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QINSHAN PHASE 3 CANDU 6 REACTOR BUILDING PROOF PRESSURE TESTS AND LEAK RATE TESTS

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ABSTRACT

Prior to the criticality of CANDU Reactor, CSA N287.6 requires that a pre-operational Proof Pressure Test (PPT) and an Integrated Leak Rate Test (ILRT) be conducted to demonstrate the structural integrity and the leak tightness of the containment structure. The PPT is conducted at a pressure of 143 kPa(g), which is 1.15 times of the design pressure of 124 kPa(g) due to a large loss of coolant accident. The objectives of the test are to confirm that the Reactor Building behaves elastically, to validate the theoretically predicted design envelope at all the pressure steps and also to confirm that the construction process has met its design requirements. The ILRT is performed to verify the leak tightness of the R/B containment structure at the design accident pressure. The acceptance criteria for this test is that the integrated leak rate shall be less than 0.5% of the volume of the building over 24 hours.

This paper presents the performance of the Qinshan Phase 3 CANDU 6 Unit 1 and 2 Reactor Building containment structures during the PPT and ILRT. Additionally, it describes the test methods, instrumentation, and the significant role in the tests of Chinese expertise.

Keywords: reactor building, containment structure, proof pressure, leak rate

1. INTRODUCTION

The Qinshan Phase 3 consists of two CANDU 6 units with a design gross electrical output of 728 MWe each. The Reactor Buildings consist of the containment structure and internal structure. The internal structure houses and supports the major nuclear systems, while the containment structure is the enveloping structure of the internal structure and the nuclear systems.

Figure 1 shows a section of CANDU 6 Reactor Building concrete containment structure. It consists of the base slab, perimeter wall, ring beam and the upper dome. The concrete components of the containment structure are pre-stressed by post-tensioning in vertical and hoop direction for the perimeter wall and ring beam, and in three directions for the base slab and upper dome. The interior surfaces of the containment structure are lined with a minimum of 4 coats of containment quality epoxy liner on top of a sand-filled epoxy base layer. It should be pointed out that the perimeter wall of the Reactor Building was built with the slip-form method, with no construction joint in its entire height. The only construction joints existing in the containment structure are at the joints of perimeter wall / base slab, perimeter wall / ring beam, ring beam / upper dome and at the temporary opening which was used for the transportation of the reactor.

The containment structure is a safety system that performs the following functions:

To provide structural integrity during all specified normal and accident load conditions imposed on the Reactor Building. The structural integrity means the maintenance of the structure in an elastic state. The post-tensioned and reinforced structural concrete of the base slab, perimeter wall, ring beam and the upper dome provide this capability.

To provide biological shielding to the staff outside of the Reactor Building and the public at large during operating and accident conditions. This is provided by the thickness of the structural concrete of the containment structure.

To provide leak tightness for the protection of the public and the environment such that the leaks do not exceed the permitted level during all specified accident events inside the Reactor Building, which have the potential to release radio-nuclides. The pre-stressed containment structure and the containment epoxy liner on its containment surface provide leak tightness capability.

To ensure the above functional requirements, CSA N287.6 (*Preoperational Proof and Leak Rate Testing Requirements for Concrete Containment Structure for CANDU Nuclear Power Plants*, Canadian Standards Association, 1994) requires that a pre-operational Proof Pressure Test and an Integrated Leak Rate Test be conducted to demonstrate the structural integrity and the leak tightness of the containment structure. Normally, this test is conducted after the completion of all civil and mechanical / electrical construction associated with the Reactor Building including its interior and exterior surfaces and the completion of the major commissioning works of the systems housed within the Reactor Building.

The Hua Xing Construction Company and the China Nuclear CNI23 Company performed the civil and mechanical/ electrical construction respectively. The Unit 1 Reactor Building first structural concrete (base slab) was poured in June 1998. The concrete containment structure was completed in July 2001 when the upper dome of the Reactor Building was completed after the installation of all large equipment (with the exception of the reactor), structural components and modules through the open top. After the post tensioning of the containment structure, completion of the epoxy liner on the containment boundary surface and the completion of major installation / commissioning work related to the Reactor Building, the unit 1 Reactor Building Proof Pressure Test (PPT) and Integrated Leak Rate test (ILRT) were successfully performed in May 2002. The unit 2 PPT and ILRT were performed in January 2003.

2. TEST METHODS

2.1 Pressure – Time Curve

The PPT was conducted at a pressure value of 143 kPa(g), which is 1.15 times of the design pressure of 124 Kpa(g). The ILRT is performed at the design pressure of 124 kPa(g). The acceptance criteria of the leak rate test is that the integrated leak rate shall be less than 0.5% of the volume of the building over 24 hours at the design pressure of 124 kPa(g).

The pressure inside the Reactor Building (R/B) during the test was applied in steps, and at each step the specific inspections and commissioning works are performed. Figure 2 shows a recommended pressure-time curve for the combined PPT and ILRT, along with the inspection activities at each step. It should be noted that the PPT and ILRT can be performed separately and modified pressure-time curves can be used.

The pressurization of the R/B was performed through a penetration in the perimeter wall by a pressurizing system located outside of the Reactor Building. During the testing, the non pressurized systems were set up to be in an equalized state with the R/B and the entire containment was buttoned up to prevent leakage through the systems. Similarly, all the doors inside the Reactor Building were left open to stabilize the pressure inside the R/B.

2.2 Visual Inspection for both PPT and ILRT

Visual inspections on the containment structure were performed on both exterior and interior surfaces of R/B containment structure before, during and after the testing. The inspections during the testing were made at each of the pressure steps as shown in the pressure-time curve of Figure 1. The inspection teams formed by TQNPC (the owner), the contractors (CNI 23, HuaXing and Beijing Metallurgical Research Design Institute), and the AECL staff performed the inspections. Each team was equipped with inspection tools and drawings of the containment structure on which they were to mark any observed crack or leak. For the ILRT, the inspections were focused on the construction joints (shown in Fig. 1) and the penetrations through the containment..

2.3 Instrumentation for PPT

Besides the visual inspections, various instruments were used to monitor the structural behavior of the containment structure. The purpose of the instrumentation was to determine if the response of the containment structure remains within the predicted bounds of the theoretical analysis results and within the elastic range during the PPT. During the test, readings of each instrument were taken at the Main Control Room and plotted and subsequently compared to the theoretical values derived from the structural analysis.

2.3.1 Embedded Strain Gauges

The concrete strain and temperature measurements were performed by the embedded strain gauges, which are a permanent component of the building. The strain gauges are sustained vibrating wire type (Type C110) made by ROCTEST of Canada. These strain gauges contain a temperature sensor, which corrects the effect of the temperature change on the strain. A total of 107 strain gauges were embedded in the containment structural concrete and were located to provide sufficient redundancy to cover the damaged strain gauges during construction. Thirteen levels of strain gauges were installed at six meridian sections, namely 45°, 105°, 165°, 225°, 285° and 345°. The strain gauges were placed in meridian and hoop directions, and at the exterior, interior and center of the concrete structure. Fig. 3 a) describes the general strain gage layout.

2.3.2 Surface Mounted Strain Gauges

Based on the pretest monitoring readings, 25 of the 107 embedded strain gauges were not functioning properly. Though, as stated above, the embedded strain gauges have sufficient redundancy to cover these damaged ones, nine surface mounted gauges were installed at selected locations. The surface mounted gauges were of the same type as the embedded ones.

2.3.3 Deformation Meters (LVDTs)

The perimeter wall and dome deflections were measured with 23 Linear LVDTs connected to the points of measure through invar wires. The fixed point of the invar wire was located at the internal structure in the radial direction. This system was provided by the Beijing Metallurgical Research Design Institute and pre-tested in its Engineering Structural Lab (ESL) as per the actual configuration of the set-up in the reactor building. The system was re-calibrated after installation on the reactor building surface. Of the 23 LVDTs, 3 of them measured the vertical deformation of the upper dome. Twenty LVDTs measure the horizontal displacement of the perimeter wall and they were installed at five levels, namely 97.5m, 105m, 110m, 114.5m and 119.5m, with each level of four LVDTs at 90° apart. Fig. 3 b) shows the typical LVDT set-up.

2.3.4 Other Instrumentation

Besides the above specified measurements, the following additional instrumentations were used during the testing:

Water level sign heads: Installed, monitored and recorded by ESL on the top of the R/B to measure the displacement of the R/B roof.

Extensometers: Installed at the sub-base of the R/B to measure the settlements of the R/B over the life of the plant from the beginning of construction to the completion of the operating life of the plant, including during the PPT/ILRT.

Load cells: Installed at the selected pre-stress greased tendons to monitor the force in the pre-stressing tendons.

2.4 Instrumentation for ILRT

Pressure gauges were installed to measure atmosphere pressure outside of the R/B, pressure inside the R/B and the differential pressure between the inside and outside of the Reactor Building.

Temperature gauges and humidity sensors were installed at various locations inside and outside of the Reactor Building to measure the temperature and humidity. These measures were used to correct the effect of temperature and humidity changes on the pressure readings.

During the Integrated Leak Rate Test, the pressure measuring system was validated by introducing a known air leak from the Reactor Building through an independent airflow measuring system (Fig. 2, step d).

To ensure that the leak rate results were not affected, the R/B was isolated from the station instrument air system and a dedicated compressed air system was installed within the R/B to provide air to the ILRT instrumentation

3. TEST RESULTS

Qinshan Phase 3 CANDU 6 Unit 1 Reactor Building PPT and ILRT were separate tests. The PPT was performed during the period of May 3 to May 9, 2002, while ILRT were conducted from May 22 to May 25, 2002. Fig. 4 shows Unit 1 PPT pressure – time curve.

Qinshan Phase 3 CANDU 6 Unit 2 Reactor Building PPT and ILRT was a combined test. The tests were performed in the period of January 21 to 28 of 2003. The Unit 2 combined PPT/ILRT pressure – time curve is also shown in Fig.4.

Readings from over 200 instruments were continuously recorded as described above, together with the visual inspections during the tests. None of the readings or observations was outside the expected range of values predicted by analysis.

Both Unit 1 and Unit 2 ILRT’s were led by TQNPC with technical assistance of Beijing Metallurgical Design Research Institute and Atomic Energy of Canada Limited (AECL). The PPTs were lead by AECL with the assistances of CNI 23 Company and Huaxing Company and strain / deformation measurements by the Engineering Structural Lab (ESL) of Beijing Metallurgical Design Research Institute.

3.1 Strain Gauges

The measured strains followed the predicted strain trend and generally fall within the theoretical upper and lower strain limits which are calculated mainly to cover the variances in the material properties of the concrete, including the ageing effects. Fig. 5 and Fig. 6 show the typical strain gauge vs. time in comparison to the theoretical predicted values and upper and lower bound limits. The relation of the theoretical strains vs. time was calculated through the pressure-time curves shown in Fig.4. All the strain gauge readings went back to approximately zero reading as the structure was depressurized to zero, confirming that the containment structure was always in an elastic state during the PPT.

3.2 Deformation Measurements

The deformation meter measurements showed that the performance of the containment structure followed closely the pattern of response predicted by the theoretical analysis. Fig.7 and Fig. 8 show the deflection measurements at the dome for the Unit 1 and Unit 2 respectively.

The largest deflection of the structure at 142 kPa(g) was 9.82 mm at the center of the dome, compared to the theoretical deflection of 13.02 mm for this point.

All the deformation went back to approximately zero reading after the structures were depressurized to zero, confirming that the structure was always in an elastic state during the PPT. It shall be pointed out that Fig.7 shows a 1.4mm deflection (downwards) for the upper dome after the pressure reduced to zero. This was caused by deferential ambient temperature between the start of the testing (28 ^{o}C) and finishing of the testing (19 ^{o}C).

Fig. 9 shows the actual deformed shape of the Reaction building at 143 kPa(g), along with the predicted upper bound deformed shape.

3.3 Visual Inspection

No sign of distressing and cracking was observed on the containment structure throughout the testing of the Unit 1 and Unit 2 PPT and ILRT. Very tiny air leaks were detected by SNOOP bubbling solution at some spots of construction joints and penetrations, including the piping seal plates. It is considered that the reason for the leaks in the concrete at these locations is due to the higher degree of difficulty to achieve homogenous concrete construction in these areas. However, it should be noted that the presence of these leaks did not affect the building to meet its leak tightness requirement (section 3.4). All noted leaks in the concrete were repaired by injection and by welding in the seal plate connection to the piping during the tests.

3.4 Leak Rates

The official leak rate of the Reactor Buildings was measured at the design pressure of 124 kPa(g). As shown in Fig. 2, The ILRTs were performed after the PPT when the Reactor Buildings were re-pressurized to 124 kPa(g), The official leak rate test was performed after the pressure stabilized for approximately 6~8 hours. Immediately after the official leak rate test, the leak rates were verified by introducing a known superimposed air leak flow measured by an independent system, continuously for a period of 6 ~ 8 hours.

As shown in Fig. 2, indicative leak rate readings were also taken at reduced air pressures, which were used to monitor the Reactor Building leak tightness condition.

Qinshan Phase 3 CANDU 6 Unit 1 Reactor Building official integrated leak rate result was 0.21% of the Reactor Building volume over 24 hours, and Unit 2 official integrated leak rate was 0.13% of the Reactor Building volume over 24 hours. Both leak rates meet the design leak rate requirement of 0.5% by a significant margin.

It should be pointed out that these integrated leak rates, 0.21% for Unit 1 and 0 .13% for Unit 2, were the best leak rates for the Reactor Building in the CANDU history at the time the tests were performed respectively.

4. CONCLUSIONS

In general, the response of the containment structure of Qinshan Phase 3 unit 1 and unit 2 Reactor Buildings falls well within the theoretically predicted bounds at all the pressure stages up to 143 kPa(g). After depressurizing the Reactor Buildings to zero pressure, the strains and deformations came back to the zero reading. This confirms that the structural behavior is within the elastic range throughout the test.

The visual inspection results confirmed that there was no distress to the containment structure as no cracks were caused by the pressure throughout the test up to 143Kpa(g).

The official integrated leak rate test results of 0.21% for Unit 1 and 0.13% for Unit 2 confirm that both Unit 1 and Unit 2 Reactor Buildings meet the leak tightness design requirement with a significant margin.

The integrated leak rates, 0.21% for Unit 1 and 0 .13% for Unit 2, were the best leak rates for the Reactor Building in the CANDU history up to the time the tests were performed.

The success of the Qinshan Phase 3 Unit 1 and 2 Reactor Building structural integrity tests and leak tightness tests confirmed the acceptability of the construction with respect to the containment structure design requirements.

5. ACKNOWLEDGEMENT

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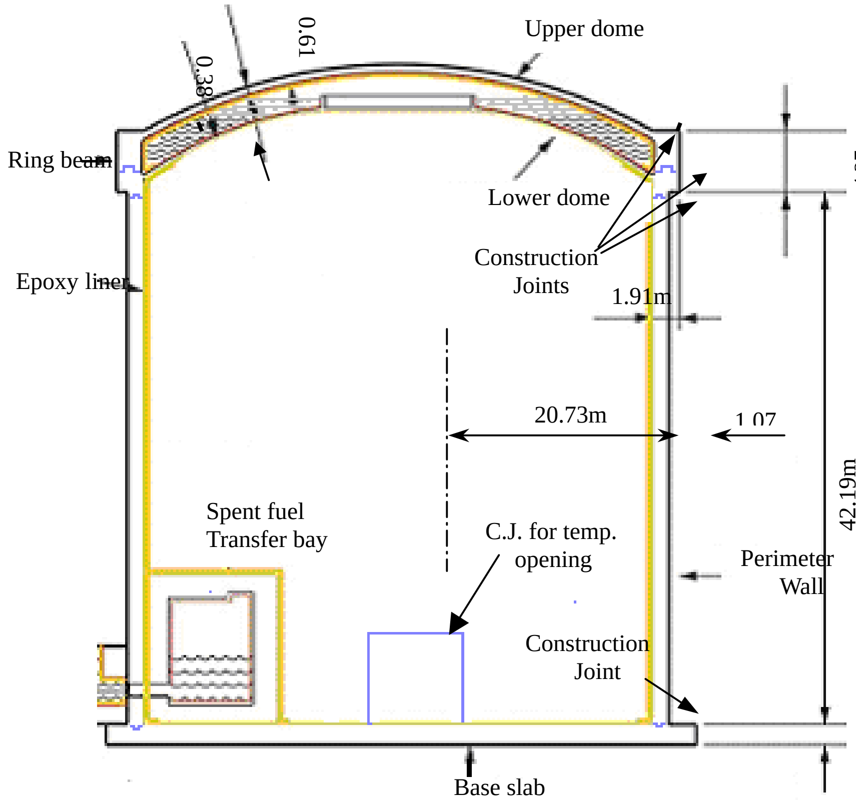


Figure 1 Qinshan Phase 3 CANDU Reactor Building Containment Structure

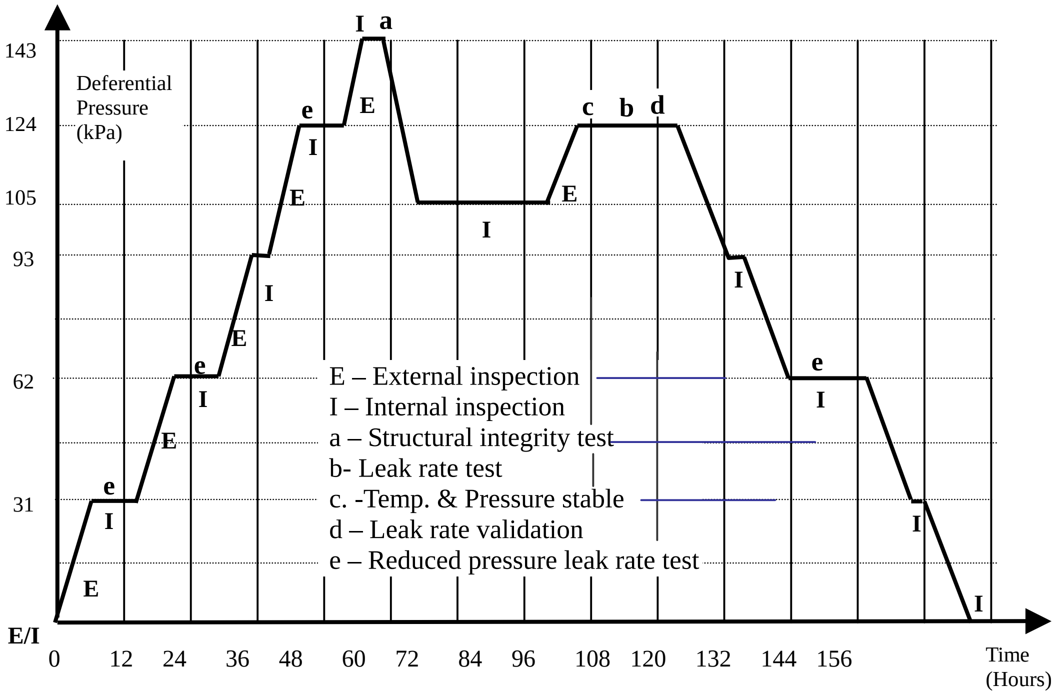
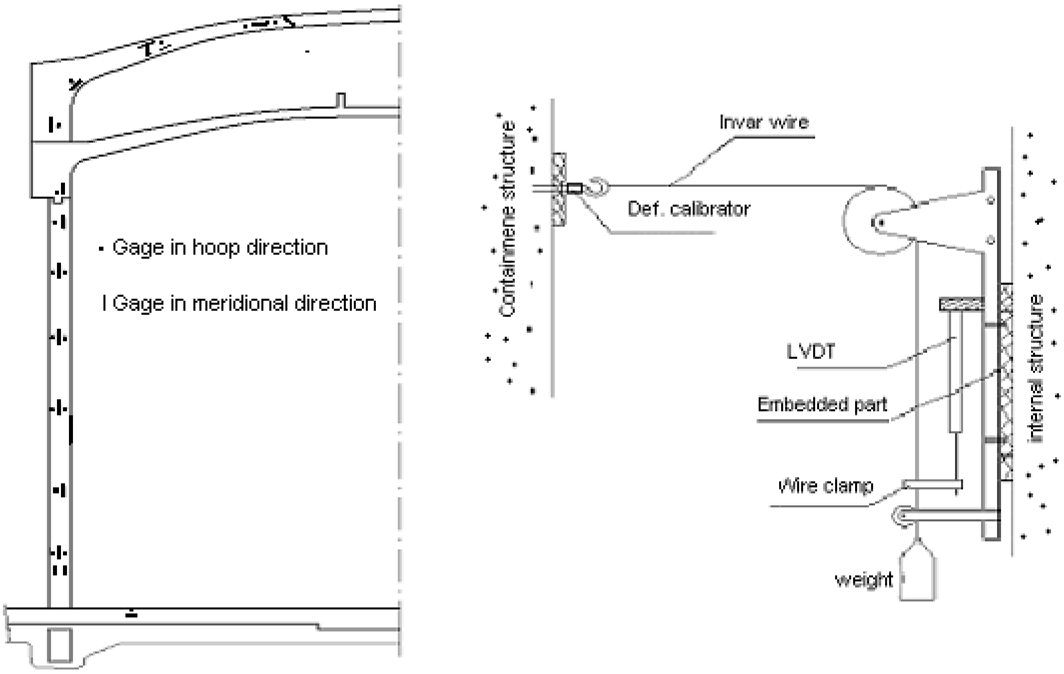


Figure 2. Typical Pressure –Time Curve for PPT/ ILRT and Inspections



a) Strain Gage at Containment Structure b) LVDT Deformation Meter Set-up

Figure 3 Strain Gage And Deformation Measuring

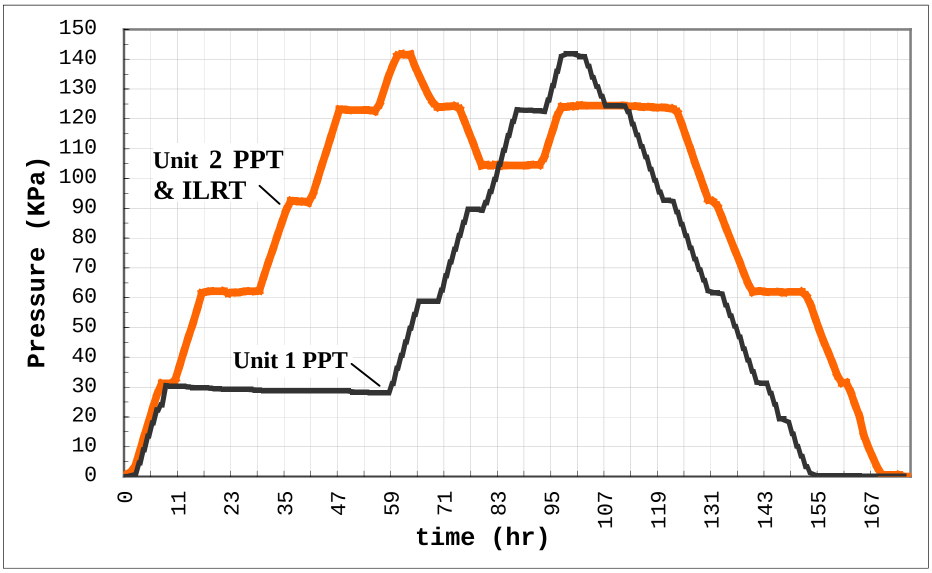


Figure 4 Pressure-Time Curves for Unit 1 and Unit 2 Test

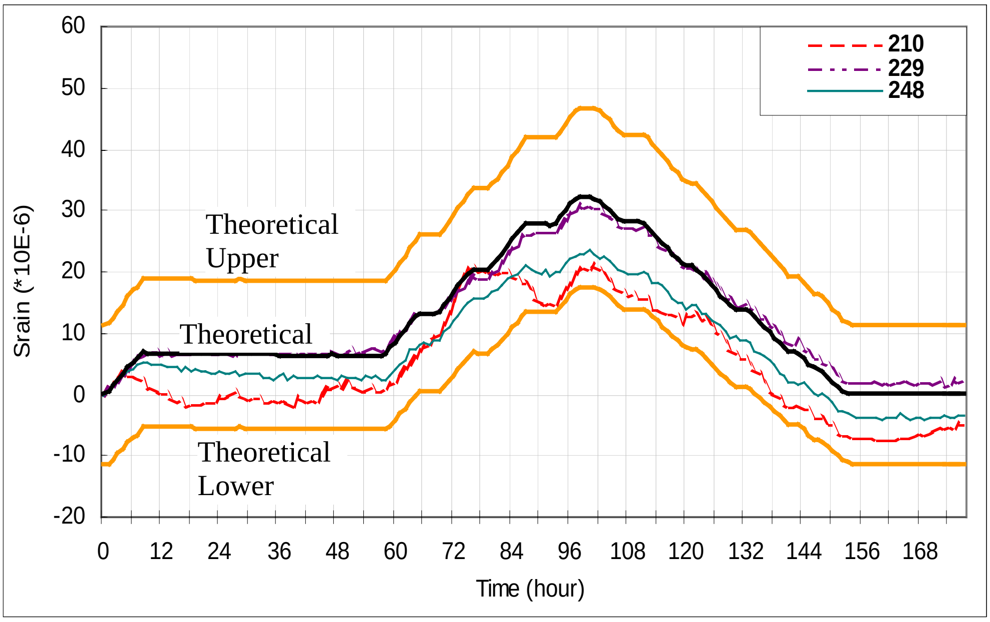


Figure 5 Typical Strain Gage Readings from Unit 1 R/B PPT
(At Perimeter Wall 114m, Center and Matrimonial direction)

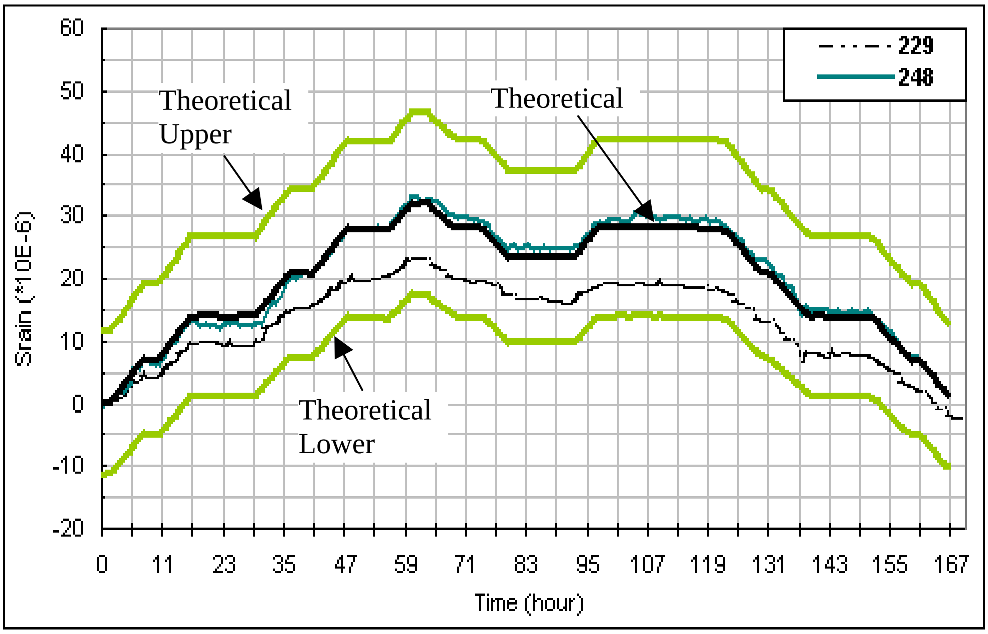


Figure 6 Typical Strain Gage Readings from Unit 2 R/B PPT
(At Perimeter Wall 114m, Center and Matrimonial direction)

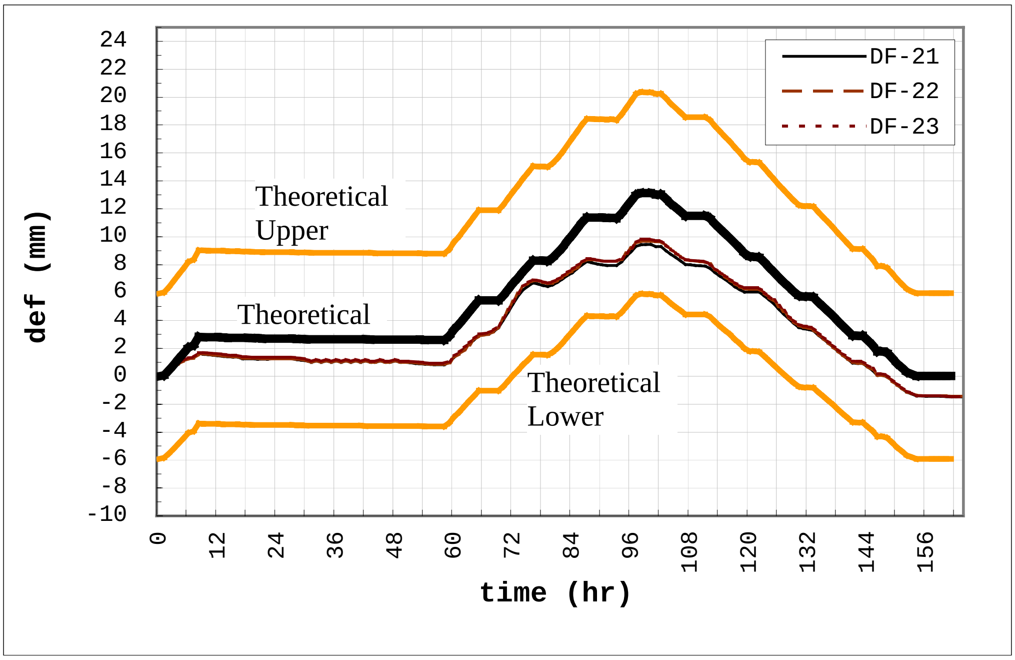


Figure 7 Upper Dom Deflection of R/B Unit 1 PPT

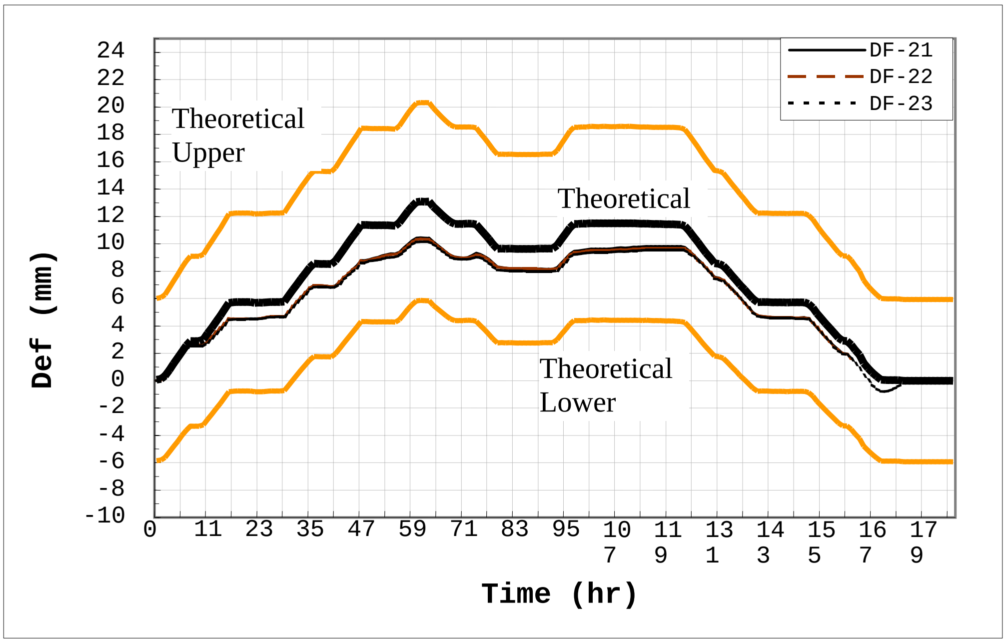


FIG. 8 Upper Dom Deflection of R/B Unit 2 PPT

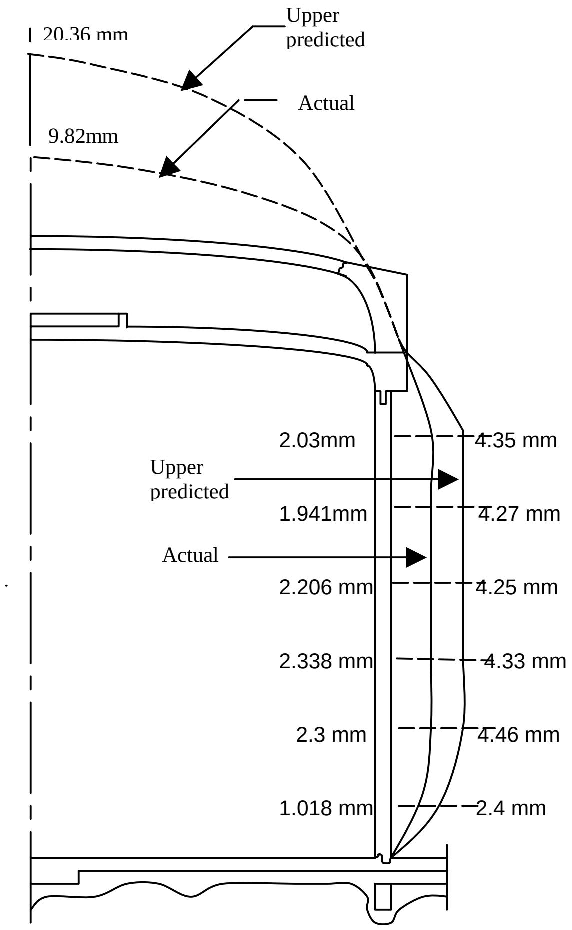


Figure 9 Unit 1 Reactor Building Deformed Shape

Figure 10 Qinshan Phase 3 CANDU Power Plant