MEASURING DEFORMATIONS IN A CANDU™ 6 CONCRETE CONTAINMENT STRUCTURE

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ABSTRACT

The CANDU™ 6 reactor system is contained within a post-tensioned concrete containment structure. The New Brunswick Power (NBP) owned, Point Lepreau CANDU™ 6 Generating Station (PLGS) located in New Brunswick, Canada, has been in service since 1983. Investigations are being undertaken to evaluate the significance of any age-related degradation. Particularly, a survey is being conducted to assess the expected long term performance of the structure. For part of this survey, *in-situ* deformations that occur during normal reactor operation and a leak-rate test, for which the structure is internally pressurized, are being measured.

During the early life of the structure, deformations were measured using both embedded and surface mounted gauges on the concrete surfaces. The record shows that neither of these strategies provided results which can be used to evaluate the current stress conditions. A reason for this may be related to the type of instrumentation used.

Subsequently, various types of commercially available instruments have been appraised for application at PLGS. Laboratory and *in-situ* tests on mechanical, vibrating wire and fibre-optic deformation measuring devices confirm that the accuracy of the measurements can be expected to vary significantly between instrument types. In addition, for each instrument type, the instrument stiffness, the temperature and the manner in which the instrument is installed all strongly influence output.

Recently, three gauge types were retrofitted to the outside surfaces of the PLGS containment structure to provide a further assessment of the usefulness of the instrumentation and, ultimately, the condition of the structure. Taking the determining factors of instrument type and environment into account, measurements were made during and following a leak-rate test. These tests have shown that all of the instrument types can be used to assess the condition of the structure. It is shown that concrete containment structure is required to endure distortional stresses due to environmental conditions. It is concluded that monitoring of deformations occurring in concrete containment structures during the leak-rate pressure tests as well as continuously over the period of their operating life is an essential element in a structural ageing management program.

BACKGROUND

In the mid 1990's, Atomic Energy of Canada Limited (AECL) and New Brunswick Power (NBP) initiated a series of investigations to determine the need for a Plant Life Management Program (PLiM) at Point Lepreau Generating Station. Recently, a program was designed to provide the basis for a statement of "fitness for service" for the structures partially through measurements on the concrete containment. The plan included activities designed to provide details for an ageing management program (AMP) and an assessment of the condition of the structures. The physical installation of instrumentation on the concrete containment structure was required for both of these purposes. Part of the proposed *in-situ* work was recently completed.

This paper presents a summary of the ageing management program, the physical condition survey and the monitoring scheme designed to evaluate the effects of age-related change, if any, for the containment structure. The monitoring program carried out during and following a leak rate pressure test is briefly described. For the latter, instruments were installed on the exterior surfaces of the containment structure at PLGS, and measurements were taken during a leak-rate (pressure) test. A brief summary of some of the test results is presented.

AGEING MANAGEMENT PROGRAM

The concrete containment structure of the CANDU™ 6 system provides final protection to the public against radioactive emissions occurring during normal reactor operation and in the unlikely event of an accident. For original design purposes, the structure would be required to function for a minimum of 30 years. The concrete containment structure at PLGS is over 20 years old. Studies are being undertaken to determine ageing effects that the structure has experienced. How the ageing effects have affected the projected service life of the structure is being assessed and measures to mitigate adverse ageing effects, if they are found to be of concern, will be defined.

A detailed ageing management program was undertaken at PLGS. These studies were carried out to provide the following three products:

- A description of containment structures, their design, construction, operation/maintenance histories and environmental conditions.
- An assessment of the ageing conditions found at the CANDU™ 6 concrete containment structures.
- A general description based on world experience of the various ageing degradation mechanisms, which could affect containment performance with time and review of the relevance of these ageing mechanisms to the station.

With the completion of these studies, the following recommendations were made:

a. Areas identified to be affected by ageing should be inspected in detail and monitored with time;

b. *In-situ* measurements, tests and associated laboratory work should be carried out to minimise the gaps in knowledge, and;

c. A data bank including items such as construction and maintenance records, benchmarks for each type of identified degradation, and acceptance criteria defining the limiting values to which ageing effects should be restricted, should be compiled.

It was indicated that only after completion of these actions can other phases (i.e., condition assessment and maintenance) of an AMP follow. In 1998, further AMP activities, following the recommendations above, were initiated at PLGS.

CAN/CSA N287.6 [1] and CAN/CSA N287.7 [2] specify the requirements of leak-rate pressure testing and in-service examination for containment structures for CANDU™ Nuclear Power Plants. In addition to the requirements for leak-rate tests, CAN/CSA N287.6 requires that the concrete containment structure should be instrumented during construction for structural components that are not similar in design to those which have previously been proved by pressure tests during commissioning. A typical instrumentation scheme used for a CANDU™ 6 concrete containment structure includes mainly embedded vibrating wire strain gauges in the base slab, perimeter wall, ring beam and the dome. The Gentilly-2 (G-2) containment structure at Gentilly, Quebec, was constructed before that at PLGS and hence the G-2 structure was considered to be the Canadian prototype structure for CANDU™ 6 reactor systems. Thus, for the PLGS containment, there were no regulatory requirements to make the deformation measurements. Accordingly, at PLGS, there was no reliable record of deformations occurring in the structure since it was built. To meet the requirements of the PLiM program, the instrumentation on the inner and outer surfaces of the structure was required to measure deformations occurring during the normal operation and during specific periods, such as during the leak rate pressure tests.

CONTAINMENT STRUCTURE

The reactor building is divided into two parts i.e., the containment structure and the internal structure. The containment structure is designed to satisfy mainly three functional requirements:

- To house the reactor and auxiliary systems and protect them from environmental conditions and severe accidental loads;
- To provide radiation protection during operation and accident conditions;
- To withstand the design accident pressure and to provide containment of radioactive materials following a release within the containment envelope.

The containment structure consists of a base slab, perimeter wall, ring beam and upper dome. These are all prestressed post-tensioned structural elements. The post-tensioning tendons are protected from corrosion with cement grout pumped into the sheath. Figure 1 shows the general arrangement, containment boundary and physical dimensions of the structure.

The base slab is nominally 1.68 m thick and sits on the sub-base and tendon gallery structure, which in turn is founded on rock. A sliding membrane is provided under the base slab to facilitate radial deformation during the prestressing of the base slab. A central shear key and a set of radial shear keys are provided in the base slab for transferring the horizontal and torsional forces due to environmental and accident loads.

The perimeter wall thickness is 1.07 m, with an inside diameter of 41.46 m and a height from the top of the base slab up to the bottom of ring beam of 42.19 m. The perimeter wall has 4 buttresses where the wall thickness is 1.9 m. These buttresses are provided to anchor the perimeter wall horizontal post tensioning grouted tendons.

Two large openings, approximately 7.92 m and 10.36 m square, are left in the perimeter wall during construction, to permit the installation of larger pieces of equipment such as the calandria and the steam generators. These openings are closed after the installation of heavy equipment, and the closing sections act as integral parts of the perimeter wall to which they are connected by a system of horizontal and vertical prestressing cables and reinforcing steel connections.

The ring beam gives support to the upper dome and to the top of the perimeter wall. The ring beam consists of two parts. The first part (Phase I) of the ring beam is 1.9 m in width and 1.37 m in height and supports the lower dome and the perimeter wall. The second part (Phase II) of the ring beam is 1.9 m in width and 2.9 m in height and supports the upper dome. All the prestressing cables for the upper dome and the vertical cables of the perimeter wall are anchored in the phase II ring beam. The Reactor Building upper dome, with a radius of 41.45 m and a minimum thickness of 0.61 m completes the weather cover and the pressure-retaining component of the containment.

The walls of the spent fuel transfer bay structure are generally 1.8 m thick and the roof consists of 1.8 m thick reinforced concrete or 1.20 m of heavy concrete.

PHYSICAL CONDITION SURVEY

As a part of the AMP, the existing condition and degree of degradation of the containment building was determined. A detailed survey identified the exterior surface and near-surface defects and related features on the upper dome, ring beam and perimeter wall of the structure. This survey comprised a detailed visual examination of all the exposed surfaces, the determination of concrete cover thickness and an assessment of concrete compressive strength across the dome surfaces using non-destructive technique at random locations. The type and degree of rehabilitation of the exterior surfaces and near-surfaces necessary to meet the performance requirements was determined based on the findings of the condition survey.

During the visual inspection, it was found that portions of the structural elements mainly ring beam and the top portion of the perimeter wall exhibit some signs of leaching and cracking. It was concluded that the observed surface defects are minor and have no impact on the functionality of the containment structure. In the future, rehabilitation of these areas is required to preserve the service life of the structure. The mean concrete cover thickness is about 45 mm, which is acceptable, and the concrete compressive strength is in a range of 45 to 55 MPa. These values exceed the design specification of 35 MPa for the concrete strength and thus it appears that ageing has not affected the compressive strength of the concrete. More detailed analyses of physical and chemical properties of the concrete are being carried out to further qualify durability of concrete.

INSTRUMENTATION FOR CONCRETE CONTAINMENT STRUCTURE

The types and positioning of the instrumentation installed on the outside surfaces of the perimeter wall and upper dome at PLGS are shown in Figure 2. These installations represent the first phase of a multiphase plan. Further installations are expected to be made at a later time. These will include instrumentation on the inside of the wall and at other spatial locations on the exterior of the structure. The final installation will provide measurements that will permit observations on both the local and global behaviour of the structure under different loading conditions. The installations shown in Figure 2 were made in June and July 2000, to take advantage of a leak-rate (pressure) test carried out in August

2000. The positioning of the instrumentation on the exterior of the structure was influenced by the presence of auxiliary buildings, shield walls, steam pipes etc.

The installed instrumentation included the following:

a. Four 27.5 meter long gauge fibre optic sensors (LGFOS) installed horizontally on the outer surface of the containment wall between the buttresses as shown in Figure 2. These gauges are intended to measure the global deformation occurring in the circumference of the structure at, approximately, 2/3 height of the wall.
b. Eight primary and three secondary clusters of strain (deformation) gauges to measure deformations on the wall and dome are shown in Figure 2. Figure 3 (a) shows typical primary and secondary clusters used on the perimeter wall and dome. Primary clusters include sets of vibrating wire strain gauges (VWSG's, 150 mm gauge length), fibre optic sensors (FOS, 500 mm gauge length) and DEMEC mechanical gauges (1000 mm gauge length) mounted orthogonally in horizontal and vertical directions. These different types of gauges are sufficiently close to each other so that the output can be compared, contrasted and used to validate each other. The secondary clusters consist only of VWSG's and DEMEC gauges (300 mm gauge length). Figure 3 (b) shows the junction boxes of VWSG's and FOS's.
c. Stress-followers were installed in holes drilled into the concrete from the outer side of the wall. Similar to the surface mounted VWSG's the embedded stress-followers carried a thermistor to measure temperatures. The holes used for the stress-followers were formed during the overcore stress measurements that were made to determine the residual stresses in the concrete prior to the execution of the leak-rate test. Two stress followers were mounted orthogonally, horizontally and vertically, in each overcore test hole, which was then sealed.
d. Pendula systems to measure the lateral and vertical displacements along the height of the concrete containment wall were part of the program. After the pressure test, all the stations were installed on the wall (see Figure 2) and systems were attached to the data acquisition. Unfortunately these installations could not be completed before the leak-rate test in 2000 and are now to be used for continuous monitoring of the structure and during future leak-rate tests.
e. A multi-tasking PC-based data acquisition system was installed so that all instruments, except the DEMEC gauges, could be monitored simultaneously and in real time. The data is regularly backed up and recorded to disc and, as required, is transferred via a modem to a central office for long term storage and future analysis.

LEAK RATE PRESSURE TEST

To demonstrate the continuing function and safety of the containment structure and its ability to otherwise meet the regulatory requirements, several in-service leak rate tests have been performed. In August 2000, a leak rate pressure test was carried out at the beginning of the planned maintenance outage. The pressurization of the building started on August 23, 2000 at about 7:00 p.m. Figure 4 shows the measured pressurization and depressurization curve for the containment structure. The maximum pressure of 124 kPa (g) was obtained in three stages with intermediate steps at about 42 kPa (g), 98 kPa (g) during the pressurization cycle. During the depressurization, the intermediate pressure steps were at 80 kPa (g) and 38 kPa (g). As noticed from this figure the rate of pressurization is higher (about 8 kPa /hour) than the depressurization (about 4 to 6 kPa/hour) cycles.

RESULTS

Based on the preliminary assessment, the results indicate that the instrumentation strategy has been successfully implemented. The following general observations are presented:

- Nearly all of the deformation and stress gauges have provided reliable and usable data and continue to do so six months after the pressure test.
- The data from the VWSG's compare well and favourably with those from the equivalent FOS's in the primary clusters of gauges. It is observed that the FOS's are easier to install and their output is simpler to read and follow than that of the VWSG's.
- From the limited analyses undertaken, it appears that the deformations occurred during the leak rate test were within the ranges expected from numerical analyses of the structure, which were performed before the test was undertaken. The structural model appears to be successfully validated.

In addition to these general comments, the following more detailed results and observations on the measured stresses in the concrete wall and the deformations measured by the LGFOS's are presented.

In-Situ Stresses

The *in-situ* stresses acting within the perimeter wall at eight locations (see Figure 2) and at depths from the exterior surface of 50 mm to 350 mm were determined using an overcoring technique. The stress measurements were conducted before the leak rate pressure test. The intention was to confirm that the stresses in the wall remain at design values. Four doorstopper cell overcore tests were performed at nominal depths of 50, 150, 250 and 350 mm, from the exterior surface of the wall, in each hole for a total of 32 measurements. Prior to the start of test drilling, a survey using a device (Ferroscan®) to identify the locations of reinforcing steel and post-tensioning cable ducts had been completed. This surveying technique along with the use of "as-built" drawings detailing the location of the reinforcing steel was entirely successful. No reinforcing steel was encountered during the drilling of the eight test holes. The data show that, as expected, all of the measured in-situ stresses (both horizontal and vertical) were compressive. The compressive stresses ranged from 3.8 to 10.2 MPa and 2.7 to 10.9 MPa, in horizontal and vertical directions, respectively. Globally, these values are within the expected ranges. Local variations appear to conform with the results of numerical analyses of the structure. However, further evaluation of the data will be required to firmly conclude that the structure conforms fully to design expectations. Furthermore, overcoring technique can provide invaluable information to assess the effects of ageing on the prestressed elements of the structure. It is important to recognize that the key factor is the compressive stresses in the concrete. The overcoring technique has clearly provided direct and good measure of these values.

Deformations using LGFOS

During the leak rate test, only three of the 27.5 m long gauge fibre optic sensors (LGFOS) on the North, East and South Side of the perimeter wall were functioning. These gauges, which are as designated LGFOS-E, LGFOS-N and LGFOS-S for East, North and South directions, respectively provided measurements of the global deformations that occurred during the leak rate test.

Measurements were taken continuously at an interval of 15 minutes during the test. Figure 5 presents the total deformations (i.e., deformations due changes in pressure and temperature) and expressed as micro strain with time during the leak rate pressure test for the three long gauge fibre optic sensors. At a test pressure of 124 kPa, total strains of 82, 63 and 86 $\mu\varepsilon$ were measured in the East, North and South directions, respectively. It can be seen from the results that the measured strain response of the building exhibited similar trends to the imposed load curve. This is particularly valid during the first two days of the test, when due to weather conditions, the temperature effects were minimal. During the pressure test, the LGFOS gauges were not protected by weather covers and were exposed to direct sunshine. However, unlike VWSG's, the FOS gauges are self temperature compensating and the peaking of strain during the latter period of the test as depressurization was occurring are real measurements of concrete strain occurring due to exposure of the concrete to sunshine. Temperature measurements were also taken. It was cloudy and wet during the first (August 23) and second (August 24) day of the pressure test with short spans of sunshine in the afternoon. As noticed from this figure that LGFOS-N and LGFOS-S showed very similar trends and magnitudes during the first 2 days when the effect of direct sunshine was not significant. The sharp increase in the strains of LGFOS-E and LGFOS-S on August 25 and August 26 are directly attributable to exposure of the concrete surface to direct sunshine. The data show that temperature effects can be significant on the measured strain. During a pressure test in summer conditions, numerical simulations indicate that a the total strain will range in between 25 to 102.3 $\mu\varepsilon$ at 124 kPa (g). The measured response fell well within the predicted range.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made:

1. Measurements taken during the leak-rate test have shown that all of the instrument types implemented can be used to assess the condition of the structure.
2. A successful start to the assessment program for the concrete containment at PLGS was accomplished. Long term monitoring of the structure has begun and initial results of the leak-rate pressure test indicate that measured strains and stresses are within the expected range.
3. It is recommended to monitor the structural behaviour not only during the leak-rate tests but also continuously over the period of the extended life of the structure. The instruments installed during construction do not

provide the information required for plant life management and extension programs. The monitoring program will enable the identification of mechanisms causing the age-related changes in the structure.

4. It would be cost effective if lessons learned from one site can be applied at others. Mechanisms should be established for this information transfer to be effected. There are many common features between concrete containment buildings. The development of an international data base on the assessment of concrete containments should be encouraged.

ACKNOWLEDGEMENTS

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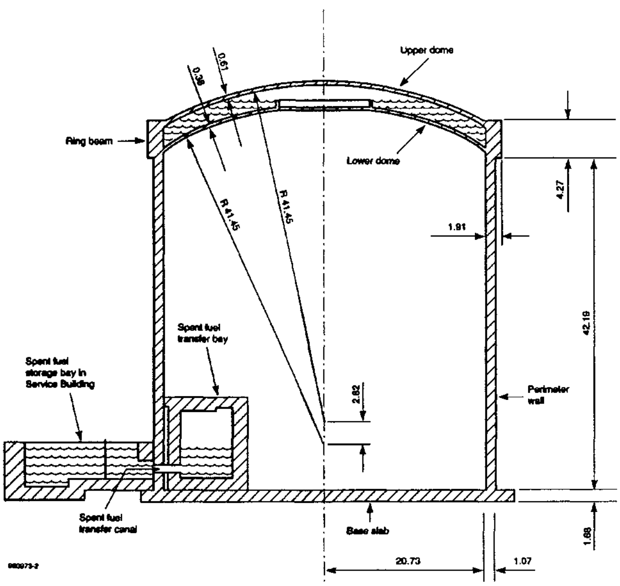
2. CAN/CSA-N287.7-96, "In-Service Examination and Testing Requirements for Concrete Containment Structures for CANDU Nuclear Power Plants", July 1996, 22 pp.



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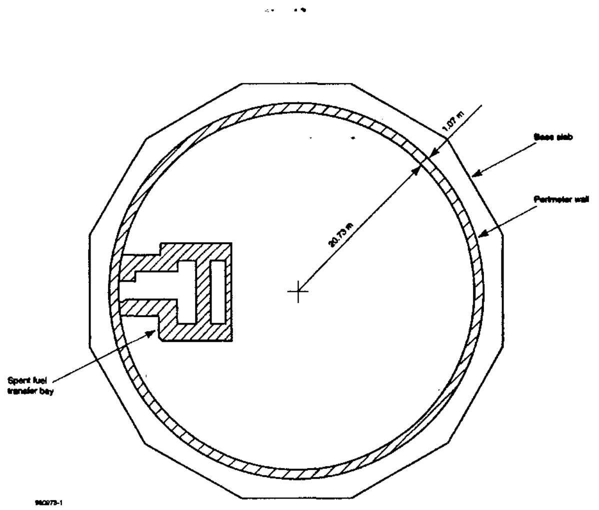


Plan

Figure 1 General arrangement of Concrete Containment Structure

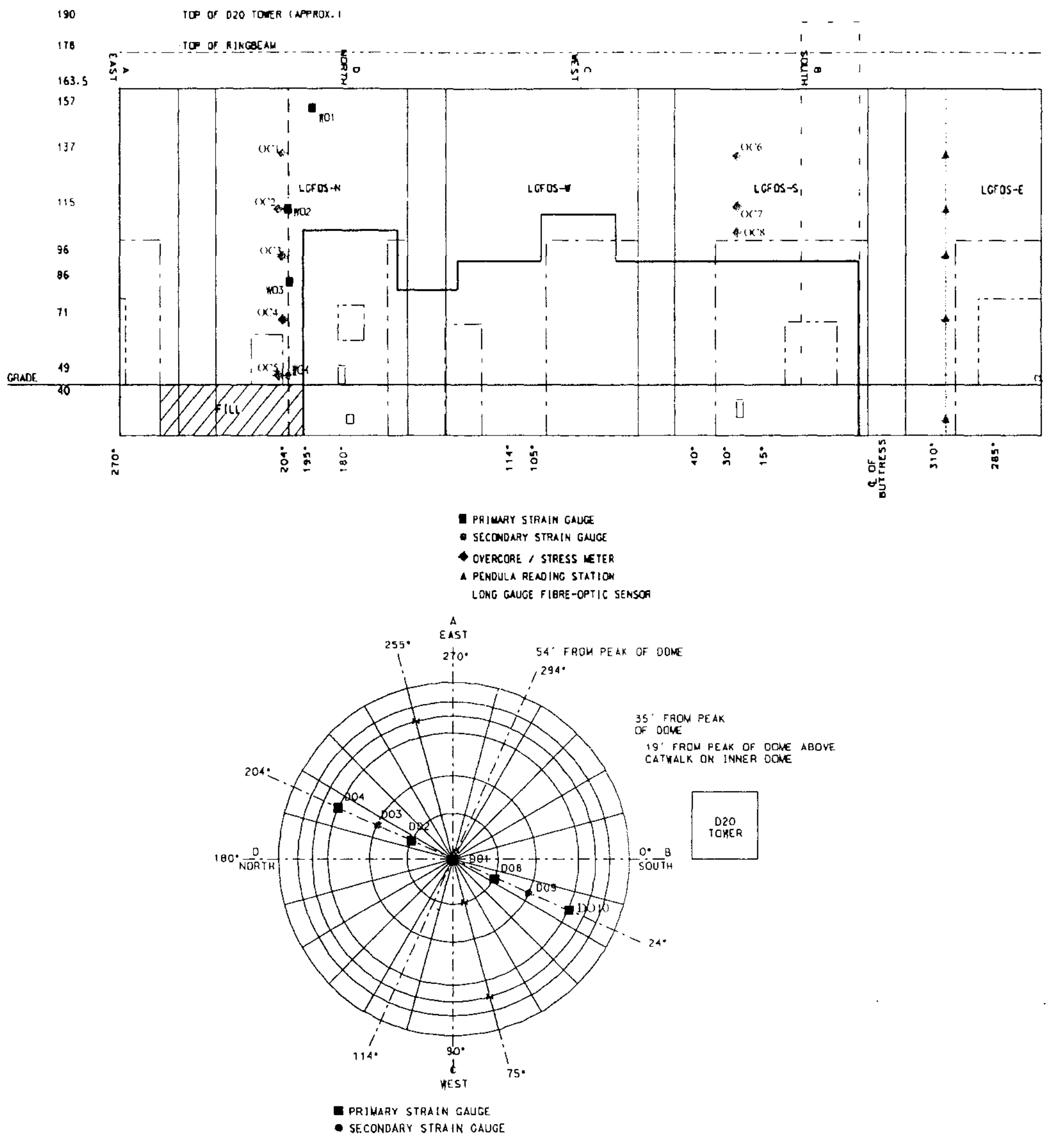
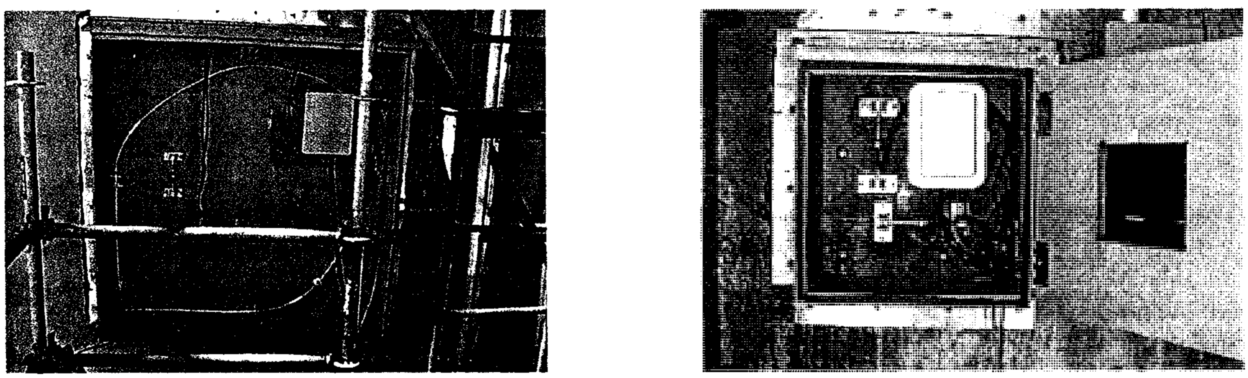
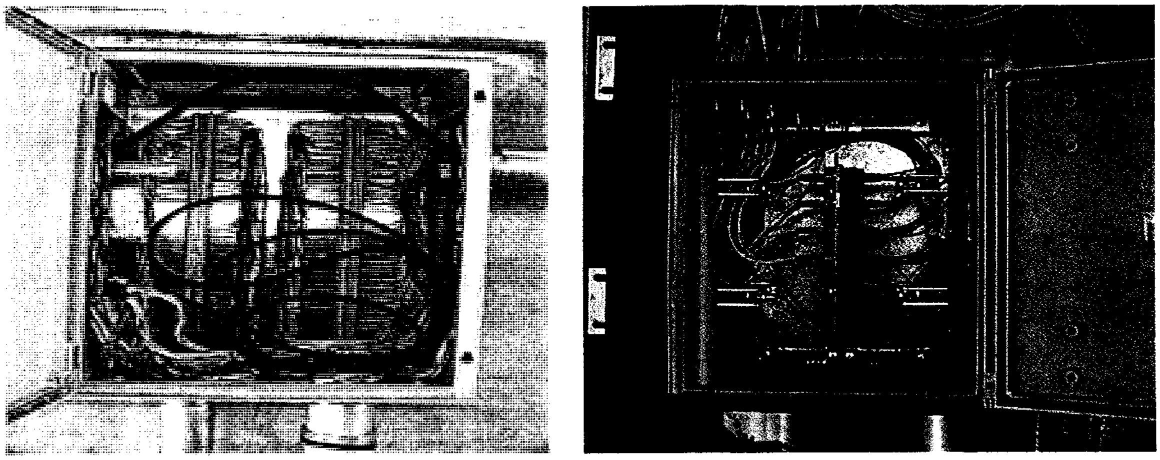


Figure 2 As-Built Instrumentation Scheme for the wall and dome of Containment Structure



a) Primary and Secondary Boxes



b) VWSG's and FOS Junction Boxes

Figure 3 Instrumentation Clusters and Junction Boxes

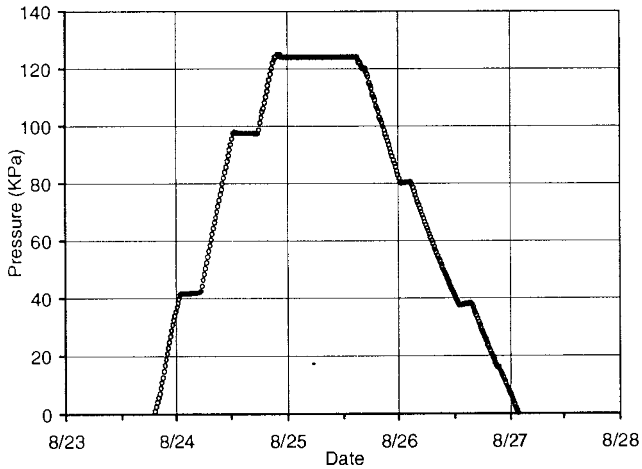
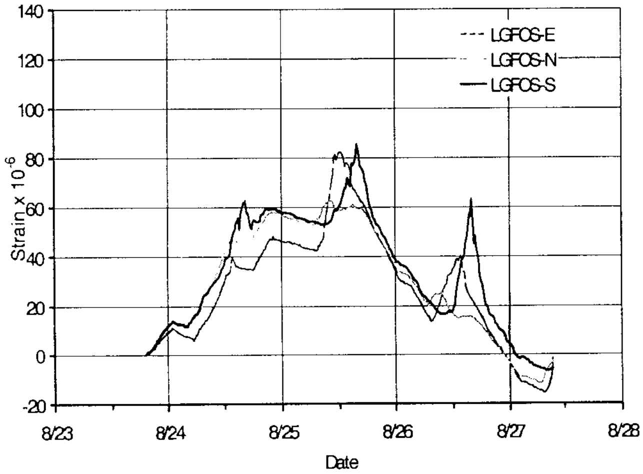


Figure 4 Applied Pressure During the Leak-rate Test



Figuer 5 Variation of Total Strain for Long Gauge Fibre Optic Sensors