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Overview of the Use of Prestressed Concrete in U.S. Nuclear Power Plants

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Abstract

The containment system of a nuclear power plant provides a key part of the overall plant's engineered-safety features. The structure serves as the final barrier against release of any radioactive fission products to the environment and consideration of public safety is one of the primary criteria in providing such a barrier.

Originally the containment was envisioned as a static pressure envelope fabricated of steel and which would adequately contain the fission products released from the primary system during any credible accident scenario. As the size of the nuclear power plants increased, the costs of fabricating containment structures from stress-relieved steel plate became significant and it became advantageous to fabricate the containments of concrete. In addition to economic advantages, the concrete containments could be fabricated in virtually any size (thickness) and shape, they generally utilize indigenous materials for their construction, and they exhibit a ductile mode of failure (leak before break) which is predictable and observable. The paper outlines the extent of the use of prestressed concrete containments in nuclear power plants. However, the accident at Three Mile Island has changed the design parameters associated with the containment. In addition to containing the radioactivity during a postulated maximum LOCA, future containment designs should also provide for pressures generated during degraded core accidents. The change might give a slight edge to the application of prestressing in containment design.

The evolution of large size prestressing systems in the United States and abroad has been the result of the need to resist high pressures with the minimum number of tendons. Furthermore, corrosion inhibiting materials evolved simultaneously with the use of large size prestressing tendons. Cement grout and organic-petrolatum-based compounds needed to be specially formulated to assure thorough penetration through the tendon elements. Early in the development of prestressed concrete containments extensive dialogue occurred between the Nuclear Regulatory Commission (known then as the Atomic Energy Commission) and the industry relative to the use of portland cement grout as a corrosion inhibitor. Concern by the regulators relative to the inability to inspect the prestressing tendons to insure their structural integrity resulted in the issuance of two regulatory guides (RGs) by the NRC: (1) "Qualifications for Cement Grouting for Prestressing Tendons in Containment Structures (RG 1.107)" and (2) "Inservice Inspection of Prestressed Concrete Containment Structures with Grouted Tendons (RG 1.90)." According to some observers this action eventually eliminated any incentives for the use of grouted tendons in prestressed concrete containments.

In the United States it is required that the condition and functional capability of the ungrouted post-tensioning systems of prestressed concrete nuclear power plant containments be periodically assessed. This is accomplished, in part, systematically through an inservice tendon inspection program which must be developed and implemented for each containment. An overview of the essential elements of the inservice inspection requirements is presented and the effectiveness of these requirements is demonstrated through presentation of some of the potential problem areas which have been identified through the periodic assessments of the structural integrity of containments. Also, a summary of major problems which have been encountered with prestressed concrete construction at nuclear power plant containments in the United States is presented; that is, dome delamination, cracking of anchorheads, settlement of bearing plates, etc. The paper will conclude with an assessment of the overall effectiveness of the prestressed concrete containments.

1. Introduction

The principal use of prestressed concrete in the U.S. Nuclear Power Plants is in the construction of their containment structures. The containment structure (or containment) is a vital engineering safety feature of a nuclear power plant. It encloses the entire reactor and reactor coolant system, and serves as the final barrier against release of radioactive fission products to the environment under postulated design basis accident (DBA) conditions. To perform this function it is designed to withstand loadings associated with loss-of-coolant accident (LOCA) resulting from a double-ended rupture of the largest size pipe in the reactor coolant system. The containment is also designed to retain its integrity under low probability ($<10^{-4}$) environmental loadings such as those generated by earthquake, tornado and other site specific environmental events such as floods, seiche, and tsunami. Additionally, it is required to provide biological shielding under both normal and accident conditions, and is required to protect the internal equipment from external missiles, such as tornados or turbine generated missles and aircraft impact (where postulated).

An additional functional requirement for containments has come into play since the accident at Three Mile Island. This requirement consists of maintaining the integrity of the containment under thermal and pressure loads (symmetrical or nonsymmetrical) ensuing from the detonation of hydrogen generated as a result of the metal-water (steam) reaction under degraded core conditions. Dry containments, such as the one at Three Mile Island, which are designed for high LOCA pressures, are not affected by this additional requirement; however, the pressure suppression type containments (PWR ice-condenser, and some BWR containments), designed for low LOCA pressures, are subjected to a thorough evaluation. This requirement may become one of the controlling criteria in the design of future containments.

The functional requirements for containments are satisfied by various types of composite and hybrid steel-concrete constructions. Originally, the containment was envisioned as a static pressure envelope fabricated of steel with a separate radiation shield. As the size of the nuclear power plants increased, the costs of fabricating high pressure containment structures from stress-relieved steel plate became significant, and engineers started looking for alternatives such as steel-lined reinforced concrete which, in addition to economics, had advantages with respect to: improved construction schedules, earlier construction of interior containment structures and erection of equipment, and they can be designed to carry loads other than pressure and temperature (pipe anchors, equipment supports, etc.). Table I presents a distribution of construction types relative to various containment concepts utilized in the United States.

2. Evolution of Containment Configurations and Prestressing Systems

2.1 Containment Configurations

The first prestressed concrete containments were partially prestressed in the vertical direction only with mechanically spliced reinforcing steel in the hoop direction and in the dome. Fully prestressed concrete containments were first built in the late 1960's being cylindrical in shape with shallow dome and resting on a reinforced concrete slab. The dome is prestressed by three sets of tendons at 60° to each other and which are anchored at the side of the thickened dome-cylinder transition (ring girder). The cylinder walls are prestressed with both vertical and hoop tendons. The vertical tendons are anchored at the top to the ring girder and at the bottom of the foundation mat in specially constructed tendon galleries. Anchorage of the hoop tendons is to buttresses protruding from the cylindrical wall. Initial containment designs used six buttresses with subsequent designs utilizing either three or four buttresses. Although anchorage of hoop tendons at three buttresses, as compared to six, increased the length of tendons and friction force, the combination of a low coefficient of friction ($\mu<0.1$) of pre-coated prestressing tendons and the reduced number of buttresses and anchorages produced cost savings. It was for these same reasons that the present-day prestressed concrete containment design evolved; that is, a cylinder with hemispherical dome using inverted-U tendons.

2.2 Prestressing Systems

A posttensioned prestressing system consists of a prestressing tendon in combination with methods of stressing and anchoring the tendon to hardened concrete. Three general categories of prestressing systems exist, depending on the type of tendon utilized: wire, strand or bar. The wire systems utilize a grouping of parallel wires. Strand systems utilize groupings of factory-twisted wire. Bar systems utilize a grouping of high-tensile-strength steel bars. Anchorage is provided by wedges, button-heads, or nuts.

The primary evolution in prestressing systems over the past few years has been with respect to system capacity. Prior to the advent of PCCs the prestressing systems were relatively small size; that is, less than 4.45 MN (500 ton) ultimate capacity. The requirement to withstand high forces resulting from a combination of increased volumes and pressures of the dry pressurized-water reactor (PWR) containments necessitated the development of tendon systems with increased capacity [8.0 to 10.7 MN (900 to 1200 ton]. This development permitted increased spacing of tendons and reduced congestion by almost halving the number of tendons, tendon ducts and anchorages. The large size tendons were developed by using groupings of multi-wire, multi-strand, or bar systems. In the United States, the 8.9 MN (1000 ton) systems approved for use include: (1) BBRV (wire), (2) VSL (strand) and (3) Stressteel S/H (strand).

3. Evolution and Performance of Corrosion Inhibitors for Prestressing Tendons

Prestressed concrete containments essentially are spaced steel structures since their strength is derived from a multitude of steel elements made up of deformed reinforcing bars and prestressing which are present in sufficient quantities to carry imposed tension loads. The prestressing therefore plays a vital role in insuring the structural integrity of the containment throughout its 30- to 40-year design life. However, because the tendons are fabricated from high-strength steels [>1.6 GPa (230 ksi)] in the form of many relatively small-diameter wires or several strands fabricated from small-diameter wires, and the tendons can be subjected to sustained stresses up to 70% of their ultimate tensile strength, they are more susceptible to corrosion than ordinary reinforcing steels and must be protected. Protection of the prestressing steel is generally provided by filling the ducts with portland cement grout or microcrystalline waxes (petrolatums) compounded using organic corrosion inhibitors.

3.1 Grouting

The effectiveness of portland cement grout as a deterrent to corrosion of steel is evidenced by its performance history in prestressed concrete for over 50 years and its use in reinforced concrete construction for over 100 years. Corrosion of steel in correctly formulated concrete (cement) is prevented by the high alkalinity (pH >12.5) of the $Ca(OH)_2$, which produces a passivating gamma iron oxide film on the steel surface [1, 2]. When corrosion does occur it is generally the result of a destruction of the passive layer. This can result from reduction of the alkalinity associated with calcium hydroxide, calcium silicates, and aluminates [3]; from carbonation; or from the presence of high concentrations of chloride, sulfide or nitrate ions. Current grouting materials have evolved over the years to try to ensure that the prestressing materials are completely encapsulated to prevent corrosion; that is, grouts are specially formulated with water reducers and expansive agents to minimize the potentially deleterious effects of water separation and shrinkage.

3.2 Petrolatum-Based Coatings

Although the introduction of petrolatum-based coatings as corrosion protection is much more recent than the use of portland cement grout, the coatings have gained prominence in PCCs in the United States because of their ease of inservice inspections. Additional advantages include: (1) encapsulation provides an approximate 50% reduction in friction factor which permits the use of longer tendons; (2) tendons may be relaxed, retensioned, and replaced as required; and (3) during construction there is the possibility of more efficient scheduling of event sequence because the tendons are protected in the shop.

The petrolatum-based coatings have evolved over the years to better attune the products to the nuclear unbonded tendon containment applications. Initially the product was a casing filler containing polar wetting agents, rust preventative additives, micro-crystalline waxes and proprietary items formulated to be water displacing, self-healing and resistant to electrical conductivity. The next generation of materials were formed by adding a plugging agent to the casing filler to increase the low flow point of the products (∿39°C (100°F)] to keep them from seeking loose sheathing joints and flowing into concrete hairline cracks. A subsequent refinement involved incorporation of a light base number (3 mg KOH/gm of product) to provide alkalinity for improved corrosion protection. Finally, the current generation of materials have evolved through a series of modifications to produce products which have been formulated to: increase the viscosity without sacrificing pumpability, raise the congealing point to 57-63°C (135-145°F), increase the resistance to flow from sheathing joints, improve the water resistance, and raise the base number (35 mg KOH/gm product) to provide higher reserve alkalinity [4].

3.3 Overview of the Performance of Prestressing Tendons [4-8]

Prestressed concrete was first used for nuclear pressure vessels in 1960. As of April 1982, 27 prestressed concrete reactor vessels (PCRVs) were either in operation or scheduled for operation in Europe (France, United Kingdom, Spain and Germany) and the United States. In addition, there are 116 containments for pressurized water reactors (PWRs) and 33 containments for heavy-water reactors (HWRs) commissioned or scheduled for commission throughout the world. Of the 116 containments for PWRs, 62 are in the United States. Reviews of the performance of the prestressing tendons in these structures have revealed that corrosion-related incidents are extremely limited. The evolution of corrosion inhibitors and the use of organic-petrolatum-based compounds designed especially for corrosion protection of prestressing materials have virtually eliminated corrosion of prestressing materials. The few incidences of corrosion that were identified, occurred early in the use of prestressed concrete for containment structures. Where these failures involved tendons coated by petroleum-based materials, the failures generally resulted from the use of off-the-shelf corrosion inhibitors that had not been specially formulated for prestressing materials.

4. Problems and Experiences During Construction of PCCs

In general, the development of the various components of prestressing systems has been substantiated by careful study, testing and thorough evaluations by vendors, engineers and regulators. However, there have been a few occasions, either due to breakdown of the quality control, or due to nonscrutinized construction methods, where significant component failures have occurred. The following is a summary of such reported failures.

At Calvert Cliff nuclear plant (Units 1 and 2) some of the bearing plates under anchor heads of vertical tendons became depressed into the concrete [9]. These depressions ranged in size from 0.8 mm (0.03 in.) to 4.8 mm (0.19 in.) and were generally on the inside edges of the plates. Removal of the plates identified the cause to be inadequate concrete compaction under the plates which produced large size voids. The problem was corrected by detensioning the tendons of affected plates, reinstalling the plates, pressure grouting and retensioning.

Failures occurred in the top anchor heads of 170-wire rock anchor tendons at Bellefonte nuclear plant (Units 1 and 2) [10]. Anchorage of the 12.2 m (40 ft) long tendons to the rock was to be performed using a two stage grouting operation. Initially the tendons were to be grouted over about one-half their length to anchor the bottom heads. This was to be followed by addition of sufficient material to grout the tendons over their remaining length except for the final 0.9 to 1.5 m (3 to 5 ft.). Coupling of the containment vertical tendons to the rock anchors was to be by means of threaded coupling devices. However, during installation of the rock anchorages failures of the top anchor heads were observed just prior to the second stage of grouting. One anchor head failure was observed in which failure of 23 of 170 wires in a tendon occurred. (Figures 1-2 note some of the features of the anchor head cracking and fractures.) In-depth metallographical and fractographical examinations in conjunction with the study of the environment indicated that the failures were the result of stress corrosion cracking of highly stressed AISI 4140 anchor heads in an aqueous environment of varying pH levels. In addition it was noted that during the period between the first and second stage grouting the top anchor heads were covered with grease cans filled with lime water having a pH of 11 to 13.

In November 1979 four anchor heads of 179-wire tendons failed between 1 and 64 days after post-tensioning the Unit 1 containment at the Byron nuclear plant [11]. A thorough study of the chemistry, metallurgy and fracture phenomena indicated that the failure was due to tempered-martensite embrittlement. Failures were time delayed and occurred in a decreasing stress field.

Concrete cracking and grease leakage were noted at various locations on the dome surface, predominately in the southern portion as shown in Fig. 3, after tensioning of approximately two-thirds of the dome tendons at Turkey Point Nuclear Power Plant (Unit 3) [12]. After a thorough examination of the concrete materials, construction method and prestress tensioning sequence, it was concluded that the dome delaminations were caused by the combined action of inadequate concrete consolidation and weakness at construction joints. Some engineers at NRC, however, believe that the delaminations were caused by exceeding the radial tensile strength of "weak" concrete and that well designed radial reinforcing would help prevent the situation from repeating in the domes of similar containments.

In April 1976, surface cracking and voids in the dome concrete at Unit 3 of Crystal River Nuclear Power Plant were discovered (by accident) after the dome had been constructed and fully post-tensioned (Fig. 4) [13]. Primary causes of the delaminations were thought to be the use of low quality coarse aggregate materials accompanied by high radial tension forces above the top tendons, and compression-tension interaction. Other potential contributing factors were tendon misalignment and construction methods. Corrective measures included detensioning of some of the tendons, removal of the delaminated cap, installation of top orthogonal and radial reinforcing, and installation of a new cap concrete.

5. Regulatory Requirements and Effectiveness of Inservice Inspections of Prestressing Tendons

5.1 Background

Early in the development of PCCs extensive dialogue occurred between the Nuclear Regulatory Commission (known then as the Atomic Energy Commission) and industry relative to the use of portland cement grout as a corrosion inhibitor. Extensive tests were conducted to ensure adequate penetration of grout through vertical bar, hoop, and vertical strand tendons [14-16]. However, the regulators were concerned about not being able to positively check the integrity of the prestressing system throughout the life of the structure. As a result of discussions and public meetings, two regulatory guides were developed: (1) "Qualifications for Cement Grouting for Prestressing Tendons in Containment Structures (RG 1.107)" and (2) "Inservice Inspection of Prestressed Concrete Containment Structures with Grouted Tendons (RG 1.90)." This action permits the use of grouted tendons in containments without time consuming meetings and discussions. Though the intent was to thoroughly scrutinize grout material and installation, and to periodically check the status of containment, these actions did not encourage the use of grouted tendons in PCCs.

5.2 Regulatory Requirements

In the United States it is required that the condition and functional capability of the unbonded post-tensioning systems of prestressed concrete nuclear power plants be periodically assessed. This is accomplished, in part, systematically through an inservice tendon inspection program which must be developed and implemented for each containment. The basis for conducting the inspections is presented in Regulatory Guide 1.35 "Inservice Inspections of Ungrouted Tendons in Prestressed Concrete Containment Structures (Rev. 2)." The intent of RG 1.35 is to provide utilities with a basis for developing inspection programs and to provide reasonable assurance, when properly implemented, that the structural integrity of the containment was being maintained. The NRC does not require periodic reporting of inspection results except when the technical specification requirements (generally based on RG 1.35) of particular nuclear units are not met, or where there are obvious problems with materials, tendon prestress measurements, and/or an appreciable amount of cracking, grease leakage, etc. Because of the variety of factors such as tendon corrosion, anchorage failure, and material defects which can weaken the containment's structural integrity, the Guide has sought to examine all sources of potential problem areas before they become critical. Basic components covered by the Guide include: sample selection, visual inspection, prestress monitoring tests, tendon material tests and inspections, and inspection of the filler grease.

Tendon sample selection criteria are specified for typical prestressed concrete containments having a shallow dome-shaped roof on cylindrical walls. For the shallow-dome roof containment sample selection includes six dome tendons (two from each 60° group or three from each 90° group), five vertical tendons and ten hoop tendons. For the hemispherical dome-shaped roof containment sample selection criteria include 4% of the U-tendon population (not less than four) and 4% of the hoop tendon population (not less than nine) with each result rounded to the nearest integer. If no problems are uncovered during the first three surveillances (scheduled 1, 3, and 5 years after the initial structural integrity test) then the criteria for sample selection are relaxed. For the shallow-dome roof containment the criteria become three dome tendons (one from each 60° group or one from each 90° group plus one additional randomly selected dome tendon), three vertical tendons and three hoop tendons. For the hemispherical-dome roof containment the criteria becomes: (1) 2% of the U-tendon population with results rounded off to the nearest integer, but not less than two; and (2) 2% of the hoop tendon population with the result rounded off to the nearest integer but not less than three. In all cases, the tendons are to be selected on a random but representative basis.

Anchorage assembly hardware of all tendons selected for inspection are to be examined visually. The method used for removing grease in order to permit examination of the stressing washers, shims, wedges, and bearing plates should neither increase the effects of corrosion nor damage the steel. During integrated leak rate testing (ILRT), while the containment is at its maximum test pressure, visual examination of the exterior of the concrete surface is performed to detect areas of widespread concrete cracking, spalling or grease leakage.

Stress levels of each of the tendons in the sample selected for inspection are monitored by performing lift-off or other equivalent tests. These tests include the measurement of the tendon-force level with properly calibrated jacks and the simultaneous measurement of elongations. Allowable elongations, jacking loads, tolerances, and the influences of such variables as temperature are to be predetermined. Acceptance criteria for the results state that the prestress force measured for each tendon should be within the limits predicted for the time of the test. No more than one tendon per sample may be considered defective or a reportable condition occurs, and the cause of the defect must be located and corrected. If only one tendon per sample is defective, then two additional tendons (one on each side of the defective) are tested. If either or both of the two additional tendons are defective, a reportable condition occurs and the cause of the defect is located and corrected. Otherwise, the single defective tendon is considered unique and acceptable.

Previously stressed tendon wires or strands from one tendon of each type are to be removed from the containment for examination over their entire length to determine if there is evidence of corrosion or other deleterious effects. At least three samples are to be cut from each wire or strand (each end and mid-length) and tensile tests conducted. Where either stress cycling is suspected or a potentially corrosive environment is thought to exist, tests simulating these conditions are to be conducted. At successive inspections, samples should be selected from different tendons.

A sample of grease from each tendon in the surveillance is to be analyzed and the results compared to the original grease specification. The original grease specification is subject to the ASME Code which has limits on the amounts of impurities that may be present at the time of installation (10 ppm on the quantity of water-soluble chlorides, nitrates, and sulfides, but no limit is specified for water content). Also the presence of voids in the grease is to be noted. The method for checking the presence of grease is to take into account: (1) minimum grease coverage needed for different parts of the anchorage system; (2) influence of temperatures variations; (3) procedure used to uncover possible voids in grease in trumpet; and (4) requirements imposed by grease specifications, qualification tests and acceptability limits.

5.3 Experiences from Inspections of PCCs [5, 7]

Three instances of tendon force measurements (lift-off tests) have been reported where the force measured was lower than the minimum required prestress level (40 year losses considered). Probably the most frequently found defect is missing buttonheads, but this problem is generally identified during construction or subsequent inservice inspections, and account is also taken in the design for a few non-effective wires in a tendon or group of tendons. Cracking of anchorheads of buttonhead systems made of AISI 4140 steel has also been reported (apparently due to hydrogen stress cracking); but these incidents also have been identified during construction. Two incidences have been reported of grease leakage through cracks to the exterior surface of the containment apparently due to a combination of inadequate duct joints and grease expansion due to thermal effects. There have also been two incidences of grease discoloration due to containments with the probable cause being entry of contaminated rain water into the tendon ducts during construction. Except for one instance in which a significant amount of water was found in several tendon ducts (despite presence of water, corrosion was found to be minor and steps were taken to eliminate recurrence), little water has been found during inspections. Only a few occurrences of wire corrosion have been identified, but these did not result in wire breaks and were so minor that component replacement was not required (it was concluded that the corrosion had occurred prior to filling the ducts with corrosion inhibitor). There have also been a few incidences of incomplete filling of the tendon ducts with corrosion inhibitors, but this has not caused any serious difficulties and has been corrected.

6. Summary

The evolution of containment systems in the United States is presented as well as motivations for changes. Prestressing systems and the mechanisms utilized for providing corrosion protection of these systems are reviewed. A summary of experiences and problems during construction of PCCs is presented. Results obtained indicate that the few construction problems which occurred were identified and remedied prior to a structure being placed in service. A review of regulatory requirements relative to inservice inspections of prestressing tendons is presented. The few incidences of problems or abnormalities that were identified in these inspections were found to be minor in nature and did not threaten the structural integrity of the containments.

In conclusion, the frequency of occurrence of incidences which could lead to a decrease in the functional capability of PCCs is small, especially considering the number of PCCs in service in the United States. Where problems did occur, they generally were the result of construction practices, and were identified and corrected during either the construction phase, the initial structural integrity test, or in subsequent inservice inspections. Thus it can be concluded that the inspections have been effective in achieving their desired objectives of uncovering and correcting potential problem areas.

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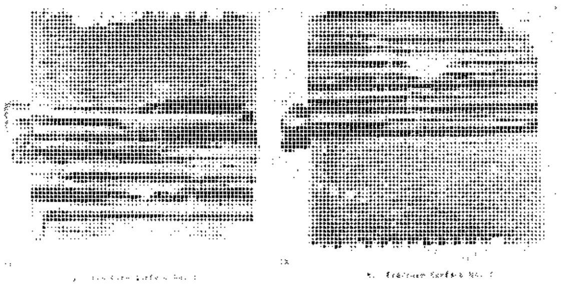
Table 3. Summary of operating and future U.S power reactor containment structures*

COMMERCIAL U.S. POWER REACTORS		CONTAINMENT STRUCTURES: CONCRETE: Prestressed Vertical Cylindrical and Dome, Flat Base	CONCRETE: Reinforced Concrete Hemispherical Dome Vertical Cylindrical Body And Flat Base	CONCRETE: Other Concrete Structures	STEEL: Light Bulb Torus Containment	STEEL: Steel Sphere	STEEL: Hemispherical Dome Cylindrical Body and Ellipsoidal Base	STEEL: Hybrid Steel Steel Dome and Body Reinforced Concrete Base	NUMBER OF STRUCTURES: Sub-total	NUMBER OF STRUCTURES: Sub-total
PWR's	Atmospheric Containment Structures Without Pressure Suppression Systems	55	20	2		11	11		99	120
	Sub Atmospheric Containments		11					*	11	
	Ice Condenser Containments		2					8	10	
BWR's	Mark I			2	23				25	60
	Mark II			10					10	
	Mark III		6					15	21	
	Pre-Mark			2		2			4	
Number of Structures	Sub-total	55	39	16	23	13	11	23		
	Sub-total	110			70					
	Total									180

*Washington 2 is not included in the table.

ORNL PHOTO 0410-83

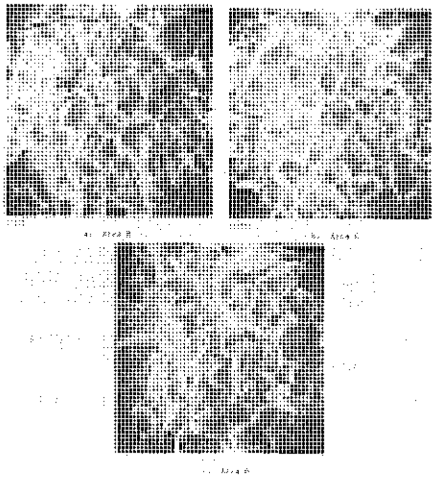


a. Fracture Surface No. 1

b. Fracture Surface No. 2

Fig. 1. Appearance of two fracture faces on anchor JA-81-1: Bellefonte.

ORNL PHOTO 0411-83



a. Area B

b. Area C

c. Area D

Fig. 2. SEM photographs of areas B, C and D in Fig. 1.

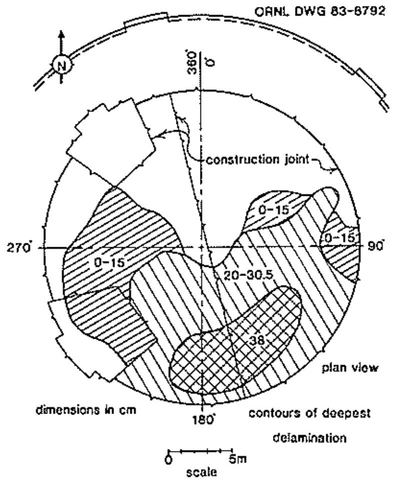


Fig. 3. Extent of dome delamination in Unit 3 containment at Turkey Point.

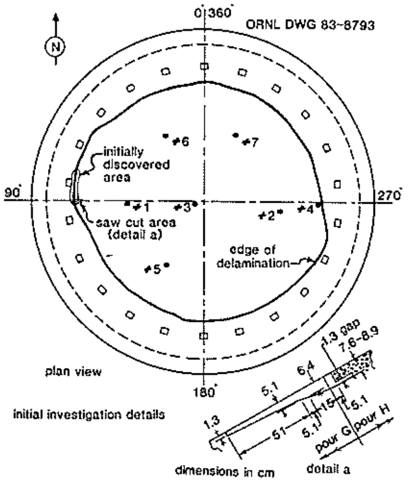


Fig. 4. Extent of dome delamination in Unit 3 containment at Crystal River.