EVALUATION OF NUCLEAR POWER PLANT CONCRETE TO MAINTAIN CONTINUED SERVICE

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ABSTRACT

Nuclear power plant concrete structures in addition to satisfying structural requirements are a major part of the safety and containment systems. As a result, the structures are required to operate satisfactorily for the life of the plant and until well after decommissioning. Successful life management requires an understanding of potential degradation mechanisms that can impact on the performance of these structures, regular well planned inspection programs and the use of specialized repair and maintenance programs. These aspects of nuclear life management are discussed with an example of inspection and repair conducted at one of Ontario Hydro's nuclear generating stations. The example is discussed in terms of the performance requirements of the containment concrete. The plant referred to has been in operation for over 20 years, making it currently the oldest operating commercial nuclear power plant in Ontario, Canada. The information on the concrete containment structures included baseline construction data on the concrete material properties and the results of periodic scheduled and other interim specialized inspections. Also available were the results of laboratory testing of concrete cores obtained from the structures. The data from these inspections and laboratory testing were used to monitor the aging characteristics of the structures and to plan appropriate repair activities.

Key Words: concrete, nuclear containment, degradation factors, aging management, service life

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INTRODUCTION

Ontario Hydro is the largest owner of nuclear power plants in Canada with the electricity produced from these plants accounting for approximately 60% of the total electrical production in Ontario. As a result, these power plants make a significant contribution to the province's economy, and the continued serviceability of the plants must be maintained to ensure reliable production of electricity for the province.

Concrete is used extensively in nuclear power plants for structural applications and for radiological safety. Structurally, it is used to house reactor components and provides a significant part of the safety and containment systems. Concrete is also used as biological shielding to protect personnel and the public.

The structural requirements must be maintained for the operating life of the plant, approximately 40 years with the possibility of extensions. The radiological safety requirements, including biological shielding and the containment of radioactive gases, liquids and materials, must be met for the operating life of the plant and until the plant is decommissioned and the radioactive components are placed in permanent storage. This may require the structures to maintain serviceability for 100 years or more.

FUNCTIONAL REQUIREMENTS

To maintain the serviceability of these structures, the unique functional requirements of concrete in a nuclear application must be understood. Degradation mechanisms affecting conventional concrete structures have been studied; however, the combination of degradation mechanisms experienced in an operating nuclear plant and the long-term effect on the performance of the concrete cannot be completely predicted. In addition, the unique functional requirements of nuclear containment structures such as very low air and water permeability have not been assessed over a long term.

Therefore, nuclear power plant concrete structures must be regularly inspected to satisfy licensing requirements, to ensure the functional requirements are maintained, and to identify any short-term deficiencies. The information from these inspections is used to identify long-term degradation processes that may affect the operating life of the station. The results from these inspections are also used to characterise the aging of the concrete and formulate repair programs to maintain the serviceability of the structures.

DEGRADATION PROCESSES

Concrete structures in a nuclear service environment are subjected to a variety of exposure environments. These include conditions experienced by many large industrial structures such as exposure to freezing and thawing, high structural stresses, prolonged high temperatures and aggressive liquids (eg. acids, deionized water) with the addition of high radiation levels. The effect of exposure to some of these conditions has been studied in the laboratory and monitored in existing structures. The long-term performance of the concrete must be predicted based on the available information which is frequently limited. The more data available on a specific exposure condition and the longer the period the data covers, the greater the accuracy of any predictions on the long-term concrete performance.

A significant difference between concrete structures in nuclear power plant applications compared to conventional industrial applications is that the nuclear structures must possess special functional properties (eg. low air and water permeability) that must be maintained for 100 years or more. A reduction in these properties or evidence of concrete deterioration is not acceptable to the regulators or the public. This long service life with special performance requirements in a unique exposure environment mandates special monitoring of concrete structures in nuclear power plants.

INSPECTION PROGRAMS

The inspection of nuclear containment structures are typically carried out for two reasons:

1. To satisfy regulatory requirements for continued safe operation /1/. These inspections are generally carried out at a regular interval with specific requirements.
2. To address unexpected operational problems caused by deterioration or damage to the containment structures. These inspections are carried out when needed and the requirements vary to address the particular problem.

These inspections should identify problems with the performance of the concrete and provide information and data to predict the long-term concrete aging characteristics. In some instances, repairs are required to return the structure to a satisfactory operating condition.

Inspection programs are designed to concentrate on critical areas based on the required performance of the structure or deterioration of the concrete. The preparation of the program includes a review of the structure in consultation with the design engineer to identify and select components or areas of high stresses or severe exposure for detailed inspection.

Various techniques are employed depending on the objective of the inspection. These include visual inspection supported with a photographic record and crack mapping, nondestructive testing techniques to identify areas of deterioration and concrete coring to obtain specimens for laboratory testing and examination to determine the physical properties of the concrete and the condition of the cement-aggregate bonds.

Baseline data is frequently available from construction records, previous inspection reports, and the literature. This data is compared to the inspection findings to identify changes in the concrete and to predict aging characteristics.

Ontario Hydro maintains a unique long-term exposure site used to monitor various types of concrete in a natural outdoor exposure environment to identify concrete aging and performance characteristics /2,3/. Data is available on concrete exposed for over 40 years. The information from monitoring specimens in this site is used to assist in predicting the performance of concrete in-service under similar conditions. In addition, programs that accelerate the aging process under specified exposure conditions are carried out in the laboratory. These include exposure to high temperatures, accelerated testing for alkali-aggregate reactivity and exposure to flowing deionized water.

On occasion, concrete samples are obtained from the reactor containment buildings or reactor shielding vaults. These samples are frequently highly radioactive and special handling and testing procedures and facilities must be utilized. The concrete is typically analyzed for changes in physical properties that may indicate progressive deterioration due to the service environment. The concrete is also analyzed to determine the radioactive inventory including the nature of radioactive isotopes present and their profile through the concrete section.

REPAIR PROGRAMS

Based on the results of the inspection programs and the predicted performance of the concrete, repairs may be necessary to maintain the continued serviceability of the structure. Generic repair materials and procedures are suitable for many applications; however, on occasion, a specialized repair may be required.

To address specialized repair requirements, suitable materials are developed and evaluated in the laboratory to ensure they satisfy the performance requirements. This may require the construction of models and the use of environmental chambers to evaluate extremes of temperature, moisture and radiation exposure. Specialized testing equipment is employed to evaluate the physical properties of the materials and repairs.

The repair procedures are developed based on a combination of laboratory testing and field trials. When the repair is performed, it is inspected and monitored using both specialized and established QA and QC procedures.

CASE HISTORY

The application of these inspection and monitoring programs to Ontario Hydro's oldest operating nuclear reactor is discussed. The plant, Pickering NGS 'A' Unit 1, has been in operation for over 20 years. As a result of these inspection programs, the need for repairs was identified to maintain the serviceability of the Unit 1 containment structure.

Background

Pickering NGS is located on the north shore of Lake Ontario approximately 20 miles east of downtown Toronto (Figure 1). This was the first multi-unit nuclear power plant constructed by Ontario Hydro with the units placed into service between 1971 and 1973.

Pickering NGS 'A' is a four unit (540 MW per unit) CANDU type nuclear station. Each unit (Units 1 to 4) and its associated nuclear components are housed in concrete reactor buildings. The turbine and conventional components are in a separate building. Radiological safety structures include the reactor buildings (one for each unit), a pressure relief duct and a vacuum building which were designed to prevent the release of radioactive gases, water vapour and particles in case of a nuclear accident. The pressure relief duct connects the reactor buildings to the vacuum building. In an emergency, such as a loss of coolant accident, gases and steam that are generated will be drawn via the pressure relief duct to the vacuum building and will be condensed by a water spray system supplied from an elevated tank enclosed within the building.

All of these containment structures (ie. reactor buildings, pressure relief duct and vacuum building) are constructed of reinforced concrete.

The reactor buildings consist of a 4 ft (1.2 m) thick circular perimeter wall supporting an 18 in (0.46 m) thick reinforced concrete dome (Figure 2).

The domes of the reactor buildings are exposed to an outdoor environment and are subjected to cycles of freezing and thawing and rain, snow and ice. At certain times of the year and depending on the operating condition of the reactor, the concrete can be exposed to high thermal gradients through the thickness of the dome causing high structural stresses.

Inspection Results

As part of the licensing requirements, the containment buildings are assessed for leak tightness by conducting periodic pressure tests approximately every five years. The structures must be leak tight to ensure all radioactive gases, steam and particles are contained in the event of an accident.

The test consists of pressurizing the buildings to approximately 6 psi (g) (41.4 kPa (g)) and monitoring the loss of pressure with time. During these tests, critical areas of the reactor building, such as those exposed to high structural stresses, are visually inspected to identify deterioration. The inspections concentrate on identifying leak paths extending through the containment boundary which could contribute to an increase in containment leakage and signal concrete deterioration. Because of the nature of these tests, they provide a unique opportunity to identify leakage paths that extend through the concrete.

During a pressure test of the Unit 1 reactor building conducted in 1992, a significant increase in building leakage was recorded (Figure 3). This increase was attributed to air leakage through numerous hairline cracks in the top part of the reactor building dome. Although hairline cracks had previously been identified in the dome, the extent and number had not been previously reported. These cracks were very narrow, typically less than 0.005" (0.1 mm) wide, and not readily visible.

The results of this test were of concern because there was a possibility that a minor increase in containment leakage in subsequent tests might cause the leakage limits specified in the operating licence to be exceeded requiring the unit to be shut down. Since this was the oldest unit, there was also concern that similar leakage could develop in the other three units. The cracking could also indicate a serious problem with deterioration of the concrete.

As a result of these concerns, a two stage program was initiated. The first stage was to identify the cause of the hairline cracks and determine the probability of increased cracking in subsequent years. The second stage was to develop a repair method to seal the cracks to allow continued operation of the unit with no concern of exceeding the leakage limit in subsequent years.

Concrete Investigation

Detailed information was available on the concrete used in the domes of the reactor buildings. The information was obtained from concrete inspector's reports prepared during construction and included information on the ambient weather conditions, method of placement, mix proportions and fresh concrete properties. In addition, the density and compressive strength at 7, 28 and 90 days was recorded. This information, used as

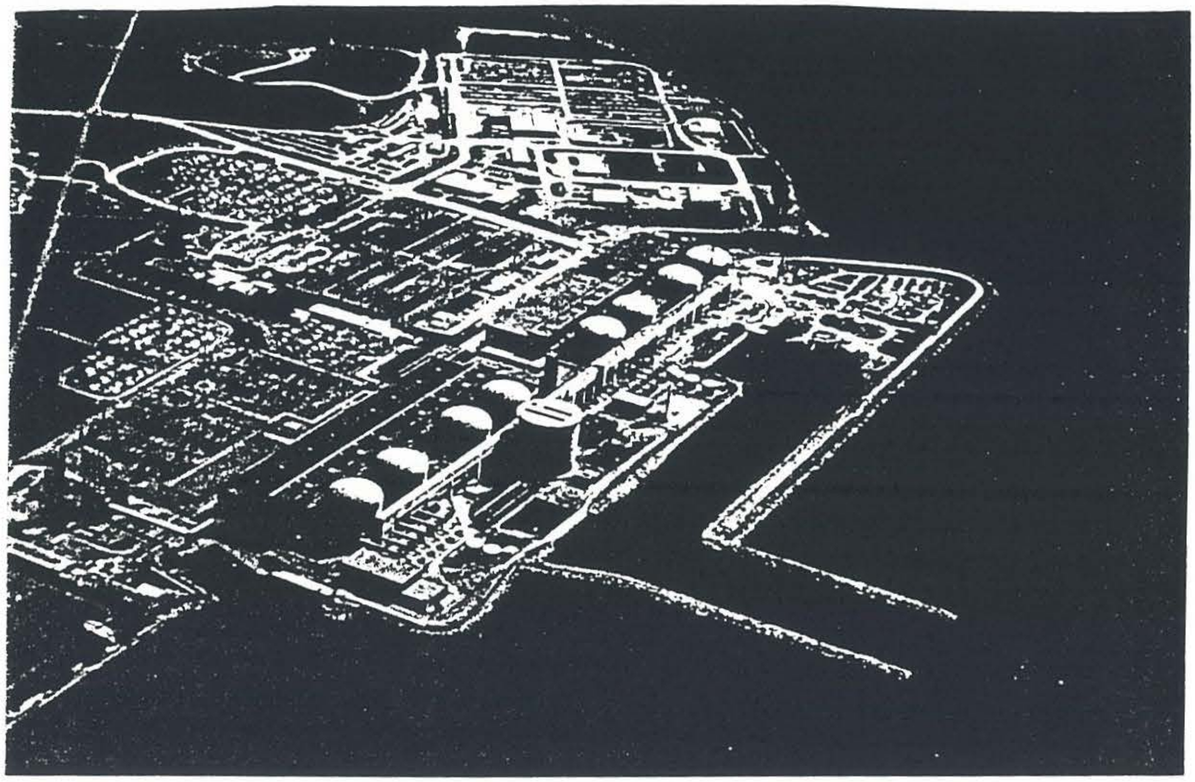

Figure 1: Pickering NGS 'A' and 'B'

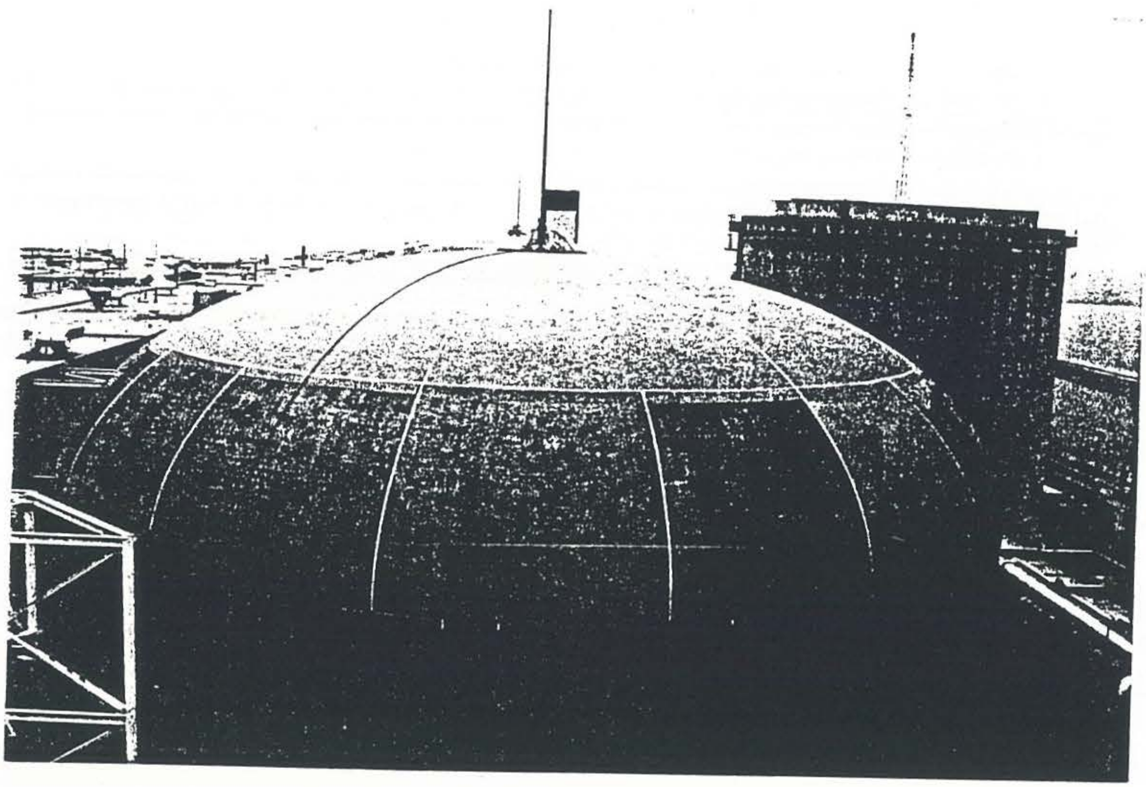

Figure 2: Reactor Building Wall and Dome

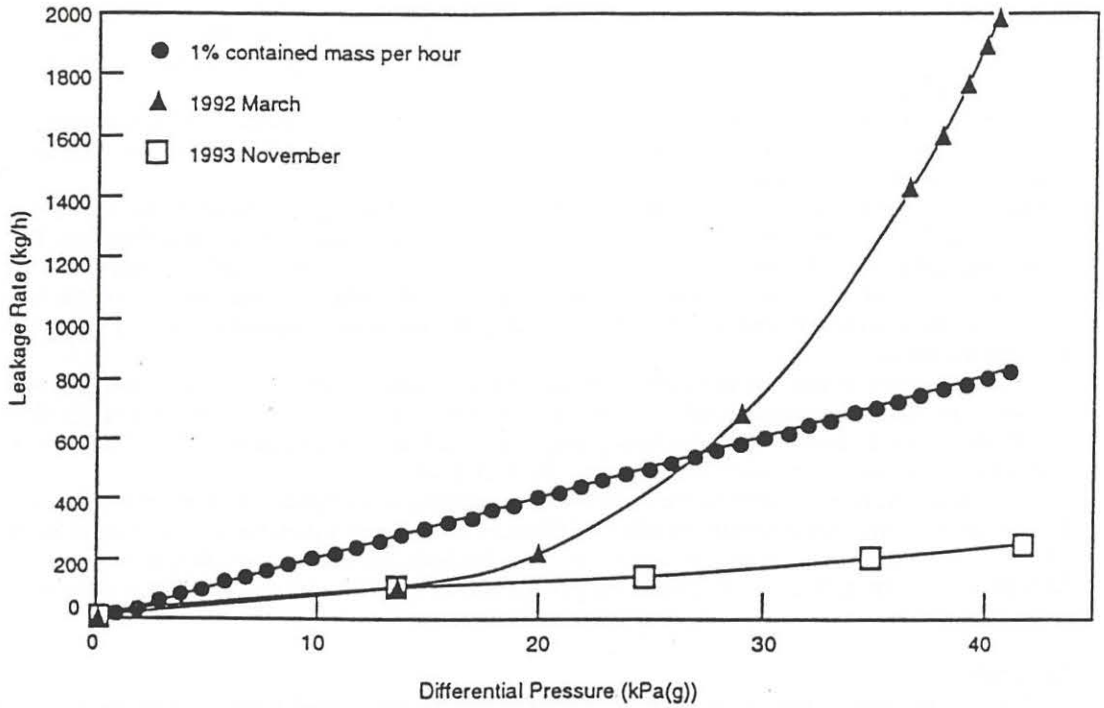

Figure 3: Pressure test results. The circles show the operation target of 1% volume leakage per hour. The licensing limit is 2.7%. The triangles show the leakage during the test immediately prior to the repair and the squares show the leakage after completion of the repair.

baseline data, was summarized and reviewed to identify differences in the concrete between the four units.

Commissioning reports were available but they did not describe the as-built condition of the concrete in detail. As an example, the reports mention radial hairline cracks in the reactor building dome but information regarding the length, width or number of cracks was not provided.

The results of the regular in-service inspections of Unit 1 conducted since commissioning were compared to the results of similar inspections of Units 2 to 4. Radial cracking was identified in the domes of all the units, however the cracking was most extensive in Unit 1.

To help in determining the cause of the hairline cracks and confirm the quality of the concrete, an investigation program consisting of nondestructive testing, concrete coring and laboratory testing was undertaken. For this investigation, Units 1 and 4 were selected as they represented the first and last units built. The walls and the domes were sampled in both units to represent concrete exposed to different structural stresses. Areas of the wall exposed to an outdoor environment versus those exposed indoors were compared to identify the effects of exposure environment.

The nondestructive testing included ultrasonic pulse velocity readings and detailed crack mapping of selected test areas. Inspections were conducted at different periods of the year and with the reactor building in different conditions (ie. unit in operation, unit shut down, building at various pressures during test). The objective of these activities was to identify any increase in cracking that may occur.

Specimens were prepared from the cores and tested for compressive and splitting tensile strengths and density. This testing was conducted to identify significant differences in the concrete from the different sample locations. Specimens were also examined petrographically to assess the condition of the cement-aggregate bonds and the features of the cracks through the concrete. The air-void system was evaluated to ensure that it was suitable to protect the concrete from damage due to freezing and thawing.

Assessment

The baseline, inspection and investigation data were reviewed and compared to identify possible causes of the cracking and identify the aging characteristics of the concrete. The properties obtained from the laboratory testing were compared to the behaviour of long-term reference concrete to ensure that the Unit 1 dome concrete was not exhibiting any unusual aging characteristic.

A review of the construction records and the results of the laboratory testing of cores from Units 1 and 4 revealed that, although the compressive strength of the concrete exceeded the required design strength, the Unit 1 concrete had a significantly lower compressive strength than that in the other units. A summary of the laboratory testing for compressive strength conducted during construction is given in Table 1 where the average 28-day compressive strength of standard cured test cylinders for the dome of each unit is presented as a percent of the Unit 1 dome concrete.

The testing of concrete cores obtained from the domes and walls of Units 1 and 4 confirmed that the Unit 1 dome concrete had lower strength than the other areas sampled (Table 1).

The compressive and tensile strength of concrete are related; therefore, a reduction in the compressive strength would indicate a reduction in the tensile strength. Cracking occurs when the tensile strength is exceeded.

A structural analysis revealed that although the domes are structurally sound, radial cracking in the top of the dome could occur under service conditions. The expected crack configuration was similar to the cracking observed in all of the reactor building domes. The design assessment also confirmed that the difference in the extent of cracking between units could be explained by a lower concrete tensile strength in the Unit 1 dome.

Based on visual inspections and laboratory examination of the concrete cores, it was determined that the hairline cracks had likely developed soon after the domes were constructed.

Although the cracks had likely been present for some time, it was found that unique thermal conditions existed during previous tests which prevented the hairline cracks from opening to the extent that allowed the loss of air from the dome recorded in 1992. These thermal conditions relate to the relative temperature of the concrete versus that of the air inside and outside the building.

TABLE 1

Pickering NGS 'A'
Units 1 to 4
Concrete Compressive Strength of Reactor Building Domes

Unit Number	Compressive Strength of Dome Concrete Construction Data (Percent of Unit 1 Dome Concrete*)	Compressive Strength of Cores After 20 Years of Service (Percent of Unit 1 Cores**)
Unit 1	100%	100%
Unit 2	130%	-
Unit 3	129%	-
Unit 4	117%	152%

* The average 28-day compressive strength of the Unit 1 dome concrete was 3450 psi. The design compressive strength was 3000 psi at 28 days.
** Based on limited test data.

Repair Program

A number of detailed repair options were reviewed to reduce or eliminate the leakage through the dome. These options included post-tensioning the dome, adding large masses to prevent the cracks from opening, sealing the surface with fibre reinforced concrete, adding an additional layer of concrete, sealing the cracks by epoxy injection and applying a coating material. Based on structural analysis, laboratory testing, economic considerations and operational limitations, it was decided to apply a coating material to the top of the dome where most of the leakage through the cracks occurred.

The selection of a suitable material was based on an extensive laboratory evaluation and testing program. Models were constructed in the laboratory and subjected to various environmental conditions including temperature extremes from -25°C to 30°C. In addition to the laboratory program, a series of field trials were conducted to optimize application procedures.

After extensive material testing of various types of polymeric coatings a single component, elastomeric polyurethane-based coating was selected to be applied to the top portion of the exterior surface of the dome (Figure 4).

Solution

Based on the review of the construction data, evaluation of the condition of the concrete and structural analysis of the dome, the cause and future development of the cracks was established. Repairs were undertaken to reduce the leakage so that the pressure test leakage would not exceed the licensing limits (Figure 3). Programs to monitor the long-term performance of this coating have been implemented in both outdoor exposure sites and under accelerated conditions in the laboratory.

CONCLUSIONS

The performance requirements and long service life of concrete structures used in nuclear power plants requires special inspection, monitoring and repair methods. Periodic in-service inspections are used to identify concrete deterioration and the need for repairs. The long-term performance of the concrete is predicted by utilizing the inspection results and information from long-term concrete studies and material databases. When necessary, repairs are undertaken to restore the performance of the structure to acceptable levels and thereby maintain the service life of the structure.

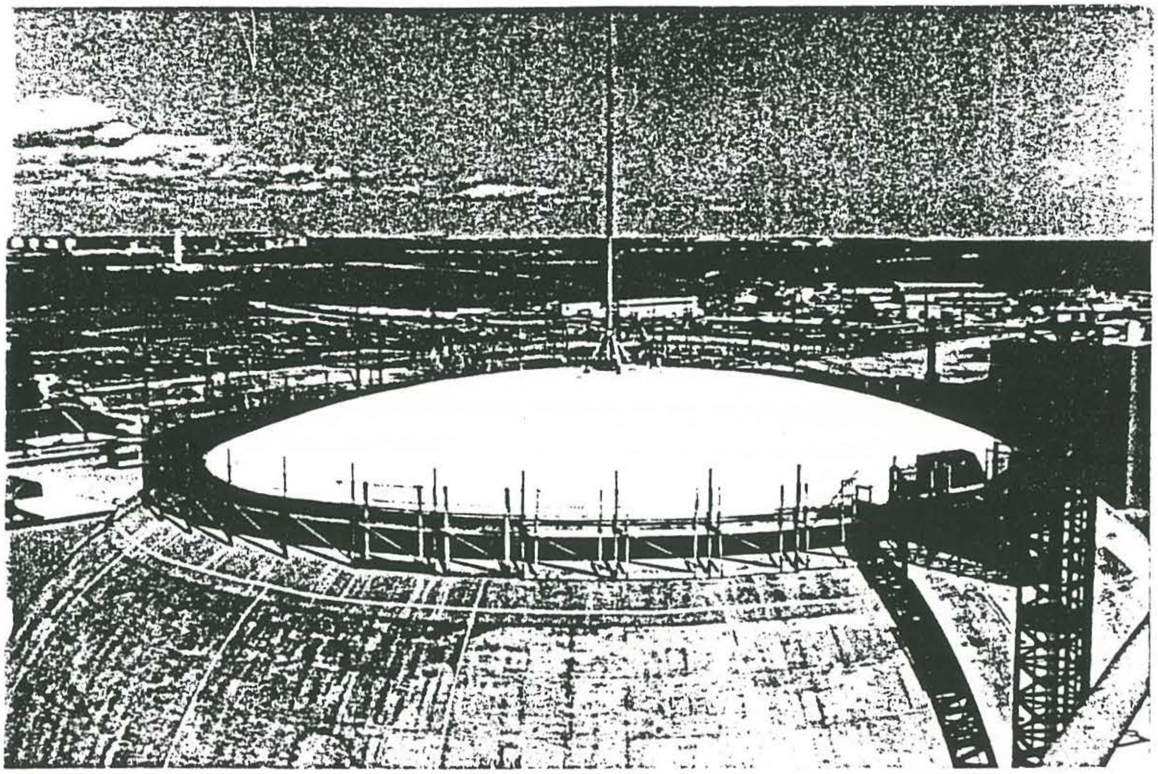

Figure 4: Pickering NGS 'A' Unit 1 after concrete coating applied.

ACKNOWLEDGEMENT

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