequency of SIT subsystem should avoid the natural frequency of the SIT subsystem~~

5.13 Piping vibration is within acceptable limits and meets the criteria of ASME OM S/G Part 3.

14.2.12.1.23 Engineered Safety Features – Component Control System Test

The internal functions of the ESF-CCS are confirmed through factory acceptance testing. The basis of this in-plant test is to confirm the correct installation of the ESF-CCS, including inter-cabinet cable interfaces, and interfaces to other I&C systems, plant instrumentation and the controlled plant components. This test includes samples that