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THE STRUCTURAL INTEGRITY TEST FOR THE SHIN-KORI UNIT 3 CONTAINMENT AND ACCEPTANCE CRITERIA

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ABSTRACT

The reactor containment acts as a final barrier to prevent leakage of radioactive material due to the possible reactor accidents into external environment. Because of the functional importance of the containment building, the Structural Integrity Test (SIT) for concrete containments shall be performed to evaluate the structural acceptability and demonstrate the quality of construction.

This paper presents an overview of the SIT for the Shin-Kori Unit 3 containment, testing methodology, acceptance criteria, and results obtained from the test. In addition, the sophisticate structural analysis model developed to predict the structural behavior is introduced. With the developed model, a comparative analysis on the differences between the measured displacements and the anticipated displacements has been performed, and it has been observed that the performance of the containment subjected to the test pressure can be predicted very precisely.

According to the acceptance criteria of ASME CC-6000, all of the test results have been analyzed, and it can be concluded that the construction quality of the SKN-3 containment has been well maintained and the acceptable performance of new design features has been verified.

INTRODUCTION

The reactor containments might be subjected to high internal pressure under the severe conditions such as the loss of coolant accident. As a final barrier, however, the containments have to prevent radioactive materials that can seriously damage the public welfare from releasing to external environment. Therefore, the containments must be able to sustain its function and performance assumed to have in the design stage for its life time.

The performance of containments varies according to the uncertainties occurred during construction in the properties of materials or geometries of structure, and to the level of quality control activities applied throughout the entire construction period. For this reason, the efforts to maintain the best quality control are very important in the construction of nuclear power plant facilities. Because of the structural complication of containments, however, it is very hard to maintain the qualities of construction at a steady level for the entire construction period.

As a part of the performance verification, the containments newly constructed are required to be tested for structural acceptability as a prerequisite for Code acceptance and stamping [ACI-ASME Joint Technical Committee (1998), KEPIC Technical Committee (2000)]. The SIT is performed at a test pressure of at least 1.15 times the containment design pressure to verify the construction qualities and to evaluate the structural integrity.

Recently, the SIT was performed by the Korea Hydro and Nuclear Power Co. Ltd. (KHNP) and Korea Electric Power Corporation Engineering and Construction (KEPCO E&C) for the Shin-Kori Unit 3 (SKN-3) containment in Korea. The test was carried out for more than 70 hours, and the deformation of containment was measured at the 49 points with the sampling period of 1 minute in the test. In addition, as the SKN3 containment was classified to prototype, the strain of rebar installed at 78 points such as the intersection of the wall and base slab and areas of major discontinuity in the curvature and thickness of the shell.

This paper presents an overview of the SIT for the SKN-3 containment, testing methodology, acceptance criteria, and the results obtained from the test. Through this study, a comparative analysis of the differences between the measured displacements and the anticipated displacements calculated using the material properties assumed in the design is presented. In addition, the measured displacements have been compared with the displacements, which are computed using more advanced finite element model and more realistic material properties, which the real structure is supposed to have.

STRUCTURAL INTEGRITY TEST

The Shin-Kori Unit 3 containment structure

The SKN-3 containment, prestressed concrete structure, consists of a cylindrical wall, dome, and foundation slab, which supporting the wall. The inside surface of the containment was covered with the steel liner plate of 6 mm (1/4 in.) thickness in order to prevent the leakage of the radioactive material [KHNP (2008)].

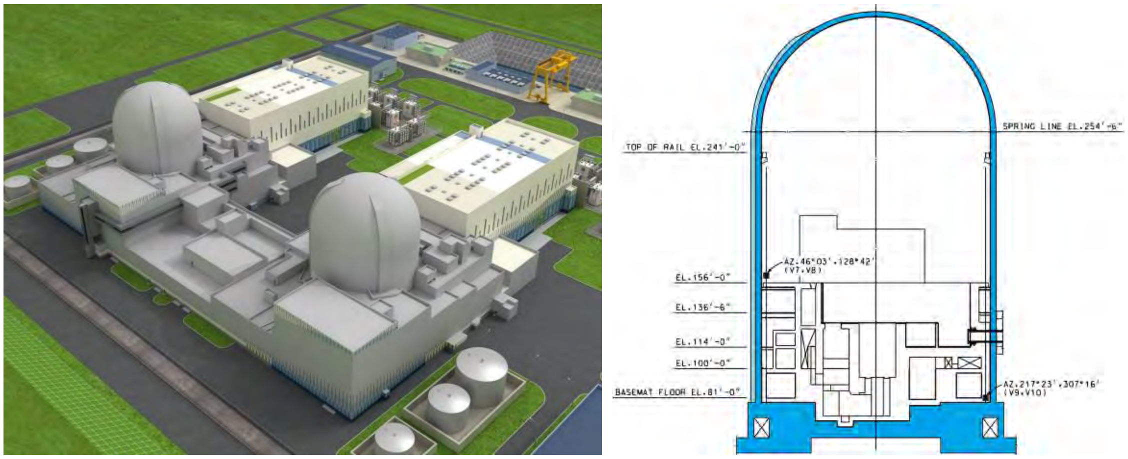


Figure 1. Bird's eye view of SKN3, and the sectional view of concrete containment.

Figure 1 shows the bird's eye view of Shin-Kori Units 3&4, and the sectional view of the concrete containment structure. The inside diameter and height of the containment are about 45.72 m (150 ft) and 76.66 m (251.5 ft), respectively, and the thickness of the wall and dome are 1.22 m (4 ft) and 1.07 m (3.5 ft), respectively [KHNP (2008)].

The cylindrical wall of the containment was prestressed by the post-tensioning method with the circular shaped horizontal tendons and inverted U-shaped vertical tendons. The containment has three buttresses, which are uniformly distributed, and the ends of each horizontal tendon were anchored in the buttresses. The horizontal tendons start at a buttress and travel 240 degrees around the cylindrical walls. The inverted U-shaped vertical tendons were installed across the outside wall, and both ends were anchored at the lower surface of the foundation, which is the ceiling of tendon gallery. Each tendon consists of 42 strands that are composed 7 wires, which are a low relaxation steel of which the ultimate strength and elastic modulus are 1,860 MPa (270 ksi) and 1.93×10^5 MPa (28×10^6 psi), repectively.

The foundation slab is rectangular shaped reinforced concrete structure, which has an axisymmetric cavity for reactor at its center. The minimum thickness and diameter of the foundation at the containment area are 3.35 m (11 ft) and 51.21 m (168 ft), respectively. In order to install and maintain the inverted U-shaped vertical tendons, the continuous tendon gallery was constructed beneath the lower surface of foundation. In the SKN-3 containment, a total of 165 horizontal tendons and 100 vertical tendons were installed, and the spacing between two neighboring tendons is equivalent [KHNP(2008)].

There are three large openings in the containment building; the largest one is equipment hatch for moving the large equipments such as reactor and steam generator, and two entrances for worker. Besides these openings, several penetrations were installed to delivery hot steam, feedwater, fresh air, power line, etc.

Preparation of the SIT

The entire process of the SIT including preparation should be performed according to the KEPIC SNB-6000, code related to the SIT of concrete containments [ACI-ASME Joint Technical Committee (1998), KEPIC Technical Committee (2000)]. The SKN-3 containment was designed to resist the internal pressure of 515 kPa (60 psig) and thus, it should be tested at the test pressure of 592.3 kPa (69 psig), which is 115% of the design pressure. In the test, the internal pressure of containment is gradually increased from atmospheric pressure to the test pressure, and held for at least 1 hr at its peak.

In case of cylinder dome containments, according to the code, radial displacements should be measured at least 5 elevations that are equally spaced between the base and the spring line, and at a minimum of 12 points, four equally spaced on each of three concentric circles, adjacent to the largest opening [ACI-ASME Joint Technical Committee (1998), KEPIC Technical Committee (2000)]. In the test, the displacements of containment were measured with Linear Variable Differential Transformer (LVDT), of which sensitivity and linearity are about 0.276 mV/Volts RMS/0.001 cm (0.7 mV/Volts RMS/0.001 in.) and 0.12%, respectively. Specifications for displacement transducers shall provide for an accuracy of ±5% of the anticipated displacement at the point of maximum displacement as predicted or within 0.25 mm (0.01 in.), whichever is greater.

The LVDT is assembled with spring and cylindrical case enveloping all instruments. The spring must have enough elastic constant to give proper tension to the invar wire, and the springs used in the test have the constant of about 0.36 N/mm (25.04 lb·f/ft). The extensometer composed of the LVDT and assembly with spring is shown in the Figure 2. In the test, fifty-two extensometers were mounted on the inside wall or the liner plate directly, and the rods of LVDT were linked by the invar wire to the point at which displacement should be measured.

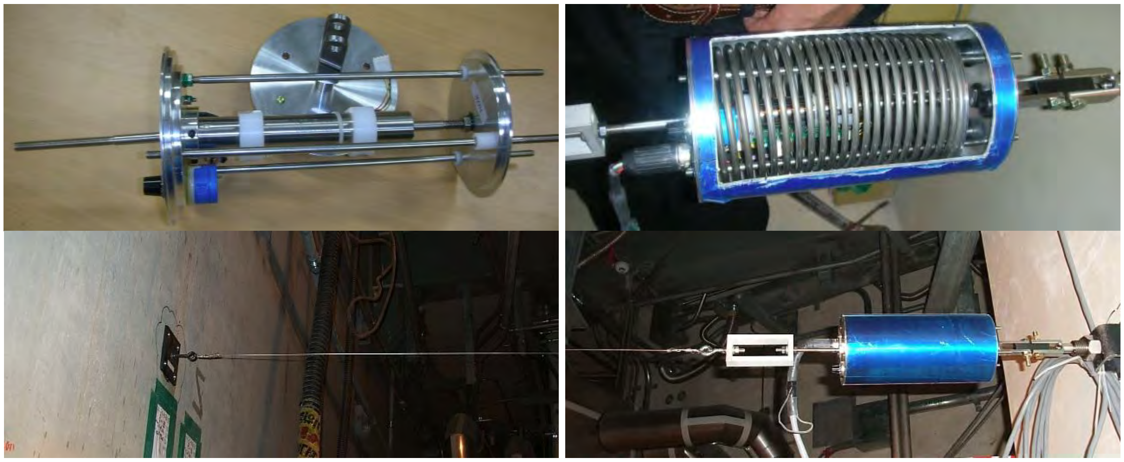


Figure 2. LVDT and spring assembly, and extensometer mounted on the wall.

The deformation of containment is delivered to the extensometer through the invar wire and it brings about the movement of the rod of LVDT. And then, the change of voltage caused by the movement of rod is conveyed to the Data Acquisition System (DAS) with sampling period of 1 minute in form of electrical signal. Finally, the displacements are converted from the electrical signals in the DAS and scattered to the screen in briefing room to monitor the behavior of structure as shown in Figure 3.

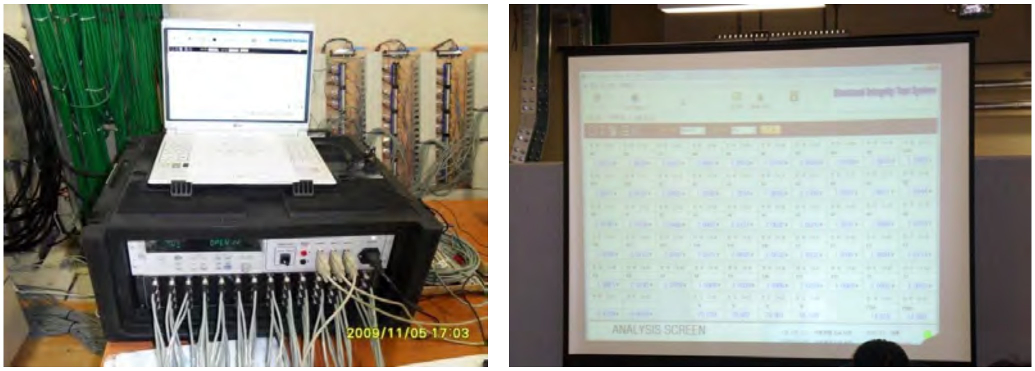


Figure 3. Data acquisition system and a screen set up in briefing room.

The measured displacement should be compensated in consideration of the effect of creep and shrinkage varying according to the concrete ageing as well as the change of temperature and elastic modulus. According to the criteria, it should be demonstrated by the SIT that the behavior of containment is not exceed the elastic range of structure, and yielding of conventional reinforcement does not develop. In addition, residual displacements at the completion of depressurization or up to 24 hr later shall not exceed 20% of measured or predicted displacement whichever is greater, plus 0.25 mm (0.01 in.) plus measurement tolerance for prestressed containments [ACI-ASME Joint Technical Committee (1998), KEPIC Technical Committee (2000)].

If the residual displacement is not smaller than 10% at the completion of depressurization, the measured displacement at the point of maximum predicted displacement should not exceed the predicted displacement by more than 30%.

TEST RESULTS AND ASSESSMENT OF STRUCTURE PERFORMANCE

Internal Pressure and Temperature

Figure 2 shows the change of internal pressure and temperature during the test period. As shown in the figure, the internal pressure increased and decreased at the rate of about 18.6 kPa/hr (2.7 psi/hr) and thus, the test has been performed for about 70 hours from the start of pressurization to the completion of depressurization. The figure shows also the internal temperature varying from 293 to 301 K (67 to 83 °F). Although the change of internal temperature is small, it can be observed that the trend of change is similar to the change of pressure.

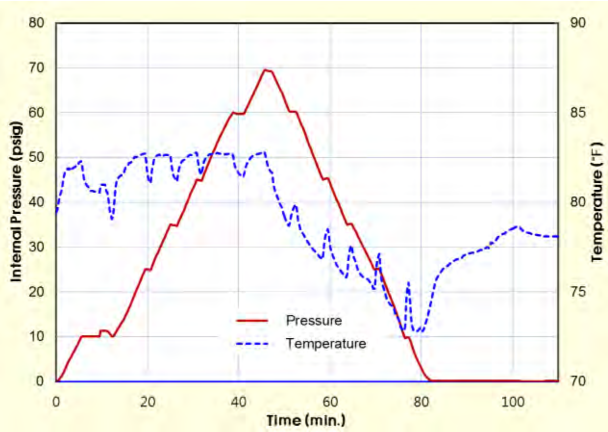


Figure 4. Variation of the internal pressure and temperature during the test.

Measured Displacements and Predicted Displacements

As mentioned above, the displacements of containment were measured at the 49 points during the entire test period. Figure 5 shows the direction and elevations where the extensometers were installed to measure the displacement of outer wall [KHNP(2012)]. And two measured displacements in radial direction are shown in Figure 6. It is observed that the displacement measured at point R1 match very well to predicted displacement, which is calculated with the values of material parameters assumed in the design. On the other hand, it can be seen that the measured displacement at point R4 is somewhat larger than the predicted displacement, which means that the stiffness of real structure is smaller than that of designed structure.

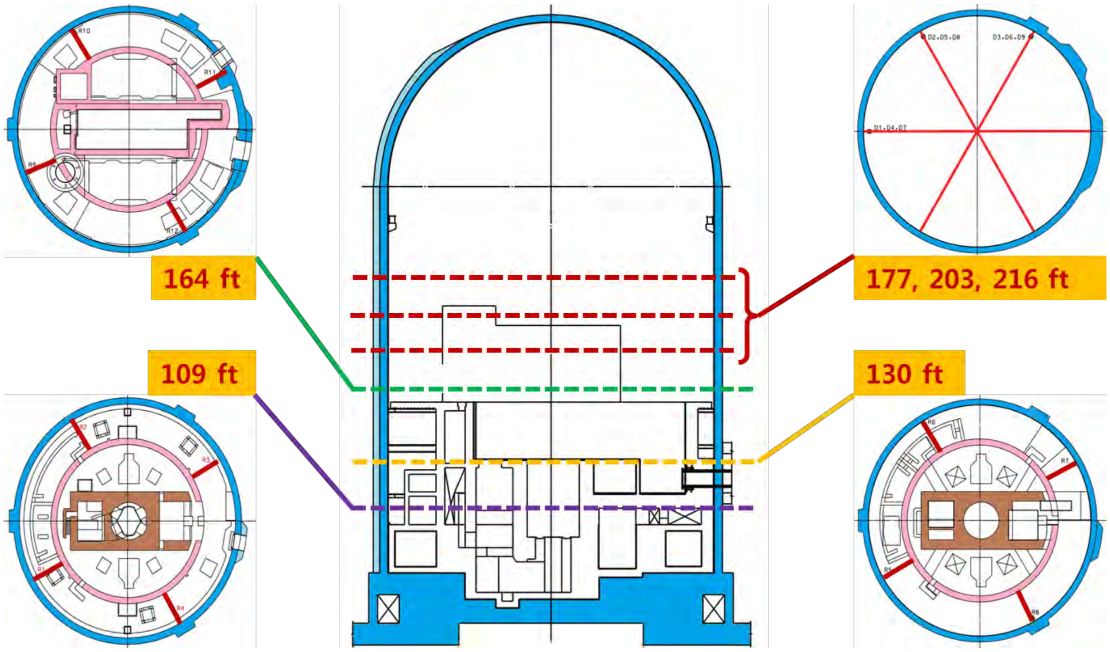
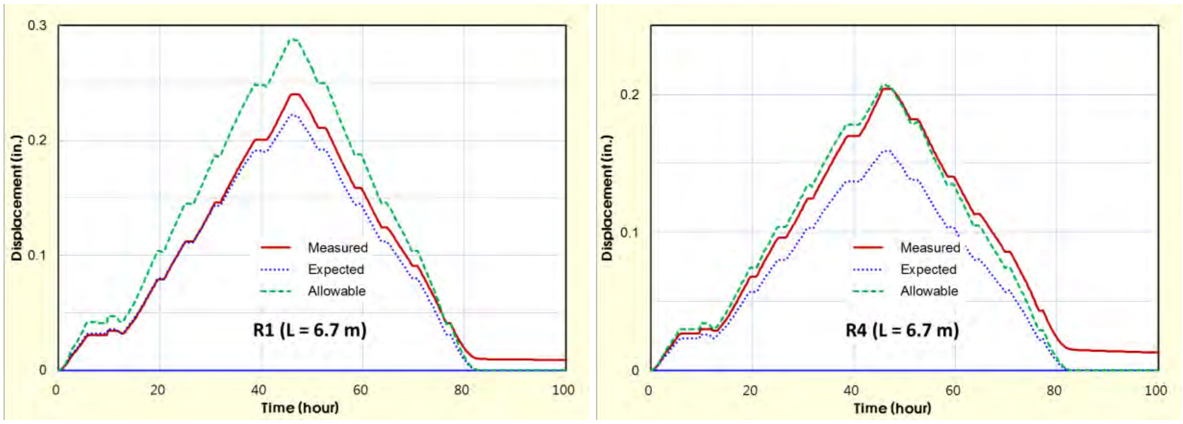


Figure 5. Locations for displacement measurement.



(a) Measured displacement at R1 (b) Measured displacement at R4

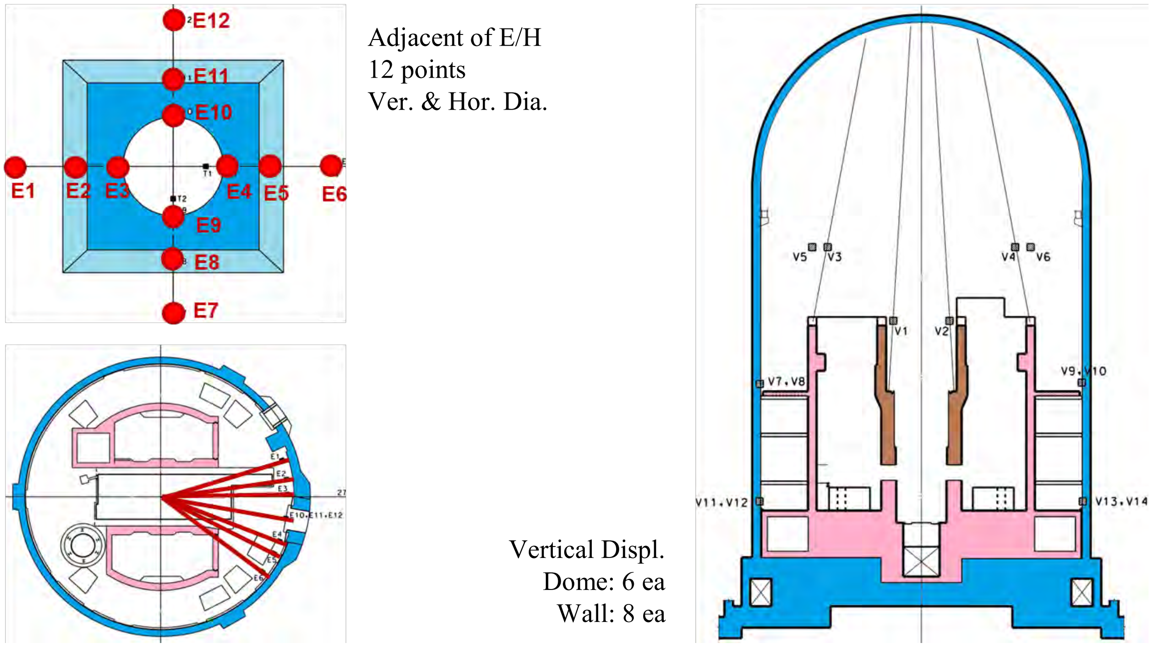
Figure 6. Radial displacements.

Table 1. Material properties of the concrete.

Parameter		Designed Value
Compressive Strength, MPa (psi)	Wall & Dome	41.37 (6,000)
	Foundation	27.58 (4,000)
Elastic modulus, MPa (ksi)	Wall & Dome	30.44 (4,415)
	Foundation	24.86 (3,605)
Poisson ratio		0.17
Shrinkage strain, ($\times 10^{-6}$)		120

The values of material parameter used to compute the displacements in this study are listed in Table 1. As mentioned above, radial displacement adjacent the largest opening, equipment hatch, should be measured at minimum 12 points. Figure 7 shows a total of 12 measuring points which are almost equally spaced in around the equipment hatch [KHNP (2012)]. As shown in the figure, in order to reinforce the opening, the wall is designed to have very thickened cross section. For this reason, the displacement in this region is very small compare with that in the other parts of the structure.

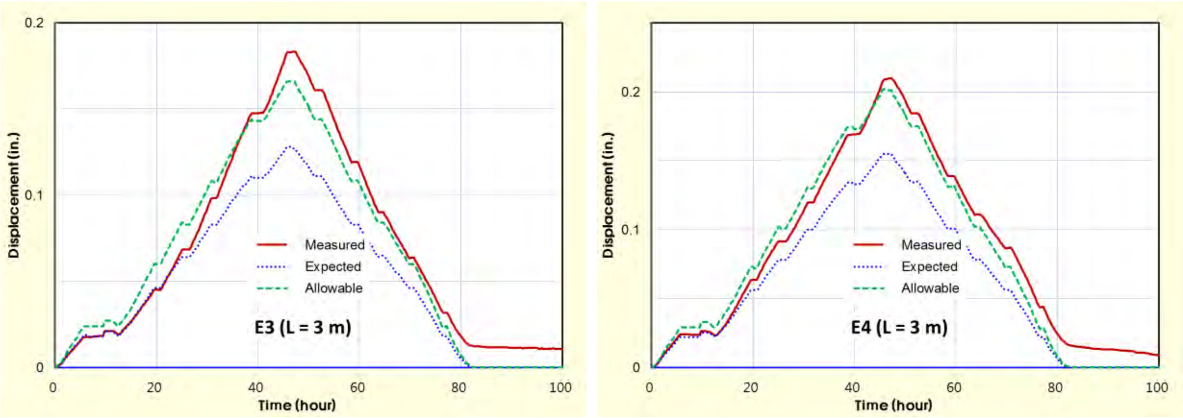
Figure 8 shows the displacements measured at two points located in the right-and-left and upper-and-lower sides of the opening, and at the apex of the containment. It can be seen that the measured displacements at the adjacent of the equipment hatch exceed the allowable displacement, which is equal to the 130% of the anticipated displacements, and the vertical displacements measured at the apex of the containment are very close to the calculated displacements. For these displacements, the residual displacements at the completion of depressurization were examined to be smaller than 20% of the measured displacement at the maximum test pressure according to the ASME CC-6410.



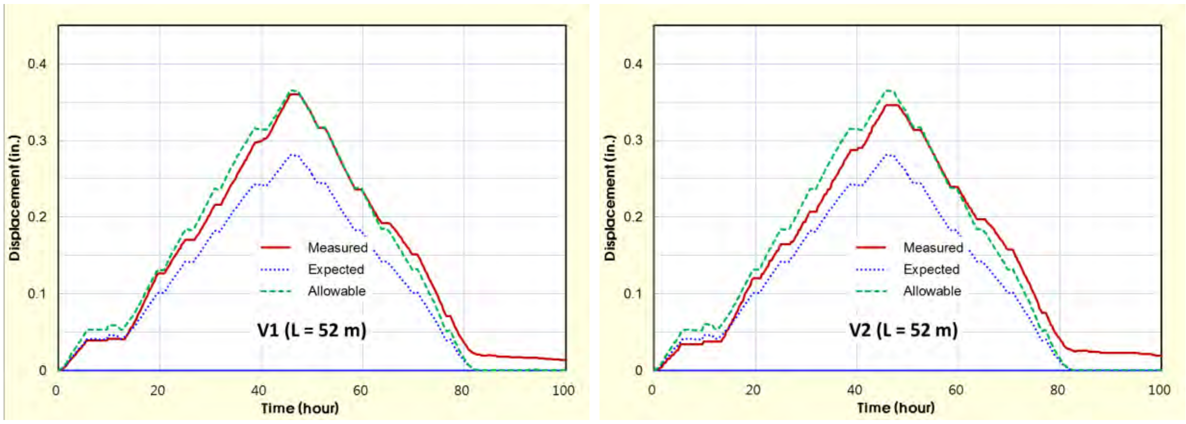
Adjacent of E/H
12 points
Ver. & Hor. Dia.

Vertical Displ.
Dome: 6 ea
Wall: 8 ea

Figure 7. Locations for displacement measurement.



(a) Displacements measured at adjacent the equipment hatch.



(b) Displacements measured at apex of the containment.

Figure 8. Comparison of measured and expected displacements.

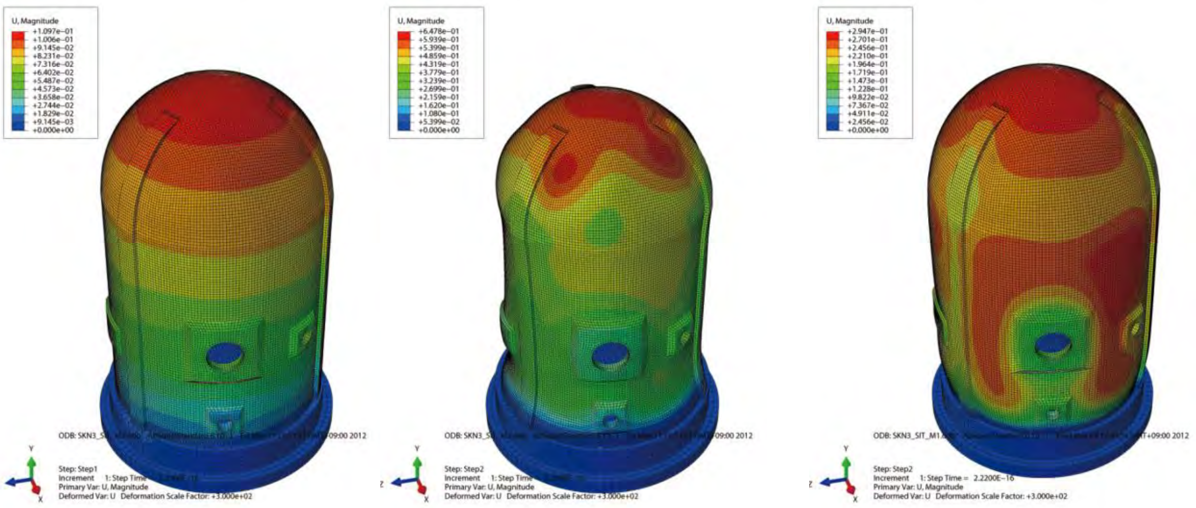
The expected displacements play an important role to determine the success of failure of the test on this wise. In order to predict the deformation of the containment in accurate manner, a structural analysis model should be carefully developed considering the refined geometry of structure and the mechanical properties of materials.

(a) Concrete structure (b) Reinforcement bars (c) Prestressed tendons

Figure 9. Finite element models and generated meshes.

To achieve aforementioned goals, very sophisticated finite element model has been developed in this study. Figure 9 shows the finite element models and meshes generated for concrete structure, reinforcement bars, and prestressed tendons. In this model, the equipment hatch, buttress, and thickened wall, which affect to the calculation of displacement, are considered as well as the realistic material characteristics.

The major material parameters used for the design of the structure listed in the Table 1. In addition, the variation of atmospheric temperature as well as that of the internal temperature of containment is considered in the detail analysis. As a computation tool, the ABAQUS, which is a commercial software programmed based on the finite element method has been employed to calculate the displacement of containment. Figure 10 shows the deformation shapes and the displacement contours of the containment when it is subjected to the self-weight, prestressing forces, and internal test pressure of SIT, 69 psig.



(a) Due to the self-weight (b) Due to the prestressing (c) Due to the internal pressure

Figure 10. Deformed shapes and displacement contours according to the load steps.

CONCLUSIONS

By means of a structural integrity test, the performance of the SKN-3 containment has been evaluated, and this paper presents the testing methodology, acceptance criteria, and the results of the test. In addition, the structural analysis model developed for evaluation of the structural deformation due to the change of internal pressure is introduced.

From the test results, it has been observed that the deformation of the SKN3 containment is not exceeding the linear elastic range of all materials composing the structure at the maximum test pressure, and the deformed structure return back to the original position at the completion of depressurization. However, it has been also observed that some of measured displacements are slightly larger than the allowable displacements which are equal to 130% of the predicted displacements. In these cases, the residual displacements were measured at the completion of the depressurization, and it was verified that the residual displacements are smaller than 20% of the measured displacements at the maximum test pressure. To evaluate the structural behavior in accurate manner, very sophisticate finite element model of the SKN-3 containment was developed in this study, and the developed model includes the realistic geometry and material properties for the reinforcement steel bars, tendons, and the liner plate.

It has been observed from the test results that all of the residual displacements are less than the 20% of the measured displacements at the maximum test pressure, and the behavior of the containment matches well to the linearly elastic load-displacement relationship. Therefore, it can be concluded that the construction quality of the SKN-3 containment has been well maintained and the acceptable performance of new design features has been verified.

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