한국소음진동공학회 2013년 춘계학술대회논문집, pp. 589~595

Comprehensive Vibration Assessment Program Measurement Test Plan for Advanced Power Reactor 1400

신형경수로 1400 종합진동평가프로그램 측정시험 계획

Do-Young Ko and Kyu-Hyung Kim

고도영† · 김규형*

Key Words : CVAP(종합진동평가프로그램), APR1400(신형경수로1400), Measurement(측정)

ABSTRACT

A reactor vessel internals comprehensive vibration assessment program(RVI CVAP) of an advanced power reactor 1400(APR1400) is being verified on the integrity of RVI for the design life of the plant by performing the non-prototype category-2 type on the US Nuclear Regulatory Commission Guide(NRC RG) 1.20, for which consists of a vibration and stress analysis program, a limited vibration measurement program, an inspection program, and the correlation of these programs. The aim of this paper is to describe the plan for the vibration measurement, test and acceptance criteria portion, and documentation and results of the APR1400 RVI CVAP. We will conduct the limited vibration measurement program of the APR1400 RVI CVAP according to the measurement plan and the vibration measurement testing in this paper.

요 약

미국 원자력규제위원회 규제지침(US NRC RG) 1.20의 비원형범주(non-prototype category)-2를 기준으로 신형경수로 1400(APR1400) 원자로내부구조물(RVI)의 설계수명기간 동안 건전성이 확보될 수 있는지를 확인하기 위해 종합진동평가프로그램(CVAP)을 수행하고 있다. US NRC RG 1.20의 비원형범주-2는 진동 및 응력 해석프로그램, 제한적 진동 측정프로그램, 검사프로그램 그리고 이런 프로그램들의 비교, 평가로 구성된다. 이 논문은 APR1400 RVI CVAP 측정프로그램의 측정계획, 시험, 허용기준과 결과 및 문서화에 대한 내용을 기술하였다. 우리는 이 논문의 진동측정 계획 및 시험에 따라서 APR1400 RVI CVAP 제한적 진동 측정프로그램을 수행할 것이다.

1. Introduction

The first Advanced Power Reactor 1400(APR1400) reactor vessel internals(RVI) are classified by the APR1400 Standard Design Approval(SDA)[1] as a non-prototype category-1 as defined in US Nuclear Regulatory Commission Guide(NRC RG) 1.20[2]. Although, we classified the APR1400 RVI CVAP as a non-prototype category-2 reactor as part of an independent validation of its design[3~10]. The assessment of the non-prototype category-2 reactor includes a vibration and stress

† 교신저자; 고도영, 한수원중앙연구원
E-mail : kodoyoung@khnp.co.kr
Tel : 042-870-5774, Fax : 042-870-5779
* 한수원중앙연구원

analysis program, a limited vibration measurement program, a full inspection program, and the correlation of these programs.

The guidance for RVI comprehensive vibration assessment program(CVAP) during pre-operational and initial startup testing of light-water-cooled power reactors is laid out in US NRC RG 1.20. CVAP is intended to demonstrate that the RVI is adequately designed to withstand flow-induced vibration(FIV) forces at normal and transient plant operating conditions for the design life of the plant.

The vibration and stress analysis program involves predictive stress analysis of RVI with respect to flow-induced vibration[3~7]. The vibration measurement program consists of selected RVI and reactor vessel components with transducers, and collecting data at selected plant conditions during Pre-Core hot functional testing(HFT). These data are used for comparative analysis to determine whether the measured stress levels are acceptable for long-term plant operation.

This paper outlines the vibration measurement plan, the vibration measurement testing, acceptance criteria, and documents and results of the APR1400 RVI CVAP[8~10].

2. Measurement Plan

This chapter provides an overview of the vibration measurement test plan. The transducer types[10], installation locations[4,5,9], and the rationale behind each measurement are listed. Also, included in this chapter are the signal conditioning and data acquisition system (DAS) requirements and planned analysis of the data to be collected.

2.1 Transducer Specifications

Specifications are applicable to all of the transducers that are placed on the RVI inside the pressure boundary. Some of the requirements are driven by the measurement locations, and the design and size of the APR1400 plant, which the transducers to consider conditions slightly different from historic CVAP programs performed on other plant designs[11~12]. Table 1 shows the requirements of the sensors for the APR1400 RVI CVAP[10].

Table 1 Requirements of the sensors

Generic requirements	· Static pressure: 158.2 kgf/㎠ (2250 psi) · Operating temperature: 291.3 ℃ (556.3 °F) · Surrounding medium: water with HFT
Dynamic strain gage	· Gage factor: 1.9 or greater (25 ℃, 2 m) · Strain limit: 8000 microstrain (25 ℃) · Frequency response: 1 to 500 Hz
Accelerometer	· Sensitivity: 50 pC/g or greater (25 ℃) · Dynamic measuring range: 200 g · Frequency response: 2 to 2500 Hz
Dynamic pressure transducer	· Sensitivity: 16 pC/psi (232 pC/bar) or greater · Dynamic measuring range: 250 bar · Frequency response: 2 to 10000 Hz

Additional requirements of the transducers for the APR1400 RVI CVAP except for the Table 1 are as follows:

- Transducer and cable shall be hermetically sealed.
- Transducer outer casing and mineral-insulated (MI) cable sheath shall be made of stainless steel or Inconel metal suitable for reactor internals application.
- The cable shall have mineral insulation approved for the reactor environment.
- The minimum insulation resistance of sensors is 10^9 (one billion) ohms at 25 ℃ and 10^7 (ten million) ohms at 291.3 ℃.
- The outer diameter of the cable shall be 2 mm.

2.2 Transducer Types and Locations

These transducers types are planned for design and manufacturing of measurement system previously identified: first, uniaxial, weldable, encapsulated strain gages for dynamic strain, second, uniaxial, piezoelectric accelerometers, lastly, piezoelectric dynamic pressure sensors.

Selection criteria for the transducers are based on desired response, prior application in reactor environment, performance, and reliability.

The major RVI components to be instrumented include IBA(inner barrel assembly) top plate, CEA(control element assembly) shroud, CEA guide tube, and UGS(upper guide structure) bottom plate. The exact location of each transducer is dependent on installation variables. Table 2 lists the instrumentation locations, transducer type, and reasoning behind each transducer[(4~5)]. The total numbers of sensors planned for vibration measurement testing are 23 sensors placed on the RVI inside the pressure boundary.

Table 2 Instrumented component and rationale of transducers

Instrumented Component	Transducer Type	Rationale
IBA top plate	Accelerometer	· IBA vertical acceleration
	Strain gage	· IBA top plate strain
CEA shroud	Strain gage	· Web strain at the web midpoint between U-type tubes · U-type tubes strain midway between webs · Web strain near the tube and web weld · Tube strain near the tube and web weld
	Pressure transducer	· Pressure levels in the CEA shroud cell near the center of the CEA shroud assembly
CEA guide tube	Strain gage	· CEA guide tube bending stress
UGS bottom plate	Accelerometer, Pressure transducer	· UGS bottom plate horizontal acceleration · Pressure on the underside of the UGS bottom plate

2.3 Transducer Design and Installation

The quantity and placement of the transducers on selected components is based on the component's sensitivity to expected vibration modes, on sensor redundancy in case of failure, and on sensor installation and removal considerations[(9)].

The transducers, the MI cables, the hardware(conduit, sensors cover, housing, etc.) and fixtures(holder, coupling, strap, etc.) securing them to the RVI are designed not to fail for the conditions expected between installation and removal. Due to scheduling concerns, installation will run parallel process during the Pre-HFT inspection(baseline inspection), and the transducers and hardware will remain installed until the end of Pre-Core HFT. The MI cables inside the reactor are routed in stainless-steel rigid and flexible conduits for mechanical protection during the testing conditions, and for ease of removal after test completion.

Transducer and lead wire insulation resistance shall be measured at different stages of installation to assess the condition of the transducer during the installation process. The positions of the installed transducers shall be measured to compare them with the intended location based on the installation documents, and the results documented for use in the data analysis. In addition, photographic records shall be maintained for all installed transducers and cable routing as part of the quality assurance program. These records are useful for comparative purpose and transducer removal at the end of the program.

2.4 Signal Conditioning Requirements

At least, all sensors are daily calibrated and certified through factory acceptance testing prior to testing. Insulation resistance will be measured at elevated temperature and pressure at different times to assure that survivability requirements are met.

Strain gages require suitable excitation and bridge completion circuits to extract the strain signals. The bridge-boxes will be installed for connection of strain gages to strain amplifiers and signal conditioners. The bridge boxes have suitable temperature compensation resistor for the operation temperature range mounted toe the board. The strain gage amplifiers will provide sufficient gain to measure very low strain levels and suitable low-pass filters will be used as needed. The desired frequency range for the dynamic strain gage system is 1 to 500 Hz. The strain gages are susceptible to electromagnetic interference(EMI) in the environment and care will be exercised to minimize the noise levels. Additional noise reduction will be performed digitally during data post-processing.

Accelerometer and dynamic pressure transducers for high-temperature applications will be high-impedance piezoelectric devices that require remote charge converters. The charge converters have configurable high-pass and low-pass filters and an optional integrator to give a velocity output. Futhermore , EMI filters protect the input and output against radio-frequency interference and other electromagnetic influences. The charge converters will be located at data acquisition room in the auxiliary building and housed in the metal enclosures for protection against moisture. The signal-conditioning amplifiers for accelerometers will have sufficient gain and double integration capability to measure displacement of a suitable resolution. Alternately, the acceleration signals can be converted to displacement digitally by the data acquisition system(DAS). The accelerometer and pressure transducers will have a frequency response from 2 Hz to 2500 Hz and 10000 Hz, respectively.

The DAS will be consist of signal-conditioning, data-recording, and data-analysis equipment. The DAS includes a computer with spectral-analysis software to perform frequency and time-domain analysis in real time and offline from recorded data. The raw and analyzed data will be saved and stored on removable storage media for archival and transmittal.

2.5 Data Acquisition and Analysis

After the transducers are installed and field wiring is completed, field calibration checks will be performed for each channel prior to data acquisition. Baseline data will be collected to determine the channel noise level.

Signals from strain gages, accelerometers, and pressure transducers will be recorded and analyzed online. The data will be recorded synchronously for all test conditions. The duration of the data recording is normally 10 minutes for each steady-state test condition. For transient testing such as pump stops and pump starts, the data collection shall begin 30 seconds prior to the start of the event and conclude several minutes after the end of the transient event. For each test condition, plant parameters such as coolant flow, coolant temperature, reactor pressure, number and speeds of operating reactor coolant pumps (RCP), and reactor temperature will be recorded, synchronously if possible. The vibration data will be correlated with selected plant parameters for trending and projection.

The DAS is performed at 500 Hz for each CVAP test condition. The sampling frequency is set to 5000 Hz based on the Nyquist–Shannon sampling theorem. The analog-to-digital signals for the resolution (A/D resolution) are set to 16 bits.

Online and offline spectral analysis and time-history analysis will be performed for all test conditions to the established acceptance criteria for each location. The acceptance criteria[8] will be based on the allowable vibratory stress limits for the instrumented components and the installed location of the transducer.

2.6 Bias Error and Uncertainties

Bias errors and uncertainties will be determined based on the type of transducer used, frequency response, temperature-based sensitivity deviation, signal conditioning, DAS settings, and other parameters. Measurement uncertainties will be reported in the test report issued after the completion of HFT. It is expected that the measurement uncertainties will be on the order of ±5 % or less. Gage-factor variation and temperature-based transducer-sensitivity deviation will be taken into account during data acquisition and calibration to reduce uncertainty in the measurement.

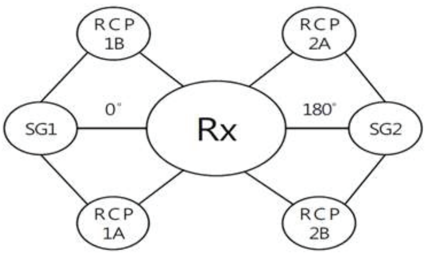

Fig. 1 Outline of the reactor coolant system of the APR1400 system

Table 3 Planed data collection test conditions

CVAP test Point	Test point description	Inlet coolant temp. (℃)	RCP			
			1A	1B	2A	2B
1	Pump start	65.6	NO	NO	S	NO
2	Pump start	93.3	S	NO	O	NO
3	Pump start	93.3	O	NO	O	S
4	Pump stop	126.7	O	NO	O	SP
5	Steady state	126.7	O	NO	O	NO
6	Steady state	126.7	O	NO	O	O
7	Steady state	126.7	NO	NO	NO	O
8	Steady state	182.2	O	NO	O	O
9	Steady state	262.8	O	NO	O	NO
10	Steady state	262.8	O	NO	O	O
11	Pump start	262.8	O	S	O	O
12	Steady state	262.8	O	O	O	O
13	Steady state	291.3	O	NO	O	O
14	Pump stop	291.3	O	NO	O	SP
15	Steady state	291.3	NO	NO	O	NO
16	Pump start	291.3	O	NO	O	S
17	Steady state	291.3	NO	NO	O	O
18	Steady state	291.3	O	O	O	O

NO: Not Operating, O: Operating, S: Start, SP: Stop

3. Vibration Measurement Testing

Fig. 1 and Table 3 show an outline of the reactor coolant system of the APR1400 system and the CVAP vibration measurement test data collection points. The test points consist of both steady-state and transient operation conditions. The test points cover the expected range of pump speeds, coolant temperatures, and flow rates from the initial no-flow condition to the hot standby temperature, pressure, and flow rate conditions. The duration of the CVAP testing must be long enough to accumulate at least 10^6 cycles[2] on the RVI component(core support barrel) having the lowest fundamental natural frequency. During the Pre-Core HFT, the RVI will be subjected to a total operating time (at normal operating modes) of at least 240 hours, which assure a cyclic loading of more than one million cycles for the lowest structural frequency of interest.

4. Acceptance Criteria

Acceptance criteria shall be developed for each of the sensor locations and data measurement parameters to be used during the vibration measurement test portion of CVAP. The acceptance criteria will focus exclusively on the dynamic responses of the structures related to FIV. Acceptance criteria shall be established by taking into account the location of the particular transducer, operating conditions for each test, uncertainties and biases, and margins to be added for conservatism to ensure that the allowable fatigue stress will not be exceeded.

Tables of expected and maximum allowable test values will be generated for the sensors for use in the detailed test procedures. These values provide guidance for the test operators when they are conducting the CVAP tests. The predicted values are those that can normally be expected for each sensor location during each test operating point and can be used as a guideline during data collection. The maximum allowable values provide levels for each test location and operating point that properly functioning sensors and DAS should not exceed; these values also establish the need for test operator intervention. This information allows the operators to determine the margins between the sensor values being measured and the maximum allowable test values as the tests are progressing, as well as providing valuable sensor signal troubleshooting information.

5. Documentation and Results

The results of the vibration and stress analysis , measurement, and inspection programs should be reviewed and correlated to determine the extent to which the test acceptance criteria are satisfied[2]. Anomalous data with potential impact on the structural integrity of the RVI shall be identified, as well as the evaluation methods for that data.

The vibration measurement test portion of the final report will include detail description of all deviations, including instrumentation reading and inspection anomalies, instrumentation malfunctions, and deviations from the specified operating conditions. It will also include a comparison between the measured and analytically determined modes of structural and hydraulic responses, a determination of the margin of safety , and an evaluation of all measurements that exceeded acceptable limits not specified as test acceptance criteria. If the results from the measurement program fail to satisfy the specified test acceptance criteria or the analysis, measurement, and inspection programs are inconsistent, the final report will be included an evaluation and description of the modifications or actions planned to justify the structural adequacy of the RVI.

6. Conclusion

In this point, protective structures for transducers and lead wires inside the reactor, and pressure boundary penetration structures for drawing out from inside the reactor to outside the reactor are being manufactured. Also, the installation and removal guidelines of transducers, hardware and fixtures, and test procedure for vibration measurement are being developed according to the APR1400 CVAP test conditions. We will carry out the limited vibration measurement program of the APR1400 RVI CVAP during the Pre-Core HFT referring to this paper.

References

(1) Korea Hydro and Nuclear Power Co., 2001, Advanced Power Reactor 1400 Standard Safety Analysis Report.

(2) US Nuclear Regulatory Commission, 2007, Regulatory Guide 1.20, Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Testing, Rev. 3.

(3) Ko, D. Y. and Kim, K. H., 2012, Vibration and Stress Analysis of a UGS Assembly for the APR1400 RVI CVAP, Nuclear Engineering and Technology, Vol. 44, No. 7, pp. 817~824.

(4) Ko, D. Y., Kim, K. H. and Kim, S. H., 2013, Structural Analysis and Measuring Locations of Upper Guide Structure Assembly in APR1400, Transactions of the Korean Society for Noise and Vibration Engineering, Vol. 23, No. 1, pp. 49~55.

(5) Ko, D. Y., Kim, K. H. and Kim, S. H., 2012, Structural Analysis and Response Measurement Locations of Inner Barrel Assembly Top Plate in APR1400, Transactions of the Korean Society for Noise and Vibration Engineering, Vol. 22, No. 5, pp. 474~479.

(6) Kim, K. H., Ko, D. Y. and Kim, S. H., 2011, Vibration Stress Analysis for Reactor Vessel Internals of Advanced Power Reactor 1400 by Pulsation of Reactor Coolant Pump, Transactions of Korean Society for Noise and Vibration Engineering, Vol. 21, No. 12, pp. 1098～1103.

(7) Kim, K. H., Ko, D. Y. and Kim, T. S., 2011, Hydraulic and Structural Analysis for APR1400 Reactor Vessel Internals against Hydraulic Load Induced by Turbulence, International Journal of Safety, Vol. 10, No. 2, pp. 1～5.

(8) Ko, D. Y., Kim, K. H. and Kim, S. H., 2011,

Response Instrumentation Test Acceptance Criteria for APR1400 RVI CVAP, Transactions of the Korean Society for Noise and Vibration Engineering, Vol. 21, No. 11, pp. 1306~1042.

(9) Ko, D. Y., Kim, K. H. and Kim, S. H., 2011, Selection Criteria of Measurement Locations for Advanced Power Reactor 1400 Reactor Vessel Internals Comprehensive Vibration Assessment Program, Transactions of the Korean Society for Noise and Vibration Engineering, Vol. 21, No. 8, pp. 708~713.

(10) Ko, D. Y. and Lee, J. G., 2011, A Review of Measuring Sensors for Reactor Vessel Internals Comprehensive Vibration Assessment Program in Advanced Power Reactor 1400, Transactions of the Korean Society for Noise and Vibration Engineering, Vol. 21, No. 1, pp. 47~55.

(11) Combustion Engineering Inc., 1984, A Comprehensive Vibration Assessment Program for the Prototype System 80 Reactor Internals Palo Verde Nuclear Generating Station Unit 1.

(12) KEPCO, 1995, A Comprehensive Vibration Assessment Program for Yonggwang Nuclear Generating Station Unit 4, 10487-ME-TE-240-03.